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DECEMBER 1989
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How the earth generates its magnetic field.

Microclusters: a new state of matter.

The first color photographs: a portfolio.

Birds of paradise: *120 years after Darwin, we continue to learn from them about sexual selection.*

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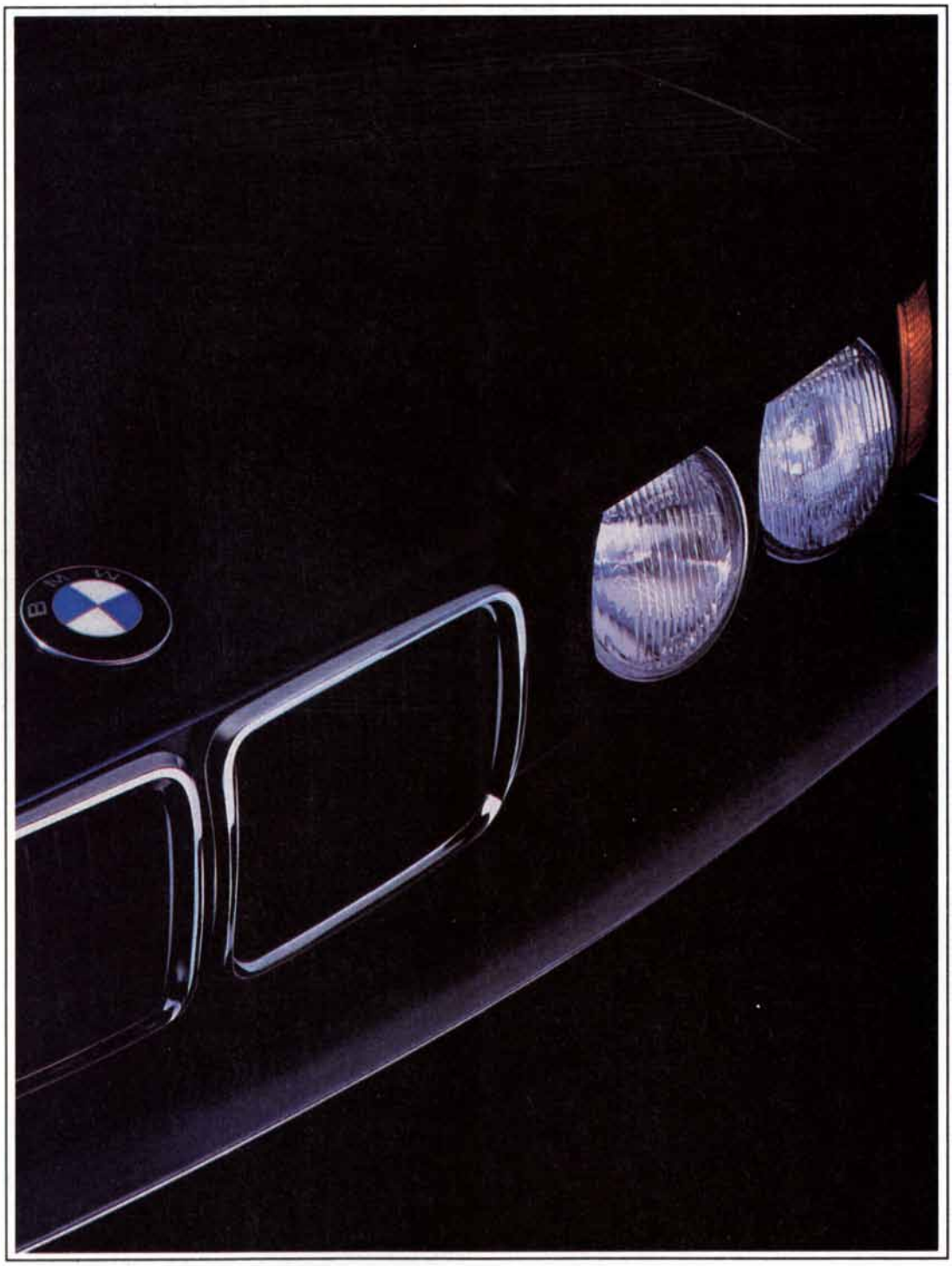
GOODYEAR



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SCIENTIFIC AMERICAN

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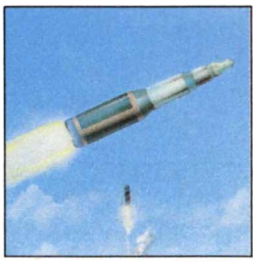
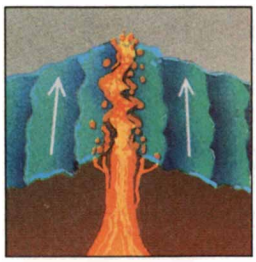
61 

Getting Out of the START*ing* Block

Sidney N. Graybeal and Patricia Bliss McFate

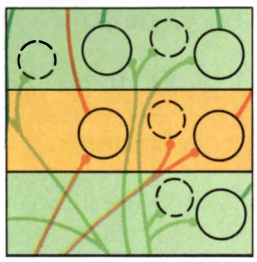
Worries about verification should not be putting the brakes on START. The best way to reach a beneficial agreement is to pursue negotiations on arms reduction and on verification together. The key, the authors say, is to try to match the arms-reduction requirements of a treaty with the ability to detect and deter militarily significant violations.

68 

The Evolution of the Earth's Magnetic Field

Jeremy Bloxham and David Gubbins

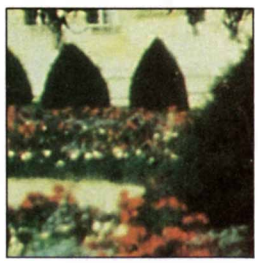
The origin of the field has fascinated more than a dozen generations of physicists. Molten iron in the outer core, driven by convection and influenced by the earth's rotation, acts as a dynamo that generates the field. Now historical records of magnetic-field changes yield new insights into the process and into how the field may behave in the future.

76 

Synapse Formation in the Developing Brain

Ronald E. Kalil

How is the brain wired? How do some 100 billion nerve cells in the developing brain come to be linked correctly to one another? Like muscles, it turns out, the nerve cells need exercise. More specifically, formation of the proper synaptic connections between neurons depends in part on the electrical activity of the developing neurons themselves.

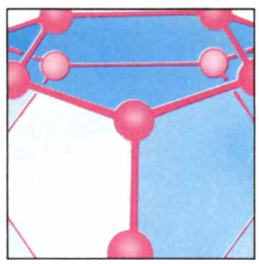
88 

SCIENCE IN PICTURES

The First Color Photographs

Grant B. Romer and Jeannette Delamoir

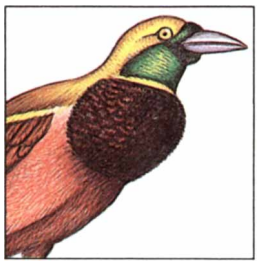
Attempts to make color images are as old as photography itself. Ingenious schemes devised in the 19th century laid the basis for most of today's processes and left behind an engaging record of bygone times and places.

110 

Microclusters

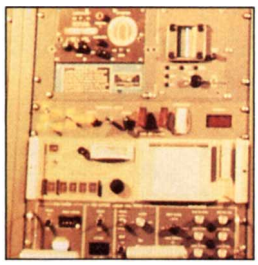
Michael A. Duncan and Dennis H. Rouvray

Divide a piece of metal again and again and eventually you arrive at a new state of matter: a microcluster of from two to 100 or so atoms. Somewhere en route, the sample will have started to behave in new ways, exhibiting novel chemical, electrical and optical properties that could have applications in catalysis and other industrial processes.

116 

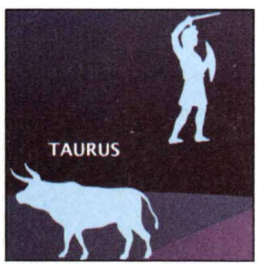
The Birds of Paradise
Bruce M. Beehler

Charles Darwin and Alfred Russel Wallace were fascinated by them; evolutionary biologists and students of animal behavior still prowl the New Guinea rain forests to observe them. In the Paradisaeidae, foraging ecology has been shown to orchestrate complex interrelations among plumage, reproductive behavior and social organization.

124 

Teleoperators
William R. Uttal

Someday, when artificial intelligence or another form of computer smarts comes into its own, autonomous robots may replace human beings in toxic, radioactive or otherwise hostile environments. Until then, new teleoperator technology can combine human intelligence and manipulative ability in real time with the long arm of mechanical linkages and advanced electronics.

130 

The Mithraic Mysteries
David Ulansey

For almost a century students of this ancient Mediterranean cult have sought an allegorical interpretation of the significance of the religion's central icon: the image of a young man killing a bull. The author and other scholars have begun to solve the mystery by refastening that image, the "tauroctony," to its astronomical and theological moorings.

DEPARTMENTS

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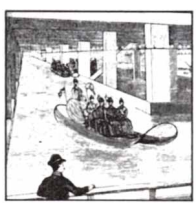
16 

50 and 100 Years Ago

1889: Gondolas glide over an indoor canal at the Boston Maritime Exhibition.

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Send in t

There's a good reason why more cars are looking more and more alike. It's called the Accord.

The Honda Accord has become the benchmark for other car makers. They take it apart. Study it. Take it apart again.

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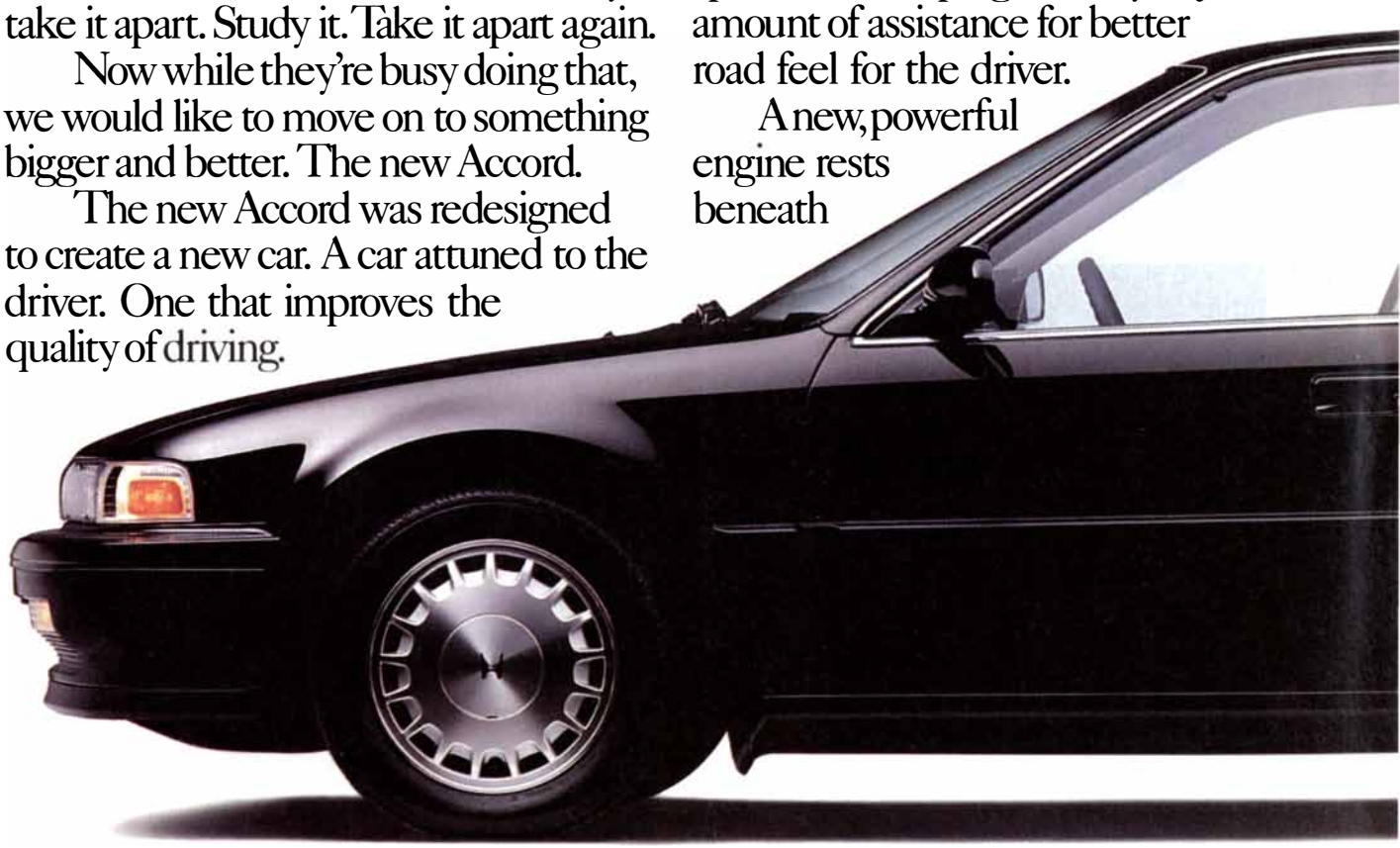

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he clones.

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HONDA

The New Accord

THE COVER painting depicts sexual dimorphism in the raggiana, a bird-of-paradise species endemic to the rain forests of New Guinea (see "The Birds of Paradise," by Bruce M. Beehler, page 116). The male is highly visible during courtship. He typically perches on a branch above the female, bending over so that his head is upside down and his wings are extended forward. In that position his bright-orange nuptial plumes are fully displayed to the rather drab female, who watches from below.

THE ILLUSTRATIONS

Cover painting from *The Birds of Paradise and Bower Birds,* by William T. Cooper and Joseph M. Forshaw. Copyright © 1977.

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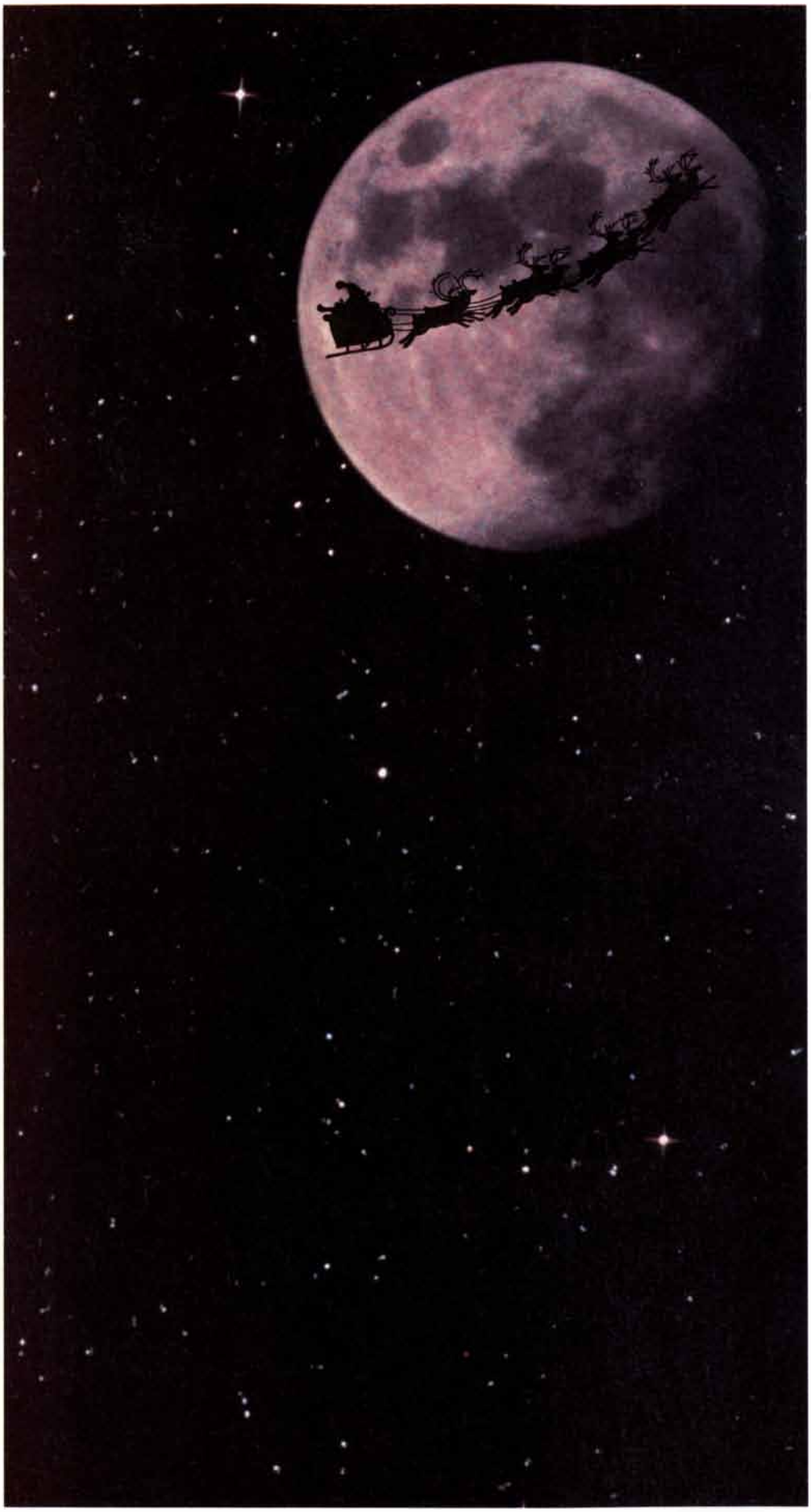

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LETTERS

To the Editors:

In "Visual Thinking in the Ice Age" [SCIENTIFIC AMERICAN, July], Randall White states of the "earliest" beads: "The Aurignacians penetrated them by gouging from either side.... Another technique was to incise a groove around the root." These beads are not Aurignacian but come from earlier Châtelperronian levels at Arcy-sur-Cure, a culture providing a Neanderthal skull and a "Mousteroid" (Neanderthal-like) industry. It is therefore possible that the beads were made by late Neanderthals. Bored beads are found even earlier at Bacho Kiro in Bulgaria, dating from some 40,000 years ago, and in Germany perhaps as early as the Micoquian period, about 110,000 years ago.

The earliest painted animal images occur in South Africa at the Apollo 11 cave during the period of the Aurignacian but with no evidence of beads or carving, contrary to White's hypothesis that the appearance of beads in Europe marks the beginnings of visual representation. There is, moreover, early South African evidence for the mining of ocher and earlier European evidence for the use of ocher by Neanderthals and late *Homo erectus*. A quartzite rubbing stone and abraded ocher were found together in Czechoslovakia, dating from about 250,000 years ago, and so body marking may have preceded beads by hundreds of thousands of years. The argument against the use of ocher for body marking assumes an incapacity for early symbol use and "visual thinking." It suggests ocher may have been used to tan hides or to stop bleeding. Yet this interpretation assumes preparation of resources at a level of sophistication the proponents are actually trying to dispute.

The Neanderthals had awls, bone points, smoothing instruments for skins, and stone tools hafted with thongs and resin. They worked wood and skins, mined flint with antler axes, built stone structures (currently being excavated at La Quina in southwestern France) and conceptually mapped the flint resources in their territory in much the same way as anatomically modern humans did. Early anatomically modern humans, in fact, had technologies and subsistence strategies similar to those associated with the Neanderthals.

I have long argued for the evolving capacity for visual thinking, visual problem solving and the nonlinguistic visual mapping and modeling of phenomenological and social processes as a fundamental aspect of hominization, and I have discussed the primate roots of that capacity. Members of a chimpanzee troop are visually differentiated on the basis of age, sex, rank and status, and they behave accordingly. During hominization, natural selection apparently led to a greater capacity to differentiate categories and processes in an increasingly complex and variable social and phenomenological-ecological reality.

This entailed an increasing neurological capacity for abstraction, visual problem solving, two-handed manipulation, thinking in time and the modeling and mapping of territory and social relations in space and time. Language is essentially a referential mode for marking the variable and diverse categories and processes being established in the visual and "envisionable" hominid world. The capacity for visual thinking and visual symbol use began not in the Aurignacian but in the earlier Paleolithic. Anatomically modern humans outside Europe and contiguous areas during the Upper Paleolithic did not, for instance, manufacture beads, although presumably they had language, social complexity and the capacity for symbol use.

The same presumptive errors occur in White's discussion of Upper Paleolithic marking. I have studied more than 20,000 incised and carved artifacts from the world's hunter-gatherer societies. In major publications I have documented the variability in Upper Paleolithic marking modes and indicated that there were at least a dozen types, varying with the class of artifact and the context: decoration, gripping marks, motif accumulations, "killing" marks on animals, pelage patterns, participatory ritual marking, at least one possible gaming tally and, in a specialized and rare category, notations that have an internal structure and organization that sets them apart from the other categories.

I have reported the differences between the internal structure of the Blanchard plaque and that of contemporaneous forms of engraving. White does not provide an analysis of the Blanchard engraving; he merely argues about its seeming similarity to other objects. I also have studied the carved seashell replicas from Blanchard, which White mentions, and I can state categorically that their mode of marking is dramatically different from that of the Blanchard plaque. Incidentally, among the thousands of bone artifacts from the Upper Paleolithic, carved and marked "seashells" happen to occur only at Blanchard.

ALEXANDER MARSHACK

Peabody Museum, Harvard University
Cambridge, Mass.

The author responds:

I respond to Mr. Marshack at the risk of giving greater credibility to his remarks than they deserve. I wish merely to enumerate his many errors of fact and logic.

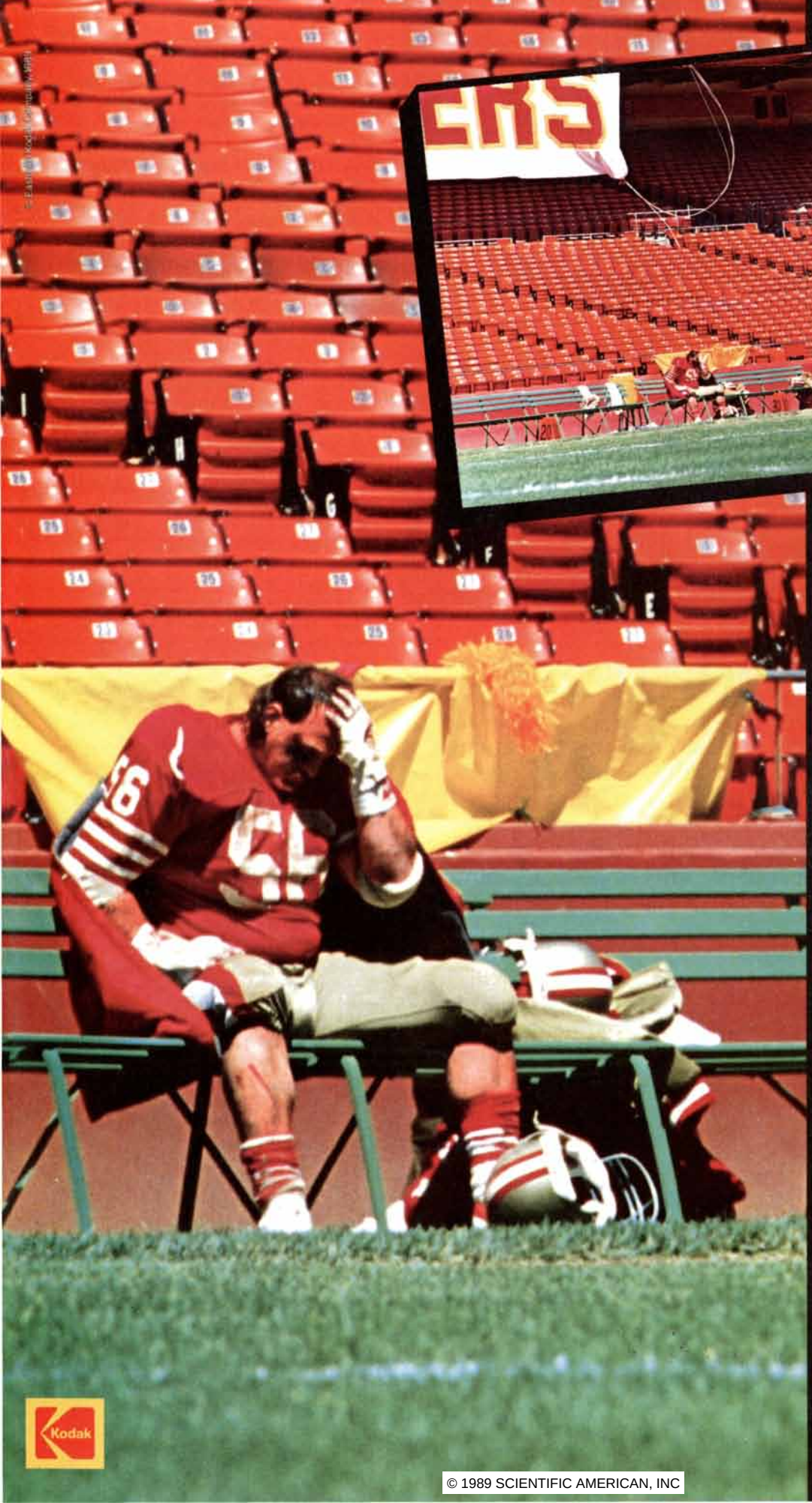
1. Nowhere have I argued that the Neanderthals were not capable of symbolic behavior. Rather, my point is that material forms of visual representation are not inherent in our neurological hardware any more than a cultural innovation such as agriculture is. The processes that selected for the emergence and perpetuation of art and body ornamentation during prehistory were intensely social ones rather than neurological ones: for tens of thousands of years anatomically modern human beings lacked material representations.

2. The earliest credible body ornaments are from the *Aurignacian* levels at Bacho Kiro in Bulgaria and Mladeč in Czechoslovakia, both of which date to about 35,000 years ago or perhaps slightly earlier.

3. Gouged holes appear in Aurignacian levels at Bacho Kiro, and an incised groove or shoulder is present on a moose vestigial metacarpal bone from Mladeč. Several such incised grooves are also present in basal Aurignacian levels at Abri Blanchard and Abri Cellier in France.

4. The 110,000-year age for the alleged bored beads from Bockstein in Germany is widely disputed. Furthermore, published drawings and photographs leave much room for doubt about whether the objects really are human artifacts. Unfortunately they have now been misplaced and are unavailable for study.

5. No convincing body ornaments occur at Neanderthal sites until the Aurignacians entered the same regions, a fact that led a recent conference in Cambridge, England, to suggest that the 33,000-year-old Châtelperronian body ornaments from Arcy-sur-Cure may have resulted from acculturation with the Aurignacian peoples who were their contemporaries in Europe. This proposal is supported by the fact that Châtelperronian ornament technology is indistinguishable from that of the Aurignacians.



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6. Marshack's belief that hematite (ocher) indicates art is an argument of plausibility, which has no place in a scientific approach to the past unless it is phrased as a hypothesis and accompanied by implications that would enable it to be tested.

7. Chimpanzees do not have social identities beyond a basic age- and sex-based dominance hierarchy. Such a simple social pattern can be superseded only through the use of visual and nonvisual symbols.

8. Marshack takes as articles of faith some of the most hotly contested and tenuous of archaeological observations, such as the dating of the Apollo 11 paintings.

9. Body ornaments of Upper Paleolithic age are not absent from areas outside Europe. They have been found in Israel, India and Australia.

10. There is no evidence to support Marshack's characterization of "hominization." Abstraction, visual problem solving and so on are attributes of modern human beings, attributes whose existence in the distant past must be demonstrated rather than merely assumed.

11. Before about 75,000 years ago, there is no empirical evidence for an "increasingly complex and variable social and phenomenological-ecological reality," whatever that might be. Rather, this is Marshack's unfounded justification for assuming a gradualist view of cultural evolution.

12. Marshack's "marking modes" (e.g., "killing" marks) have not been "documented" but rather have been subjectively inferred.

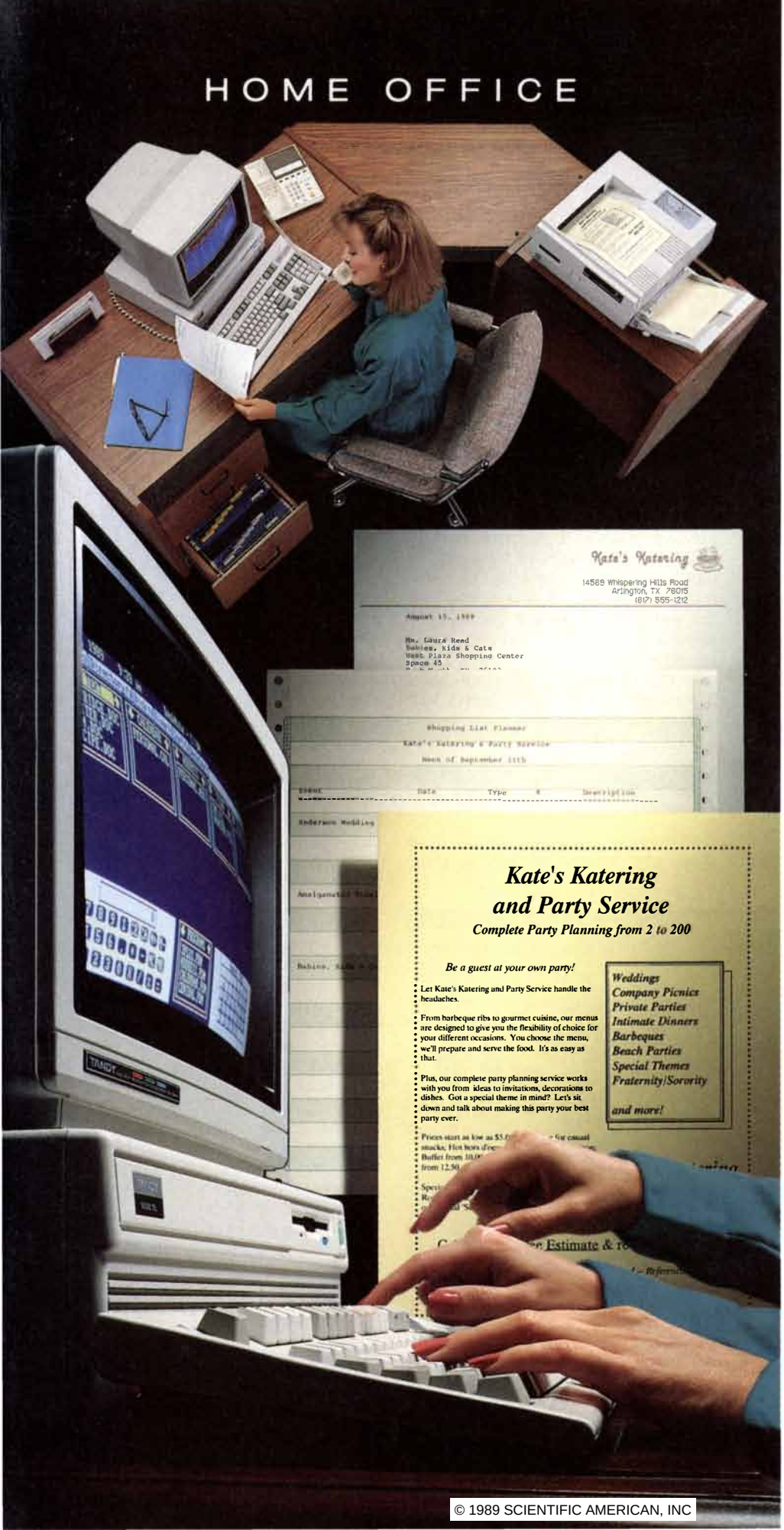
13. Is not my aesthetic interpretation of the Blanchard plaque rendered stronger by the fact that other, formally similar designs were produced by a different "mode of marking"?

14. Marshack claims to have studied the carved "seashells" from Abri Blanchard and says that such objects are found only at Blanchard. In fact, as I observed in my article, these objects are from La Souquette. Without even going into the literature, I can cite other seashell replicas in ivory from the early Upper Paleolithic sites of Pair-non-Pair and Saint-Jean-de-Verges in France and Spy in Belgium.

RANDALL WHITE

ERRATUM

In "The Amateur Scientist" for November, the four drawings on page 117 were printed in the wrong vertical order. The sequence should have been inverted.



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DECEMBER, 1939: "As the war develops, it is possible to make only a guess as to the limits to which chemistry and physics will be applied as aids to aerial frightfulness. There is also the possibility that concentrated effort is being made to seek a practical application of what has been called the greatest scientific discovery of the year—the detonation of atomic energy as exemplified in the self-catalyzing fission of uranium and other substances. Last, we cannot ignore the possibilities of biology. Reports are available that much experimental work has been done on the possibility of employing bacteria as a novel kind of 'ammunition.' If such monstrous methods should ever become practicable, probably a mere knowledge of the power of retaliatory measures will serve as an adequate deterrent against such attempts."

"The only real evidence for an expanding universe is the shifting of lines in the spectra of distant nebulae toward the red end of the spectrum—the 'red shift.' The bolder scientists point out that if the red shift can be accounted for by some other theory, then the nebulae need not be receding and the universe may not be expanding. Several of these theories fit in with the idea of a decrease in the velocity of light. One group of theories suggests that the energies of single packets of light—or 'photons,' as they are called—may gradually decrease during their journey through space, due to such causes as gravitational interaction, interaction with ionized gases, or simply by a gradual diminution of energy with time."

"British authorities have for months been puzzled by mysterious explosions in storage tanks holding their wartime fuel. After a kerosene tank blew up, bubbles of gas were noticed rising from the layer of water at the tank's bottom on which the kerosene had been floating. It was found that the water and sediment contained a new kind of bacteria that can live in kerosene and ferment it into 10 percent ethane and 90 percent methane. It was undoubtedly these gases that caused the explosion."

SCIENTIFIC AMERICAN

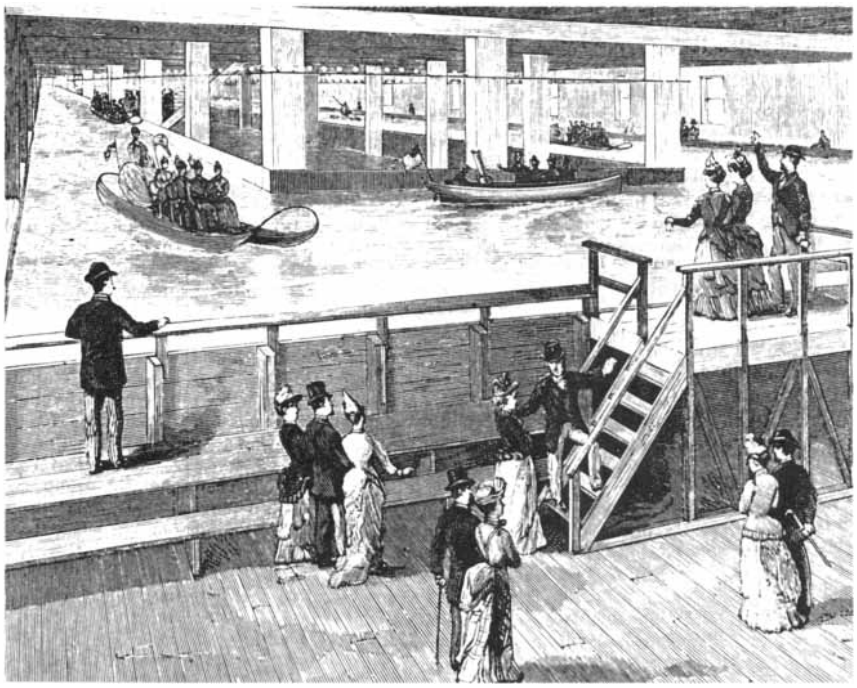
DECEMBER, 1889: "Among the most wonderful displays, electric and visual, at the recent French exposition were those pertaining to the luminous fountains, which were arranged on a grand scale and occupied a large portion of the plateau in front of the main entrance. The chameleon-like changes of color in the fountain waters were something astonishing to behold. It was not accomplished by the mere throwing of colored lights upon the exterior of a spouting jet, but was due to an interior electric illumination of the molecules of the water; the beams of light being, so to speak, thrown into and imprisoned within the crystal walls of the water."

"The most recent researches of Professor S. P. Langley indicate that the mean temperature of the sunlit lunar soil is probably not greater than zero Centigrade, or 32 degrees Fahrenheit."

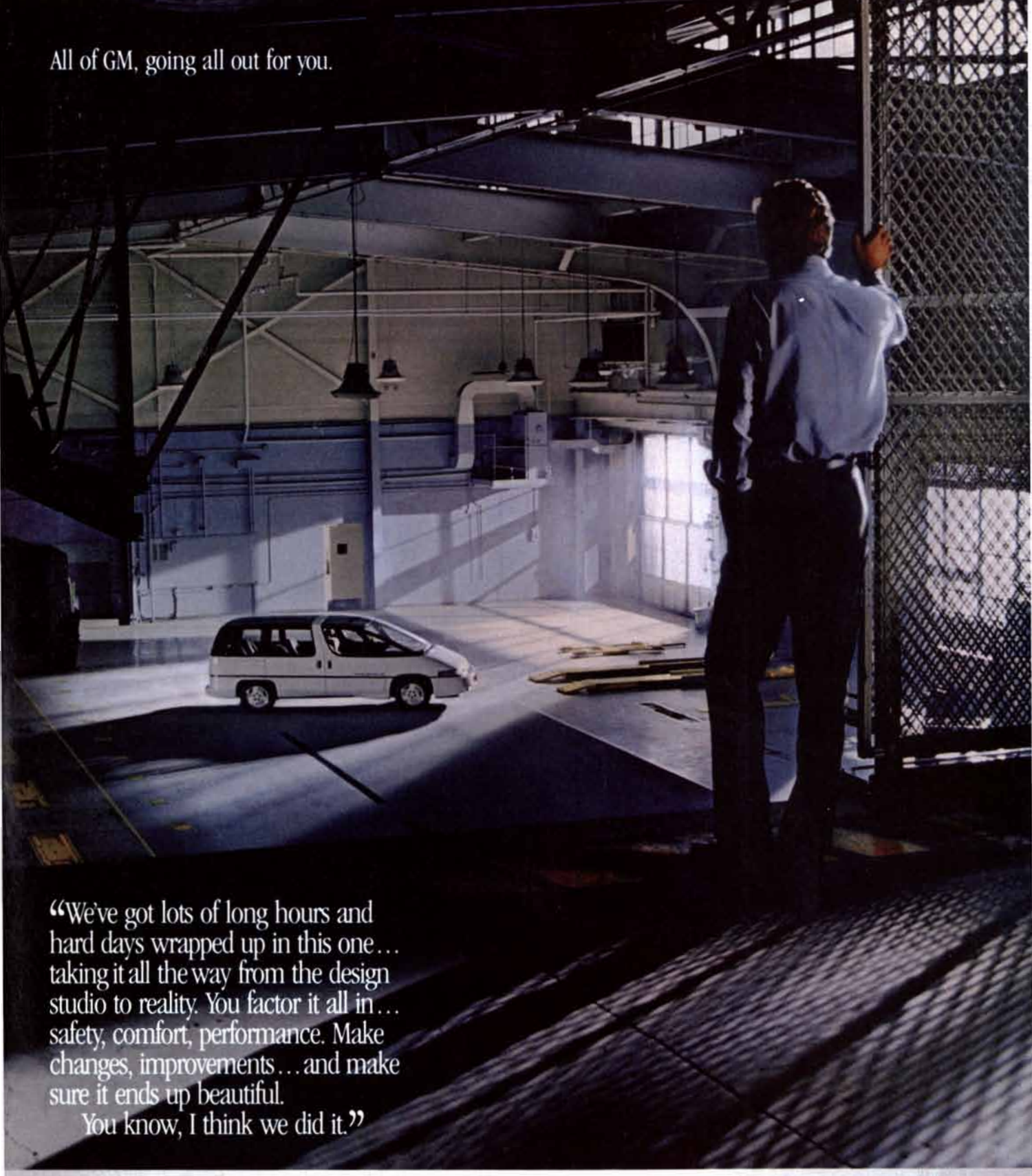
"Are currents of high potential, whether above or below the ground, a menace? We learned long since by practical experience that aerial mains were not to be trusted. As to the buried wires, we have, it seems, still less to hope for. Mr. Edison, in a recent interview, says of them: 'The placing of electric wires in subways, instead of lessening the dangers to life and property, will increase them. They are likely to be grounded through undiscoverable breaks in insulation. This is followed by making, perhaps, a lamp post dangerous to life, charging the iron frame of a store awning, a gas pipe or a telephone wire.'"

"Great cats with enormous canine teeth projecting from the upper jaw formerly roamed the earth, but have disappeared, leaving not a single analogous representative. These great-toothed cats have been called saber-toothed tigers (*Smilodon* and *Machaerodus*). They must have used their great teeth as daggers for ripping and thrusting instead of biting, for it was evidently impossible for them to open their jaws wide enough to free the lower jaw from the tips of the great upper canine teeth."

"In the basement of the big Maritime Exhibition at Boston, in the Mechanics' building, is a canal, quadrilateral in shape, 565 feet long, 12 feet wide, and 6 feet deep. Over its smooth surface glide graceful gondolas, and an electrical launch darts hither and thither, while a naphtha launch, that triumph of Yankee cunning, circles round and round the course, a practical exhibit of the most economical and convenient of marine motors."



Indoor canal at the Boston Maritime Exhibition



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SCIENCE AND THE CITIZEN

Fuel for Thought

The adoption of "clean fuels" takes a step closer to reality

The automobile and petroleum industries have been doing some lipreading recently, spurred by the Bush Administration's determination to bring about a shift in major cities to automobiles that use "clean fuel." The three U.S. manufacturers—Ford, General Motors and Chrysler—are initiating a joint research program with 14 gasoline producers to "permit objective assessment of relative reductions in vehicle emissions and improvements in urban air quality... achievable with reformulated gasolines and with methanol fuels."

The intention is to be able—if necessary—to produce and sell a million clean-fuel vehicles in each year from 1997 to 2004, a central requirement of Clean Air Act revisions the White House has proposed. At present it appears that the only way to meet that target would be to rely on a mixture of 85 percent methanol and 15 percent gasoline, known as M85.

At the same time, however, the Clean Air Working Group, whose membership includes the auto manufacturers and the petroleum industry, has been actively lobbying against the requirement. A compromise under which the manufacturers would be required only to offer the cars for sale—not to get them on the road—might emerge from a congressional battle over the plan.

Nevertheless, mounting public concern about urban air quality has made it clear that action of some kind will be necessary. The chief concern is ozone, a severe irritant at ground level. Ozone levels still exceed the Environmental Protection Agency's standards in 60 regions of the country. How much M85-burning vehicles would reduce ozone-forming volatile hydrocarbons is hotly disputed. We should "wait and see how air quality is actually improved and what the customer will buy," says Ford's John P. McTague.

Despite the enthusiasm of EPA officials for methanol-fueled automobiles [see "The Case for Methanol," by Charles L. Gray, Jr., and Jeffrey A. Alson; SCIENTIFIC AMERICAN, November], the new joint research program will also be giving a hard look at various reformulated gasolines. These blends, which can be used in today's vehicles, might be "a real good solution in the near term," says David E. Sloan of General Motors. Compressed natural gas is also thought to have some potential.

"My bias is that we ought not anticipate a single alternative fuel," says Helen O. Petrauskas of Ford. "We will end up with a multiplicity of new kinds of fuels that are going to be tailored to needs of particular areas." Ford has, for example, a prototype electric vehicle that can reach 65 miles per hour.

Some environmental groups are skeptical about methanol in particular. Because it produces formaldehyde, "methanol is not a clean fuel," says James J. MacKenzie of the World Resources Institute. The EPA itself has estimated that, under the president's program, ozone levels in nine of the nation's most polluted cities would be reduced by an average of only 1.5 percent. If pure-methanol-burning vehicles were introduced in the year 2000, average ozone reductions by 2015 would still be only 3.3 percent. Moreover, the Congressional Office of Technology Assessment concluded earlier this year that methanol fuels were the least cost-effective way of reducing emissions of volatile hydrocarbons. Far greater reductions, the OTA says, could be achieved at far less cost through modest improvements in conventional technology.

MacKenzie points out that if methanol were made from natural gas—the least expensive source—the country would still have to rely on foreign suppliers. If coal served as the methanol feedstock, production of carbon dioxide, a greenhouse gas that warms the atmosphere, would exceed what is yielded by burning gasoline, MacKenzie told Congress in October. He favors switching to hydrogen as an automotive fuel. Hydrogen can be manufactured by electrolyzing water. If that process were powered by solar energy, hydrogen could by the turn of the century be cost-competitive with methanol, according to MacKenzie.

Hydrogen may not be, however, a near-term prospect. Although it has wondrous theoretical benefits (tailpipe emissions, other than water vapor, are virtually zero), there are numerous obstacles to developing an infrastructure for delivering it safely, and its energy density is low, McTague comments. "Hydrogen is not out of the realm of possibility, but it is far in the future," according to a recent assessment by Ford. —*Tim Beardsley*

EARTHQUAKE INFORMATION

The earthquake that struck the San Francisco Bay area on October 17 has exacerbated concerns about how earthquakes occur and what can be done to predict them and mitigate their effects. The following articles and news items published by SCIENTIFIC AMERICAN address these questions.

PREDICTING THE NEXT GREAT EARTHQUAKE IN CALIFORNIA, by Robert L. Wesson and Robert E. Wallace, February, 1985.

MEASURING CRUSTAL DEFORMATION IN THE AMERICAN WEST, by Thomas H. Jordan and J. Bernard Minster, August, 1988.

DEEP EARTHQUAKES, by Cliff Frohlich, January, 1989.

HIDDEN EARTHQUAKES, by Ross S. Stein and Robert S. Yeats, June, 1989.

"Science and the Citizen" items: *Earthquake Act,* September, 1978, page 92; *Past and Future Shocks,* October, 1978, page 92; *Seismic Shift,* March, 1981, page 91; *Destructive Sway,* March, 1986, page 63; *All Shook Up,* December, 1987, page 18; *Woody Witnesses,* September, 1988, page 24.

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Photogenic Science

A colorful balloon and raft help rain-forest researchers

A team of French scientists has devised an unusual and photogenic way to explore the canopy of tropical rain forests: they ride the treetops on a raft. The 26-meter-wide hexagon made of netting stretched

"It was a very big challenge. The Air Force wanted us to develop a flight simulator for air combat training, and they gave us only two months to do it. The time frame made the project even more interesting. What's more, we knew the Air Force expected a lot more from the simulator than they were asking for.

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Well, the Air Force comes away with smiles on their faces every time they get done training with the simulators." *—Rich Cutak, Senior Engineer, Combat Aircraft Flight Simulation with Gary McDonald, Lead Engineer*

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between pontoons can accommodate up to 10 people during the day and five overnight (in a tent). A hot-air dirigible sets the raft down atop the foliage and ferries supplies from a base camp.

The project is the brainchild of Francis Hallé of the Botanical Institute at the University of Montpellier II, a botanist and veteran rain-forest explorer. He says the raft will enable scientists to study plants and insects for months at a time in a normally inaccessible region of the rain forest, as much as 40 meters above the earth. Researchers can work on the platform itself, or they can descend into the depths of the forest on rope ladders.

Hallé acknowledges that the camera-pleasing aspects of the project were no accident: they helped him raise $300,000 from Dentsu, Inc., a Japanese advertising conglomerate. In return for the funds, the scientists will help produce a film of their work that Dentsu plans to show at an exposition in Osaka next year. "These days it is very important to get a link between scientific research and financial possibilities," Hallé remarks.

It is also important to obtain the support of the country in which one intends to study. Hallé's team had planned originally to study a Brazilian forest. In fact, they ran a test flight in Amazonas this past summer, but then the government, annoyed that the French group had not obtained the required permits, forced them to wait outside the country while the paperwork was completed. "The Brazilians are very sensitive about foreigners doing research," Hallé explains.

Instead of waiting for Brazil to grant permission, Hallé decided to move the operation to French Guyana. "We don't need permits there," he says. French Guyana's rain forests are actually better—rainier, taller and more biologically diverse—than Brazil's, according to Hallé. Why didn't he go there in the first place? Because Dentsu had preferred that its film be set in Brazil, where rain forests have generated more news of late. —*John Horgan*

Range War

The value of "alternative agriculture" is disputed

When the National Academy of Sciences, a bastion of caution, gave its ringing endorsement to "alternative agriculture," it made headlines—and not just in the corn belt. Small wonder. The academy said what environmentally aware urbanites wanted to hear: farmers using methods of cultivation that emphasize organic fertilizers, little or no pesticide, crop rotation and mechanical tillage "generally derive significant sustained economic and environmental benefits." Moreover, the academy's report on the subject states that "wider adoption of proven alternative systems would result in even greater economic benefits to farmers and environmental gains for the nation."

The academy's reports (actually the work of the National Research Council, the academy's operating division) are based on a consensus of expert opinion. The authors of the report on alternative agriculture were therefore decidedly ruffled when Leonard Gianessi of Resources for the Future, a respected Washington think tank, briefed government officials and said in effect that the report's conclusions amount to mere organic fertilizer. The findings, Gianessi maintains, go "far beyond the data presented."

Gianessi argues that most farmers will actually do "far worse" if they turn to alternative agriculture. Moreover, he says, the environmental benefits (such as reduced pesticide runoff) from some of these techniques are questionable.

The academy bases its conclusions on comparisons of farm expenditures. For example, it shows that soybean growers in southwestern Minnesota who spent more on fertilizers and pesticides produced rather expensive soybeans; growers who spent relatively little on fertilizers and pesticides produced a cheaper crop. But Gianessi argues that the comparison could be misleading. Because the farms were spread out over thousands of square miles, the farmers who spent more on pesticides may have been obliged to do so because they had to contend with worse conditions.

Gianessi charges that a similar comparison in southeastern Minnesota would fail to show that using less fertilizer and pesticide leads to cheaper soybeans. In fact, he says, the academy's cost comparisons do not prove that farmers who spent less on pesticides actually used less: they might simply have bought the chemicals at a lower price.

In many areas, Gianessi says, farming is impossible without substantial use of artificial pesticides: they are required for peanut growing in Florida, for example. In any case, he says, some of the farms the academy considers alternative ones use techniques, such as integrated pest management, that rely on very toxic pesticides and produce thousands of acres of plastic mulch that finds its way into landfills. "How can you judge this an environmental improvement?" Gianessi asks.

The academy also suggests there would be environmental benefits and increases in profitability if incentives for inefficient farming, such as corn cultivation in the Mississippi delta, were reduced. Gianessi argues that the academy cannot conclude that, however, unless it specifies what should replace inefficiently grown crops.

The authors of the academy report

RAFT for studying the rain-forest canopy is carried aloft by a hot-air balloon. The equipment was designed by Francis Hallé of the University of Montpellier II.

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are certainly not about to pack up and move on. John T. Pesek of Iowa State University, chair of the committee that produced the report, says, "We believe these case studies are evidence that it is possible to obtain a safer environment and safer conditions for agricultural workers." Charles M. Benbrook, executive director of the NRC's Board on Agriculture, points out that data are scarce but that the available information substantiates generally recognized truths of farm economics. "The fact remains," Benbrook asserts, "that there is great potential for improving the environment and achieving economic benefits."

Others also defend the academy. "The general theme is one that is fairly clear to a lot of people on the ground outside Washington," notes D. Mark Ritchie of the Minnesota Department of Agriculture. "We have a crisis in the protection of land and water, and the policy [of encouraging pesticide use] is linked to it, so we have to examine the policy and make changes. This is a big contribution." —*T.M.B.*

PHYSICAL SCIENCES

The Lost Generation

New findings virtually rule out a fourth generation of particles

Within months of starting up, two powerful new particle accelerators, the Stanford Linear Collider (SLC) in California and the Large Electron-Positron (LEP) Collider in Switzerland, have yielded a major result: compelling evidence that there are no more than three "generations" of elementary particles—12 particles in all.

According to the prevailing theory, known simply as the Standard Model, the fundamental components of matter come in foursomes, called generations, each one consisting of two quarks and two leptons. Three such generations are known to exist. The first consists of the up and down quarks (which form protons and neutrons), the electron and the electron neutrino. The second consists of the charm and strange quarks, the muon and the muon neutrino. The third is made up of the top and bottom quarks, along with the tau and the tau neutrino. All of these particles, save the top quark, have been observed.

The first generation by itself accounts for all ordinary states of matter. Why two other generations should exist is a mystery, but the Standard Model sets no limit on the number of generations. Indeed, there could be an infinite number of them. The primary achievement of the workers at the LEP and at the SLC has been to eliminate that possibility.

The experiments, carried out on the SLC's Mark II detector and on the four LEP detectors (Aleph, Opal, L3 and Delphi), measured the life span of the Z^0 particle (pronounced "Z naught" or "Z zero"). The speed with which the Z^0 decays is governed by the number of particle types into which it can decay, just as the speed with which a theater empties indicates how many exit doors there are. The Z^0 "carries" the weak nuclear force, much as particles of light carry the electromagnetic force.

Both the LEP and the SLC were designed to create Z^0's in profusion: the machines collide electrons and positrons into each other at sufficient energies—about 91 billion electron volts—to forge Z^0 particles [see "The Stanford Linear Collider," by John R. Rees; SCIENTIFIC AMERICAN, October]. The Z^0 decays almost instantaneously into a particle and its antiparticle—any pair, so long as the mass of each particle is less than half the mass of the Z^0.

Measurements of the Z^0 lifetime obtained at each of the five detectors indicated that the Z^0 decays only into particles from the three known generations. A shorter lifetime would have indicated the existence of a fourth-generation particle, presumably a fourth neutrino, which would be the lightest member of the generation. All five experiments, however, have now imposed significant limits on the presence of a light, fourth neutrino. And if there is no fourth neutrino, then according to the standard theory there are no other fourth-generation particles either. "Each result alone is not overwhelming," says Jonathan Dorfan, head of the Mark II group, "but the five taken together are really quite spectacular." The SLC results appeared in the November 6 issue of the *Physical Review Letters;* the European results are in the November 16 issue of *Physics Letters.*

The new findings do not rule out the possibility of a massive fourth neutrino—one weighing more than some tens of billions of electron volts—and a fourth generation to go with it. Most physicists are reluctant to consider such a behemoth, however, because the three known neutrinos are virtually massless.

"Cosmologists have wanted three generations for a long time," Dorfan says. Three would best account for the observed abundance of helium in the universe. On the other hand, some cosmologists had nurtured hopes that a fourth neutrino weighing about 65 electron volts would provide the "missing mass" needed to halt the expansion of the universe [see "Beyond Truth and Beauty: A Fourth Family of Particles," by David B. Cline; SCIENTIFIC AMERICAN, August, 1988]. They will now have to abandon that hope.

But why should there be only three generations? "We wish we knew," says Steven Weinberg of the University of Texas at Austin. In 1979 Weinberg shared the Nobel prize for bringing the weak nuclear force into the fold of the Standard Model. "The fact we don't know is a real giveaway that we're missing something in our understanding of nature," he says.

Although the three-generation limit was announced only a few months after the SLC and the LEP began running, "the physics program is by no means over," Dorfan says. Weinberg agrees, saying that with accelerators such as the LEP now capable of producing hundreds of thousands of Z^0 particles, "this is the first time experiments will have enough accuracy" to test the fine details of the Standard Model. —*June Kinoshita*

After the Deluge

Drumlins may tell the tale of an ice-age flood

Something was wrong with the drumlins near Livingstone Lake, in northern Saskatchewan. To John Shaw, a physical geographer at Queen's University in Kingston, Ontario, "they looked quite different from classical drumlins," elongated hillocks generally thought to have been shaped when the glaciers of the last ice age overrode beds of debris. Tall and narrow at the "upstream" end and sloping to a low, broad tail, the Livingstone Lake drumlins looked to Shaw like counterparts of the pits that appear on streambeds where the flow is turbulent.

Writing in *Geology,* Shaw proposes that the drumlin field is the heritage of a vast, turbulent flood of meltwater that surged beneath the North American ice sheet late in the ice age. The floodwaters, he suggests, scoured pits in the underside of the ice; debris carried in the flood accumulated in the cavities and was thereby molded into hills, which remained after the

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ice retreated some 10,000 years ago.

The flood, Shaw argues, must have been catastrophic in scale. The Livingstone Lake field spans about 150 kilometers, and yet the long axes of the drumlins form a coherent fan-shaped pattern, which suggests that a single flood was responsible. How much water was involved? From the total bulk of the drumlins Shaw estimated first the amount of ice that must have been removed to form the cavities and then the volume of water it would have taken to erode them.

He arrived at a figure of 84,000 cubic kilometers—about seven times the capacity of Lake Superior. When this subglacial flood burst from the edge of the ice sheet and drained to the Atlantic and the Gulf of Mexico, it would have raised global sea levels by 23 centimeters—nearly a foot.

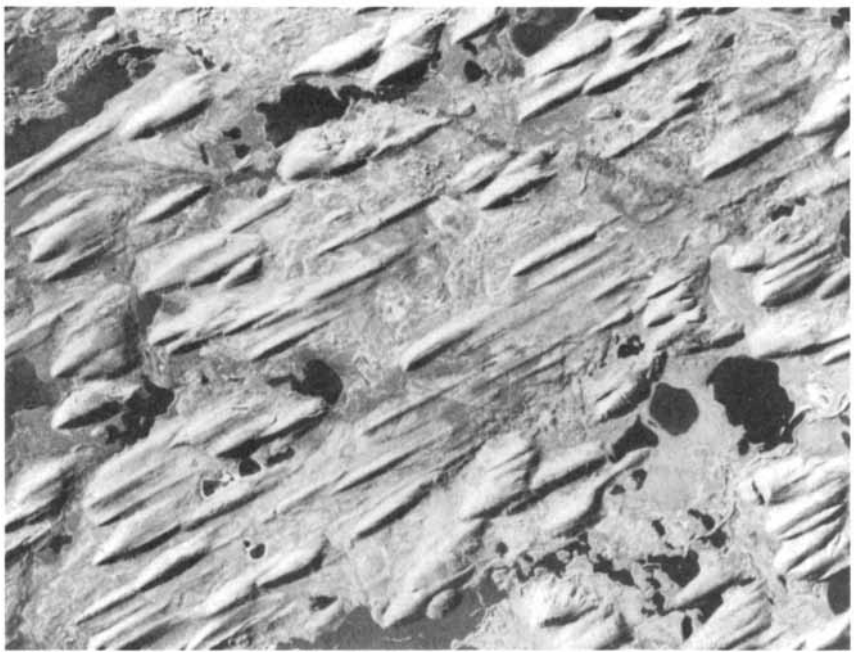
Where would all that water have come from? Shaw thinks that the friction between the ice sheet and its bed and heat from the earth itself would have melted the underside of the ice faster than the water could have drained from the edge. A reservoir might have built up until pressure reached a critical point and the stored water escaped from beneath the ice.

The Livingstone Lake district is not the only formerly glaciated region Shaw thinks was sculpted by subglacial floodwaters. "I don't claim that my mechanism explains all drumlins," Shaw says, but he does argue that certain other drumlins that seem to have been cut from the bedrock rather than deposited on it, together with similar erosional marks, are better explained by turbulent floodwaters than by ice flow.

Other workers are not so sure. "I have trouble accepting the whole scenario," says David M. Mickelson of the University of Wisconsin at Madison. The internal structure of the drumlins he has studied in Wisconsin indicates that they consist of preexisting deposits deformed by ice, he maintains. "Are there some drumlins that could have been formed by water? Based on the ones I've seen, I'm not convinced."

Still, Shaw's subglacial floods offer one way of explaining a chemical signature in sediments on the floor of the Gulf of Mexico, which suggests that large volumes of meltwater poured into the gulf in a relatively short time at the end of the last ice age. Pointing out that repeated floods might have caused the sea level to rise several meters within a few years, Shaw speculates that the floods may also have left their mark on myth—in the tale, recurrent in ancient cultures, of a primordial deluge. —*Tim Appenzeller*

Did floodwaters surging under glaciers build these hillocks at the close of the last ice age?



DRUMLINS, perhaps 40 meters high, mark what may have been the scene of a catastrophic subglacial flood in northern Saskatchewan. The floodwaters would have flowed toward the southwest—or the upper right in this aerial photograph from the Canadian Department of Energy, Mines and Resources.

A Cosmic Unveiling

Newborn stars bare some secrets about how planets form

For nearly two centuries scientists have suspected that the solar system formed out of a swirling accumulation of gas and dust that surrounded the sun in its infancy. Now observations of celestial objects called T-Tauri stars provide the first tantalizing evidence that planets are indeed forming in clouds around newborn stars and that the process of planetary formation may take only about 300,000 years—a blink of the eye by cosmic standards.

T-Tauri stars, named after a prototype discovered in the constellation Taurus, are thought to represent the first stages in the formation of stars such as the sun. Many T-Tauri stars glow prominently in infrared light, which suggests they are surrounded by dusty clouds that absorb visible light, heat up and reemit the light as infrared radiation. They also vary erratically in brightness, as if they are being intermittently obscured. These and other traits suggest that the stars are surrounded by rotating disks of gas and dust. Astronomers have long considered such disks to be a likely source of material for planetary formation, but until now they had no hard evidence to confirm this theory.

Karen M. Strom of the University of Massachusetts at Amherst, along with four colleagues, set out to study the evolution of disks; their findings have recently appeared in the *Astronomical Journal*. They observed 83 T-Tauri stars and estimated the stars' ages based on luminosity and temperature. Roughly 60 percent of the T-Tauri stars younger than three million years appeared to be surrounded by disks, compared with only 10 percent of stars 10 million years old.

Strom's group sees indications that the disappearance of disks in older stars is linked to the appearance of planets. Some T-Tauri stars show substantial excess emissions in long-wavelength infrared radiation, which is emitted by cool objects, but not in shorter wavelengths, which are emitted by warmer objects. They surmise that these stars may be surrounded by disks shaped like flattened donuts, in which the hotter, inner regions of the disk are relatively empty but the

cooler, outer regions remain intact. Strom suspects that planets or asteroids forming near the star are sweeping up the dust around them as they orbit. The fact that only the inner parts of the disks are missing may mean that planets first start to form close to a star and only later begin to form farther out, in the cooler, outer regions of the disk. Planets are far less efficient than dust at emitting infrared radiation, so they would not be directly visible; the only sign of their existence would be the disappearance of infrared emissions from hot dust.

Approximately one tenth of the 83 T-Tauri stars in Strom's survey show the infrared peculiarities that are taken as evidence of "inner holes." If this survey includes a random sampling of young stars, then evolving disks—those in the process of being cleared out—must last about one tenth the stars' average age. The average age is about three million years, which implies the clearing process lasts roughly 300,000 years. If planet-building is responsible for clearing disks, it must take place in this incredibly short time span. This imposes a serious constraint on theories of how the solar system formed.

Strom and other investigators plan to observe T-Tauri stars in a wide range of infrared wavelengths to determine whether the inferred inner holes in T-Tauri disks are indeed real. If so, they hope to find disks that represent a range of evolutionary stages so they can reconstruct the details of the clearing process. And Strom hopes the Hubble Space Telescope—which is scheduled for launch some time next year—will be able to image the faint, outer remnants of disks around seemingly naked T-Tauri stars to show that they once had disks that vanished, perhaps to form other planetary systems like our own. —*Corey S. Powell*

BIOLOGICAL SCIENCES

Big-Game Forensics

DNA fingerprinting may help discourage elephant poaching

The technique known as DNA fingerprinting—which typically involves seeking a genetic match between a suspect and blood, skin or other cellular materials gathered as evidence—has helped solve crimes against humans in the U.S. and Great Britain. Can it also stem the slaughter of elephants in Africa? That is the goal of a project started by Wildlife Conservation International (WCI), a division of the New York Zoological Society.

Poachers threaten the survival of elephants in Kenya, Tanzania and other African nations

ELEPHANTS in Kenya's Samburu National Reserve bolt at the sight of humans and hide behind bushes. Such fearful behavior suggests that the herd has previously been attacked by poachers. Photograph by Suzie Gilbert.

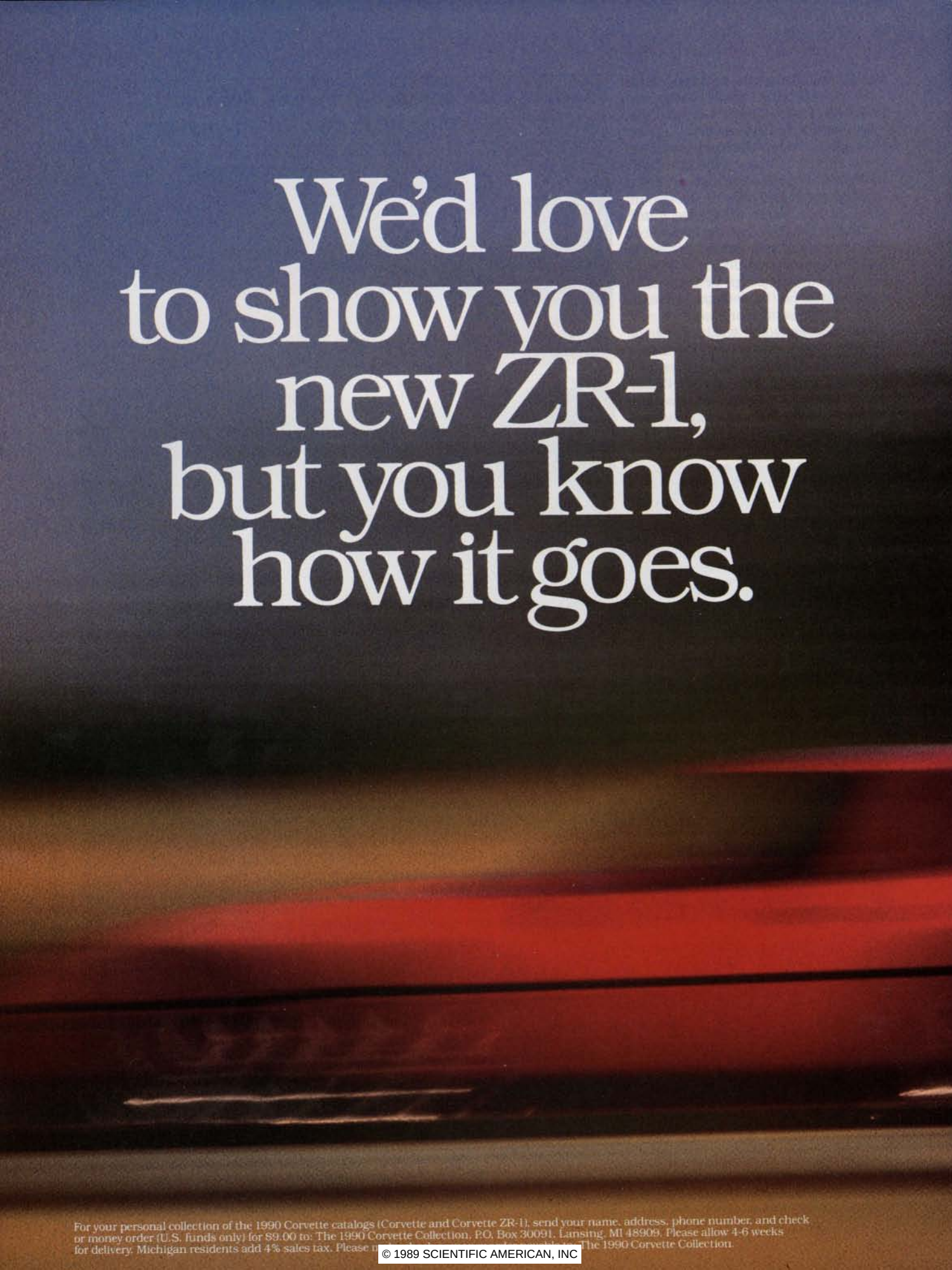
Poachers seeking ivory are largely responsible for the precipitous decline of elephants in Africa: in the past decade the elephant population has fallen from more than 1.3 million to less than half that number. Recently Kenya, Tanzania and other nations hard-hit by poaching convinced most members of the Convention on International Trade in Endangered Species (CITES), including such major importers as Japan and the U.S., to ban all trading in ivory.

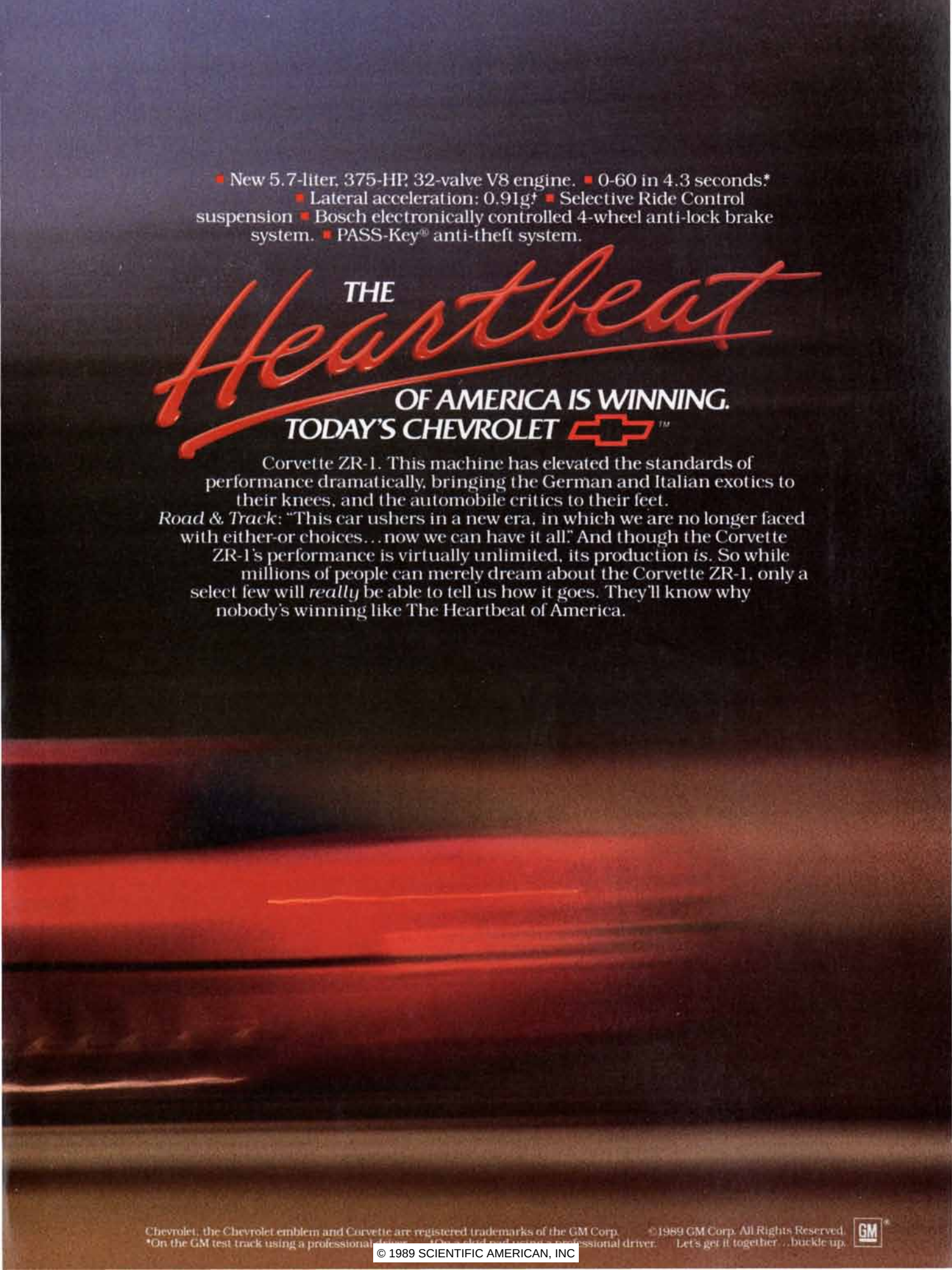
But several key CITES members—including Botswana and Zimbabwe—refuse to comply with a ban. As a result of antipoaching efforts in these countries, elephant herds are actually growing and must be culled to prevent overcrowding. Ironically, officials in Botswana and Zimbabwe say they rely on sales of elephant products—meat, skin and hair as well as ivory—to pay for conservation efforts.

Unfortunately, any legal market provides a loophole for black marketeers; they need merely smuggle illegal ivory into a country that permits trading or forge documents indicating a legal provenance. Some conservationists think DNA fingerprinting may help close the loophole. "We need a technique that can say, yes, this ivory came from this region," says David Western, the Kenya-based director of WCI.

With a grant from WCI, John C. Patton of Washington University has been investigating the technique's potential. He has analyzed blood from two Zimbabwean elephants now kept in American zoos and tissue from 100 elephants killed by poachers in Kenya and Tanzania. (Ivory itself is acellular, like tooth enamel, and so is not amenable to standard DNA analysis.) So far, according to Patton, his research suggests that elephants from different regions of Africa exhibit distinct genetic profiles, but he needs to sample a broader population to confirm the pattern.

Establishing DNA fingerprinting as a method for verifying provenance, Western notes, will require the cooperation of nations still harvesting ivory. He is urging officials in these nations to contribute blood or tissue samples from their herds in order to establish a genetic data base and to require that tusks placed on the market re-





tain enough flesh for a DNA analysis.

The project has scientific as well as forensic applications, Western says. For example, it could help scientists establish the genetic relation between African elephants that roam the open savanna and those that prefer the heavily jungled mountains. The project could also help managers of zoos and reserves to ensure that breeding pairs of elephants are genetically compatible.

Western warns that unless a verification system is implemented quickly, it may be too late to save some countries' elephant populations. After a lull of several months, he says, poachers are once again attacking Kenya's already decimated herds. —*J.H.*

What's a Hoatzin?

It looks like a bird but eats—and smells—like a cow

The hoatzin is one of the odder birds inhabiting the Amazon rain forest. Hoatzins too young to fly can swim underwater to escape predators. The mud-colored fledglings also have claws on their wings, which help them to swing through the treetops like monkeys. Adult hoatzins have blood-red eyes in a bright-blue face and sport Mohawk hairdos; this high-fashion head is attached to a rather dowdy, ungainly body.

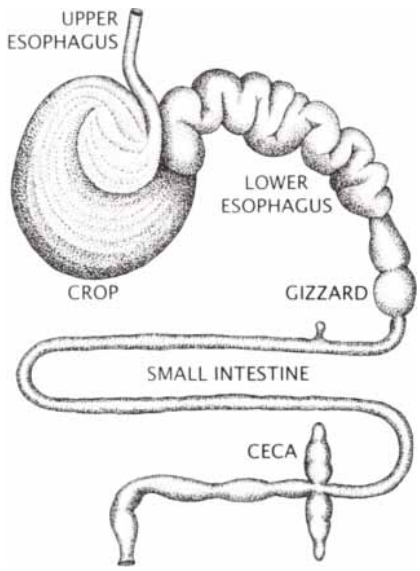
Perhaps the most distinctive trait of the hoatzin (pronounced WAT-sin) is its odor. It smells like manure—cow manure, to be precise. Indeed, some Colombians call the bird *pava hedionda,* which, roughly translated, means stinking pheasant. Now a group of investigators from Venezuela, Scotland and the U.S. has discovered the reason for the aroma. Although technically avian, the hoatzin is gastronomically rather bovine.

Unlike most other birds, the hoatzin dines almost exclusively on green leaves. What is even more unusual—unique, in fact, among birds known to science—is the hoatzin's rumenlike crop and lower esophagus. The muscular, deeply corrugated crop first grinds the leaves up—or chews the cud, so to speak. Bacteria in the crop and the esophagus then cause the mash to ferment, rendering toxins harmless and producing nutrients that can be absorbed by the intestine.

Foregut fermentation also occurs in cows, sheep, deer and a number of other mammals. But according to one of the investigators, Stuart D. Strahl of the New York Zoological Society's Wildlife Conservation International, the little hoatzin (adults weigh less than two pounds) does not share an evolutionary branch with these big ruminants; it developed its digestive system independently.

Strahl adds that some ornithologists call the hoatzin "primitive" because of its archaeopteryxlike claws, but he prefers to think of it as "highly specialized." Swans, ibis and many other birds, he notes, have wing claws; they just never make use of them.

The hoatzin flies, but not very well; its crop is so large that it leaves little room for wing muscles. Of course, one need not fly fast or far to find leaves in a rain forest. Indeed, as the investigators write in *Science,* "given the abundance of leaves as a resource base, it is not obvious why hoatzins are the only living bird with foregut fermentation." —*J.H.*



DIGESTIVE TRACT of the hoatzin. Leaves ferment for up to two days in the crop and lower esophagus. Photograph by Stuart D. Strahl.

Old Gene, New Trick

The not-so-holy engrailed *reveals the path of evolution*

The gene named *engrailed* has an exceptionally long pedigree, stretching back more than 600 million years. Diverse creatures, ranging from worms to human beings, carry a copy of *engrailed* in their cells. For it to have survived for so long and in such dissimilar species against merciless evolutionary pressures, the gene must do something vitally and fundamentally important—but what? Recently a comprehensive study of how various animals express *engrailed* has found an answer that overturns previous conjectures about the gene's function.

Engrailed is a "homeobox" gene, one that triggers a cascade of developmental, structural changes in embryos. In *Drosophila* (fruit flies), where the gene was first found, experiments clearly established that *engrailed* controls division of the embryonic body into distinct segments. Similar segmentation occurs in other animals that carry the *engrailed* gene. Many biologists wondered whether *engrailed* might therefore be a universal controller of segmentation.

Nipam H. Patel, Michael C. Ellis and Corey S. Goodman of the University of California at Berkeley and Enrique Martin-Blanco, Kevin G. Coleman, Stephen J. Poole and Thomas B. Kornberg of the University of California at San Francisco set out to test the idea. With a monoclonal antibody that bound with the protein made by the *engrailed* gene, they mapped the expression of *engrailed* in embryos from three major groups of animals: arthropods (insects, crustaceans and other animals with segmented bodies and exoskeletons), annelids (the segmented worms such as leeches and earthworms) and vertebrates (birds, fish, mammals and other creatures with backbones).

To their surprise, Patel and his colleagues discovered that *engrailed* appears to be involved in segmentation only in arthropods. Segmentation in vertebrates and annelids is controlled by other, as yet unidentified, genes.

Nevertheless, *engrailed* does have a common function in all the studied species: it is involved in the formation of the nervous system, particularly in the development of new neurons. In chickens, for instance, *engrailed* is expressed in the neural-tube tissues that become parts of the midbrain and hindbrain.

The most parsimonious interpretation of Patel's findings is that in some early flatworm ancestor shared by all the studied creatures the function of *engrailed* was to direct neurogenesis, which the gene continues to do today. When arthropods evolved, *engrailed* somehow assumed the additional task of directing body segmentation. In effect, evolution taught this old gene a new trick.

Patel's research, published in *Cell*, strengthens the argument that insects, crustaceans and other arthropods have a single common ancestor. Evolutionary biologists have long debated whether insects and crustaceans were unrelated groups that had evolved arthropod characteristics independently. The study also indicates that mechanisms for segmenting embryonic bodies evolved on separate occasions for arthropods, annelids and vertebrates. "There was never a time when animals stopped having a nervous system, so that their descendants had to reinvent mechanisms for making one," Goodman explains. "But segmentation seems to have evolved independently at several different times, presumably using different combinations of genes in the process." —*John Rennie*

MEDICINE

Stone to Bone

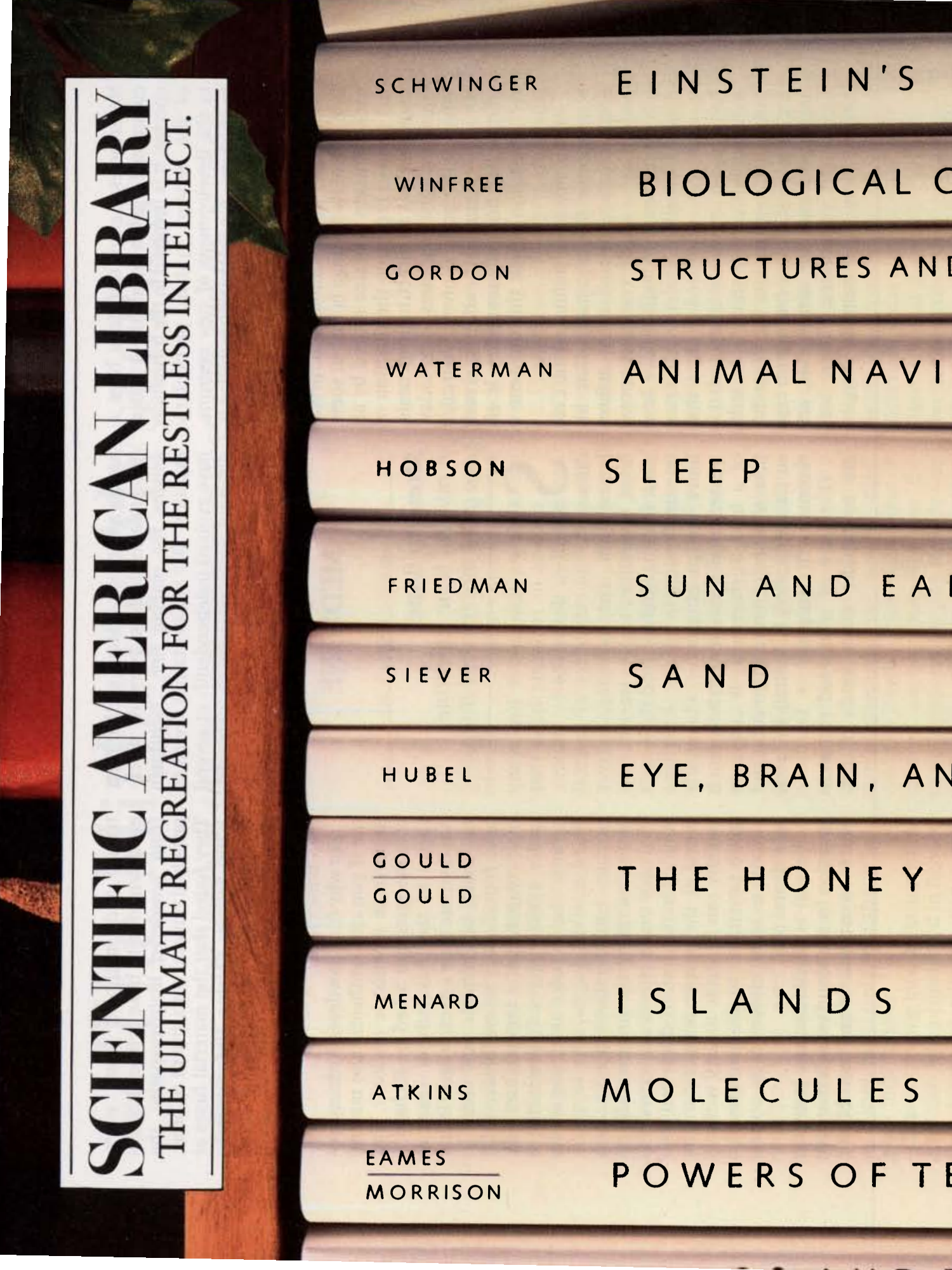
A mineral bone substitute can grow into the real thing

Surgeons have never had many options in replacing bone that has been destroyed by trauma, disease or the exigencies of surgical intervention. The mainstay, cadaver bone, sometimes retains traces of organic material that can lead the body's immune system to reject it. A perhaps more benign alternative, chemically treated coral, is too weak to bear much of a load. Furthermore, it comes in pieces no larger than a sugar cube, and so its application is limited to facial reconstructive surgery.

That state of affairs led researchers to explore other kinds of materials and methods. Some workers attempted to bake artificial bones from powdered hydroxyapatite, the principal mineral constituent of bone. They found that the material fuses at 1,200 degrees Celsius. Unfortunately, the temperature is so high that a hydrogen-oxygen group boils off, which leaves a ceramic that is even weaker than bone china.

But why fuse powdered hydroxyapatite if you can synthesize the mineral de novo in any shape desired? That was the question asked by Richard J. Lagow of the University of Texas at Austin more than a decade ago. He and his group of chemists now claim to have found a way to synthesize solid hydroxyapatite at a temperature well under 1,000 degrees C, producing a ceramic that is twice as strong as the fused material. Lagow, who says proprietary considerations prevent him from describing the process, will reveal only that a chemical precursor is molded to the desired shape and then cured at the proper temperature. Its density can be made to vary within a given prosthesis to produce areas as smooth as tooth enamel or as porous as a dental root.

Porosity is crucial because it invites invasion by the blood vessels that give entrée to osteoclasts and osteoblasts;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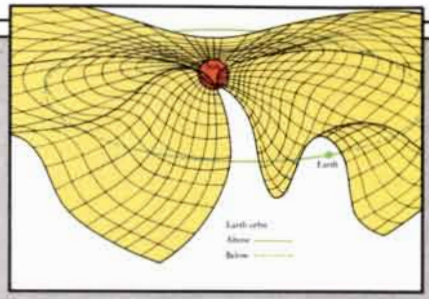

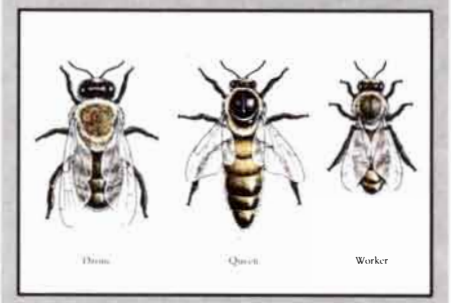

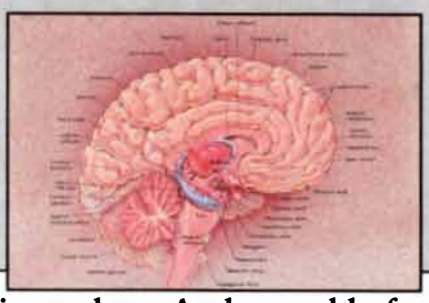

CREDITS (top to bottom)—From Sun and Earth, *the "ballerina skirt" model of the solar-interplanetary current sheet. From* The Science of Structures and Materials, *bubble formation due to the surface tension of a liquid; courtesy Stephen Dalton, NHPA. From* The Honey Bee, *drone, queen, and worker; drawing by John Hatzakis. From* Einstein's Legacy, *Chaplin and Einstein in Hollywood, 1931; courtesy The Granger Collection. From* Drugs and The Brain, *major anatomical divisions of the brain; painting by Bill Andrews.*

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these cells, respectively, break down the implant and replace it with natural bone. This indeed happens, according to colleagues of Lagow at the Baylor Medical Research Foundation in Dallas. They report that rabbits have already replaced up to 85 percent of the hydroxyapatite prostheses that had been implanted in their legs (which makes the animals a bit taller).

"Of course, our number-one project is to make a complete rabbit femur, with enamel joints and a porous shaft," Lagow says. "The problem is that our stuff wouldn't flex, because it has no collagen fiber in the bone matrix. But in three to five years the body converts it into bone, with organic filler." Lagow says that because the joints are denser than those in natural bone, such complete leg and arm bones should articulate far more easily than arthritic joints do, even though they must necessarily lack meniscal cartilage.

Human trials of Lagow's prosthetic material in the form of teeth and bones will begin next year. Some of the first applications will be in spinal surgery. "That's not my preferred use—limbs are more important, according to bone-bank statistics—but my friends in orthopedic surgery tell me it's a cinch to work," Lagow says. "Our target is to prepare bones in blank sizes and machine them to order in the operating room." —*Philip E. Ross*

Affirmative Action

AIDS researchers seek to enroll more minorities in clinical trials

Of the 106,000 people in the U.S. now reported to have AIDS, 27 percent are black and 15 percent are Hispanic. Nine percent of AIDS patients are female, and 28 percent are users of intravenous drugs. All these percentages have increased dramatically since the early days of the epidemic, when AIDS was almost exclusively a disease of white homosexual men.

Yet more than 80 percent of those enrolled in clinical trials of AIDS treatments are still white men, according to Iris Long of the AIDS Treatment Registry, an information service in New York City. Protocols for the trials often exclude women and intravenous drug users, almost all of whom are black or Hispanic and desperately poor, Long says. Women are excluded for fear that, if they become pregnant and bear children with birth defects, they will sue the drug manufacturer or the government sponsor. Addicts are viewed as unreliable and likely to drop out of trials.

Even if they are eligible, minorities may not know how to gain entrance to AIDS trials or may not have easy access to the centers—usually based at universities—where the trials are conducted. "AIDS is increasingly a disease of people of color and poverty, and our clinical research system attracts a middle-class, white population," acknowledges Lawrence R. Deyton of the National Institute of Allergy and Infectious Diseases (NIAID). "There is a mismatch there."

Reducing the mismatch is crucial, Deyton observes, because "for many AIDS-infected people research is the only avenue left for care." The Food and Drug Administration has formally approved only three drugs for AIDS: AZT, an antiviral medicine; aerosolized pentamidine, used to prevent AIDS-induced pneumonia; and alpha interferon, which hinders the spread of an AIDS-related cancer known as Kaposi's sarcoma. Many of the 60 or so other potential treatments now being investigated are available only in clinical trials.

Moreover, the results of trials involving one group may not apply to another. Many women with AIDS develop severe vaginal infections, for example, and only homosexual men develop Kaposi's sarcoma. Intravenous drug users with AIDS are often threatened by tuberculosis and endocarditis, an infection of the heart valves.

NIAID recently provided 18 organizations—including drug clinics, hospitals and community health centers—with a total of $9 million to start clinical trials for minorities and women. Deyton, who oversees the project, says the Community Programs for Clinical Research on AIDS will have less restrictive protocols than trials done at traditional research centers. "We have to have some scientific standards," he says, "but for this disease, research has to be combined with care."

Recipients of the NIAID grants see difficulties ahead. Lawrence S. Brown of the Addiction Research and Treatment Corporation in Brooklyn notes that many blacks still recall experiments in which government researchers monitored the progression of syphilis in black prisoners for several decades without offering any treatment. Although the research was discontinued more than 20 years ago, Brown says, "there is still a clear mistrust of researchers."

Another grant recipient, Jerome A. Ernst of the Bronx Lebanon Hospital's AIDS Division, foresees no shortage of minorities willing to participate in clinical trials, but he does have a shortage of doctors. "I have the money for three positions," he says, "but I can't convince anyone to come here."

Marcia Carlyn, an administrator of the NIAID project, hopes that if these problems can be overcome the project may help foster a permanent cadre of researchers in inner-city communities. Such researchers, she points out, are needed to combat not only AIDS but also drug addiction and other ills that disproportionately afflict poor Americans. —*J.H.*

NOBEL PRIZES

CHEMISTRY. Ribonucleic acid, or RNA, is not merely DNA's messenger boy. It also serves as a catalyst in many cellular reactions. For independently discovering this fact—a contradiction of current scientific dogma—in the late 1970's, Sidney Altman of Yale University and Thomas R. Cech of the University of Colorado at Boulder have been awarded the Nobel prize in chemistry. Their finding has raised the possibility that RNA can serve as an all-purpose tool for biotechnologists and, more specifically, as a defense against viral infections [see "RNA as an Enzyme," by Thomas R. Cech; SCIENTIFIC AMERICAN, November, 1986].

PHYSIOLOGY OR MEDICINE. For making the grim finding that cancer-causing genes, called oncogenes, are standard equipment in normal cells, J. Michael Bishop and Harold E. Varmus of the University of California Medical School at San Francisco won the Nobel prize in physiology or medicine. In the mid-1970's many investigators thought oncogenes were introduced into healthy cells by outside agents—namely, retroviruses. But in 1976 Bishop and Varmus found that oncogenes are actually stolen from host cells by cancer-causing retroviruses. Ordinarily benign "proto-oncogenes" in humans apparently become cancer-inducing either through this retroviral transformation or, more commonly, through exposure to radiation, carcinogens or some other influence [see "Oncogenes," by J. Michael Bishop; SCIENTIFIC AMERICAN, March, 1982].

PHYSICS. Three physicists who developed highly precise methods for measuring the quantum behavior of particles won the 1989 Nobel prize

in physics. Norman F. Ramsey of Harvard University was awarded half of the prize for devising a technique that probes the energy spectrum of atoms by stimulating them with oscillating magnetic fields; the technique, first tested 40 years ago, led to the development of the hydrogen maser (an extremely stable generator of electromagnetic radiation) and the atomic clock. Wolfgang Paul of the University of Bonn and Hans G. Dehmelt of the University of Washington shared the other half of the prize for inventing ways to trap and observe single atoms and electrons. —*J.H.*

OVERVIEW

Gaia

The smile remains, but the lady vanishes

In the late 1960's James E. Lovelock, an independent British researcher who works in his home laboratory, began to expound an idea that wove dawning public concern about the environment together with a benign mysticism. The original concept can be simply and appealingly stated: all of the animals and plants that inhabit the earth can be regarded as a single vast organism capable of manipulating the atmosphere, geosphere and hydrosphere to suit its needs. Lovelock named this organism Gaia, the Greek goddess of the earth.

Lovelock, an accomplished inventor, was inspired by his experience designing life-detecting sensors for the Viking missions to Mars. Noticing that the earth's atmosphere (unlike that of Mars or Venus) has long been far from chemical equilibrium, he proposed that Gaia strives to maintain optimal conditions in the face of changing astronomical inputs, such as the sun's slowly increasing brightness.

Lovelock's musings have had two consequences. They inspired a quasi-political movement based in London, complete with a publishing arm, that now includes thousands of adherents throughout the U.S. and Western Europe. Indeed, Gaia has almost become the official ideology of "Green" parties in Europe: it appeals naturally to scientifically innocent individuals who worry about the environment. "A lot of people who don't believe in science really like Gaia," comments one biologist, W. Ford Doolittle of Dalhousie University in Halifax, Nova Scotia.

Gaia has also triggered an acute allergic reaction among mainstream biologists. Doolittle and Richard A. Dawkins of the University of Oxford spelled out the principal objection. Gaia seems to require that some organisms restrain their reproduction in order to benefit the larger community. Yet natural selection favors genes that increase their frequency. Thus, there is no mechanism for the evolution of organisms that will altruistically sacrifice immediate advantage for some future benefit, unless life has foresight. It does not, Dawkins argued: selfish genes will therefore simply crowd out visionary genes.

In response to such criticism, Lovelock has modified Gaia. His recent book, *The Ages of Gaia,* offers in place of the original "hard" Gaia a softer version. The new soft Gaia "has the capacity to regulate the temperature and composition of the Earth's surface and to keep it comfortable for living organisms," but she does not globally optimize—a notion that evolutionists find meaningless. And Lovelock is careful to avoid endowing Gaia with foresight.

Nonetheless, Lovelock's 1988 version of Gaia still exhibits homeostasis (meaning that she tends, like a thermostat, to counteract imposed changes). "The evolution of the organisms

and the evolution of their environment are tightly coupled as a single process," Lovelock writes. "Self-regulation is an emergent property of this process."

But even global homeostasis is hard for most biologists to accept. The difficulty lies in imagining how to bridge the gap between local effects and planetary changes. An organism that alters its environment to benefit its offspring is onto a good thing: that is why birds build nests. But it is hard to see how such Darwinian nepotism could operate over many generations at continental distances.

In an attempt to answer Dawkins and Doolittle's criticisms, Lovelock has devised an illustrative mathematical model called Daisyworld. The model demonstrates how "daisies" of different colors, subject to natural selection, can regulate the temperature of an imaginary planet even as the "sun" changes in brightness. Dark-colored daisies proliferate when the sun is cooler and, by absorbing heat, warm the planet: the reverse is true of light-colored daisies.

Lovelock maintains that Daisyworld proves that Darwinian natural selection can produce global homeostasis. Others disagree. "Daisyworld is an essentially arbitrary view of how the world works," says James W. Kirchner of the University of California at Berkeley. The model regulates temperature only, he says, because the daisies are exquisitely sensitive to temperature and have contrived and implausible properties. If more realistic daisies are allowed to spring up, then Daisyworld fails to achieve stability.

Lynn Margulis of the University of Massachusetts at Amherst, an outspoken champion of Lovelock's ideas, dismisses the Doolittle-Dawkins criticism as reflecting an ignorance of chemical ecology. She maintains that Gaia can actively regulate conditions, whereas the standard Darwinian view holds that the conditions change by chance and that organisms adapt to them. Margulis argues that interactions between organisms lead to ecological diversity and hence stability because the pools of biologically active elements such as carbon and oxygen are continually recycled. Thus, a local increase in the concentration of a gas—say, methane—is counteracted by organisms waiting to use it as food. "People who call themselves evolutionary biologists have neglected the environment to an obscene degree," she charges.

Margulis admits that the criticisms of the biological establishment persuaded her, as they persuaded Lovelock, to stop describing Gaia as optimizing. She also dislikes describing Gaia as an organism (because organisms do not recycle their wastes). Moreover, Margulis disavows "homeostasis," because the regulated levels change over time. "Gaia has caused the discrepancy between what you'd expect on chemical grounds alone and what you actually see," she says.

How might "active regulation" be distinguished from mere influence? One possibility is that it would produce stability. Yet some scientists who find Gaia interesting, such as Stephen H. Schneider of the National Center for Atmospheric Research, have long maintained that some of the feedback loops that link living things and their environment are likely to be destabilizing. Moreover, climate and the composition of the atmosphere have changed drastically since the earth's formation, and many of the changes were harmful to life: the fossil record is punctuated with mass extinctions. Margulis acknowledges that there is a problem recognizing stability when ecosystems are continually changing, but she offers no solution.

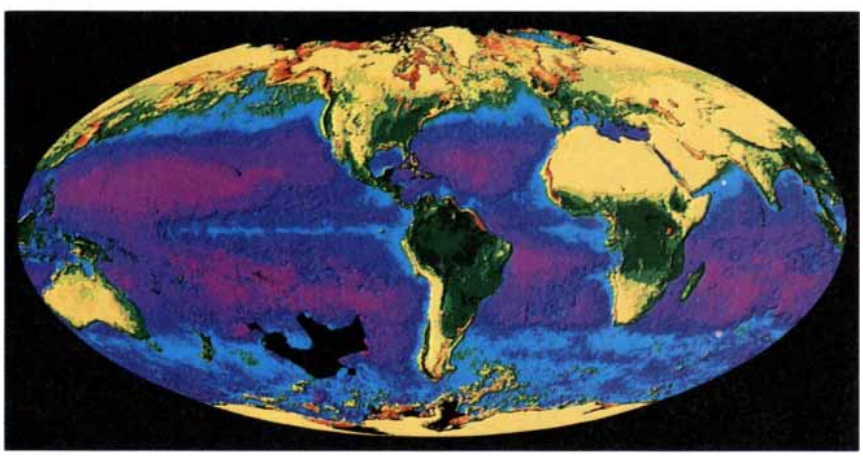
So is Gaia just a metaphor or an aphorism, like "nature red in tooth and claw"? Only insofar as all science is metaphor, Lovelock parries. In *The Ages of Gaia* he writes that attempts to prove Gaia alive are "otiose." What really matters, he believes, is that Gaia has stimulated searches for the global effects of life. Schneider agrees. "The idea is fun because it forces you to think differently about the system," he remarks.

Gaia stimulated, for example, a search for a sulfur-carrying molecule, dimethylsulfide, that is emitted by marine plankton and yields particles on which cloud droplets condense. Gaians had suggested that planktonic emissions might be able to regulate cloud cover and hence climate. (Ironically, recent analyses of Antarctic ice cores suggest that the chemical might destabilize the climate rather than stabilize it: the prime example of Gaia-inspired research may turn out to have decidedly un-Gaian effects.)

So Gaia, now approaching her third decade, does not resemble a living organism; she no longer has foresight, she no longer optimizes and (according to Margulis) she no longer maintains homeostasis. What is left to distinguish Gaia from a conventional view of evolution, in which organisms generally make the best of what they can get? How could a nonhomeostatic Gaia ever be detected? Even those geochemists who see no need to invoke Gaia in the geological record, such as Heinrich D. Holland of Harvard University, acknowledge that life has always influenced the atmosphere.

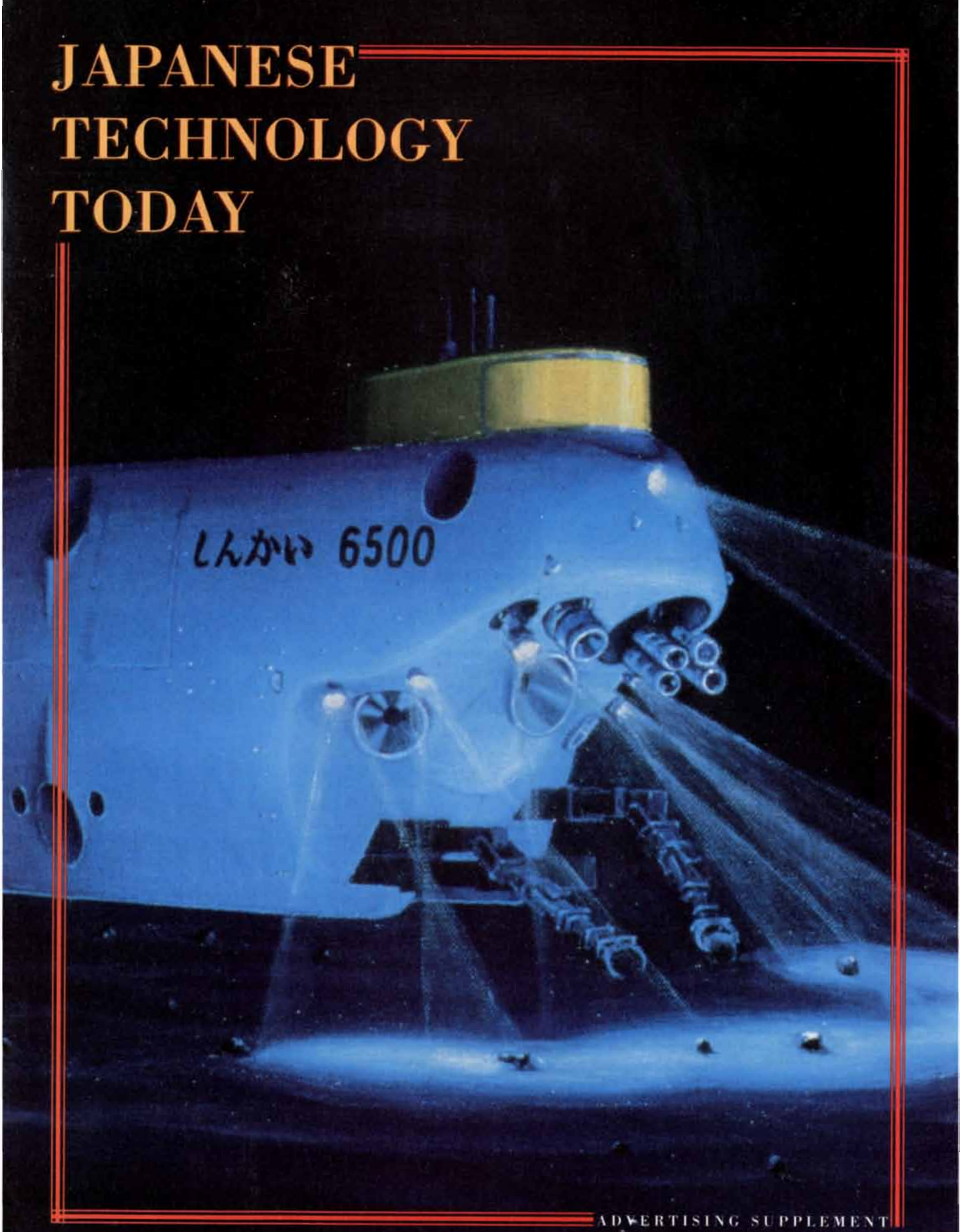
Is Gaia then anything more than the simple persistence of life? If so, she has yet to reveal herself. Her many lay followers, however, seem to be unwilling to hear that the goddess of their temple is nowhere to be found. —*Tim Beardsley*

Life pervades the planet, but does that mean the biosphere as a whole is self-regulating?



THE BIOSPHERE, as seen by NASA's* Nimbus *7 satellite. One instrument detected sea-color changes caused by plankton; another monitored land vegetation. Chlorophyll levels range from purple (lowest) to brown (highest) at sea; green is highest on land. Image by the Goddard Space Flight Center and the University of Miami.

JAPANESE TECHNOLOGY TODAY



ADVERTISING SUPPLEMENT

The International Research Exchange Programs

Research Development Corporation of Japan(JRDC)

Research Development Corporation of Japan (JRDC), established in 1961, is a government owned organization which operates under the Science and Technology Agency (STA). JRDC is to undertake the promotion of the International Research Exchange Programs.

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2. Outline of the Program

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(Standard model for joint research)
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②Budget: ¥2 to ¥3 billion
(Each side bears ¥1 to 1.5 billion)
③Site:
A research site shall be established at a suitable university or a research institute.
④Researchers:
Both JRDC and its foreign counterpart concerned may select their respective researchers from academia industry and government.
i) Research directors: 2 (one from each side)
ii) Researchers: 15 to 20 in total for both countries.

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1. Purpose

The purpose of this program is to promote the international exchange of researchers by providing fellowships to foreign researchers in the science and technology fields.

2. Outline of the Program

Fellowship awardees fall into two categories: (1) those recommended by their own governments and (2) those recommended by Japanese host institutes.

Numbers of awardees: 130 for FY 1989

Qualifications:

①Possession of a doctoral degree in a scientific or engineering field, or an equivalent qualification.
②Age under 35, in principle.
③Having sufficient language ability to be able to pursue research in Japan, Japanese ability is preferable, but in most cases English ability is sufficient. With the host institute's agreement, other languages may also suffice.

Fellowship awards:

The following items will be provided to the Fellowship awardees:
①Round-trip airline ticket (economy class).
②Living allowance: ¥270,000 per month.
③Family allowance: ¥50,000 per month.
④Housing: ¥100,000 maximum per month may be paid as housing allowance: any shortfall is to be borne by the awardee.
⑤Relocation allowance for moving from overseas to Japan: ¥200,000

Host Institutes

Host institutes comprise national laboratories (excluding universities and laboratories affiliated with universities), public (semi-government) corporations. and non-profit organizations.

IF YOU ARE INTERESTED, PLEASE CONTACT

Research Development Corporation of Japan
(JRDC)
Department of International Research Exchanges
5-2 Nagata-cho 2-chome, Chiyoda-ku Tokyo 100, Japan
Phone:03-507-3024, 3025 Fax:03-581-1486
Telex:J33135JAREDECO

Seishi Katayose

Chief Editor

SAIENSU

Japanese industry is moving toward the creation of its own unique technology through the expansion of basic research efforts. This is in part because, with Japan's role in international society on the rise, the government and industry are increasingly conscious of the basic research responsibility commensurate with the nation's growing international stature. As the background to this trend, there are intensifying trade frictions with the United States and European countries and the moves in those countries to strengthen the protection of intellectual property rights. Another major reason is that Japan is under added pressure to develop high value-added products in response to the NIEs' catching-up efforts.

"...with Japan's role in international society on the rise, the government and industry are increasingly conscious of the basic research responsibility commensurate with the nation's growing international stature."

The Japanese industrial structure is on the threshold of great change. Emphasis is shifting from "heavy, thick, long and large" products to "light, thin, short and small" goods and further to software-intensive industries. This shift has activated plant and equipment investment, while at the same time spurring organizational changes, advances into new fields, and mergers and acquisitions for organizational reinforcement. To keep pace with these changes, Japanese companies have stepped up their investments in technological development. Japan's scientific and technological research expenditures in fiscal 1987 total ¥9,836.6 billion, up 7% over the previous fiscal year. Of that amount, corporate research expenditures accounted for two-thirds. This was equal to 2.8% of the gross national product of that fiscal year, the highest ratio in the nation's history.

In the same year, expenditures on basic research, in which Japan is considered to be a laggard, grew at an extremely high rate of 13%. Many corporations, which previously gave top priority to development research, more recently have begun to establish basic research laboratories. This country has so far depended on other nations for much of its basic research needs, but for this attitude Japan is now being increasingly criticized as the intellectual property rights movement picks up momentum. The change in research focus is to deal with this situation.

Another reason for the change is that Japanese companies have reconsidered their past stance and have come to believe that, if they are to survive in the coming era of technological renovation, they must first of all tackle basic research. At the same time, they must cope with the sales offensives of the NIEs, which have in their lower costs of production a powerful weapon.

Major high-technology firms are striving to raise their ratio of R&D expenditures to total sales to approximately 10% for now. By increasing R&D spending they aim to expand not only basic research but also research for the development of equipment to meet the needs arising from the growing information orientation of the economy. Internationalization is making rapid headway in the field of research as well. In an effort to avert a further intensification of trade friction, Japanese corporations are shifting production overseas. They are trying to contribute to overseas employment, raise the rate of local parts procurement, and operate their overseas plants as local businesses. In some cases these efforts are taken a step further and research bases are also established abroad to enlist overseas researchers in development activities. Companies that are particularly oriented toward international activity are stressing research that incorporates the culture of each country.

Efforts to nurture the work of researchers and engineers are another recent notable move among Japanese businesses. Fixed working hours, for example, do not entirely serve the purpose of fully activating the originality of researchers and engineers. They can work more successfully if they are given some freedom in their work. Many U.S. and European companies have adopted a "flex time" system, and this system of flexibly scheduling work hours is also gaining ground in Japanese companies, especially at research departments.

Increasingly, companies are allowing researchers, in addition to working on the subjects determined by the company, to devote some of their time to studies on their own personal themes. Managements have come to believe that enthusiasm and willingness on the part of the researcher is a key to successful results. At the same time, the number of cases is increasing in which these personal research activities have born fruit.

Following are the strategies of a number of companies that reveal how they think and what they foresee for their business.

Hiroshi Nagano

Director of International Affairs Division
Science and Technology Promotion Bureau

SCIENCE AND TECHNOLOGY AGENCY

The pursuits of science and technology have been closely related to the progress of human life and have supported man's prosperity and the development of economies and societies throughout history. In recent years, science and technology have assumed a larger role in dealing with important global issues, such as the reduction of chlorflurocarbons (CFCs) and other environmental problems and the overcoming of cancer, AIDS and other diseases.

"Japan is preparing to contribute to the international community by promoting creative basic research and information exchanges with researchers from many countries."

At summit meetings, where leaders of major advanced nations primarily discuss economic problems, science and technology are now treated as important subjects. It is still well remembered that the Human Frontier Science Program, designed to be Japan's contribution to international society through science and technology, was proposed on the occasion of the Venice summit.

Since opening its doors to the outside world in the Meiji Era, Japan has absorbed scientific and technological knowledge from foreign countries in order to develop its national economy and further improve its people's standard of living. In an effort to raise its scientific and technological levels, Japan has also put this knowledge to the task of promoting science and technology, ranging from the basics to applications. However, it is a fact that this country has been criticized for conducting, in the course of its rapid economic growth in recent years, application-development research based on the results of basic research carried out in the United States and Western European countries, an act that ultimately has led to the generation of huge trade surpluses. Thus, there are now strong requests by countries around the world that Japan, now the second largest economy in the noncommunist world, make international contributions to science and technology, as befits its international position. To meet these requests, Japan is preparing to contribute to the international community by promoting creative basic research and information exchanges with researchers from many countries.

To respond to these international requests and also to promote science and technology, Japan has been pushing for a wide range of international cooperation agreements. Specifically, the Science and Technology Agency, which is the governmental body in charge of overall coordination of scientific and technological activities in Japan, has taken a number of steps, including the following:

Enactment of the Research Exchange Promotion Act in May 1986, thereby establishing a legally open research milieu for facilitating exchanges among industrial, academic and government circles as well as with overseas researchers.

Promotion of advanced basic research aimed at the discovery and development of new knowledge that can serve as the basis for technological renovation in the 21st century. This is being carried out by RIKEN, one of Japan's most advanced research institutes, by conducting pacesetting basic studies under an internationally open new system (Frontier Research System) that allows a free mobilization of foreign researchers.

Implementation of the Human Frontier Science Program—a program aimed at conducting basic research conducive to the creation of scientific knowledge as a common asset of the human race.

Establishment of the Science and Technology Agency Fellowship System to promote international exchange of researchers. Under this system, the acceptance of 100 foreign researchers by national laboratories in fiscal 1988 was arranged. Plans for the current fiscal year call for the acceptance of 130 researchers.

Acceptance by the Research Development Corporation of Japan of foreign researchers under the Science and Technology Agency Fellowship System, starting in the current fiscal year. Practical assistance is also being offered to these researchers through the improvement of housing facilities and the extension of language training and counseling services in English in order to further accelerate international research exchanges in the area of science and technology. The Ministry of International Trade and Industry, the Ministry of Agriculture, Forestry and Fisheries, and the Ministry of Education have introduced measures to actively promote international exchanges.

Japan intends to continue its active promotion of international cooperation in science and technology, based on the view that such promotion is an obligation of a country advanced in these fields.

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A World of Difference

Shoichiro Yoshida

Senior Managing Director

NIKON CORP.

On the occasion of the 70th anniversary of its founding, in 1987 our company determined to focus its research and development efforts on "light and micro."

In consideration of the international economic environment characterized by trade friction among advanced countries and the catching up of the NIEs, there seem to be no other ways for Japan to continue in the world but to strive to manufacture products based on higher technology. Meanwhile, borders between technologies are rapidly disappearing, as evidenced by the fact that optical engineering and electronics are merging and creating new possibilities. Amid these currents, individual companies must avoid competition with one another both inside and outside this country by establishing their own unique technology. Based on this viewpoint, we are placing "light and micro" at the base of our technological efforts.

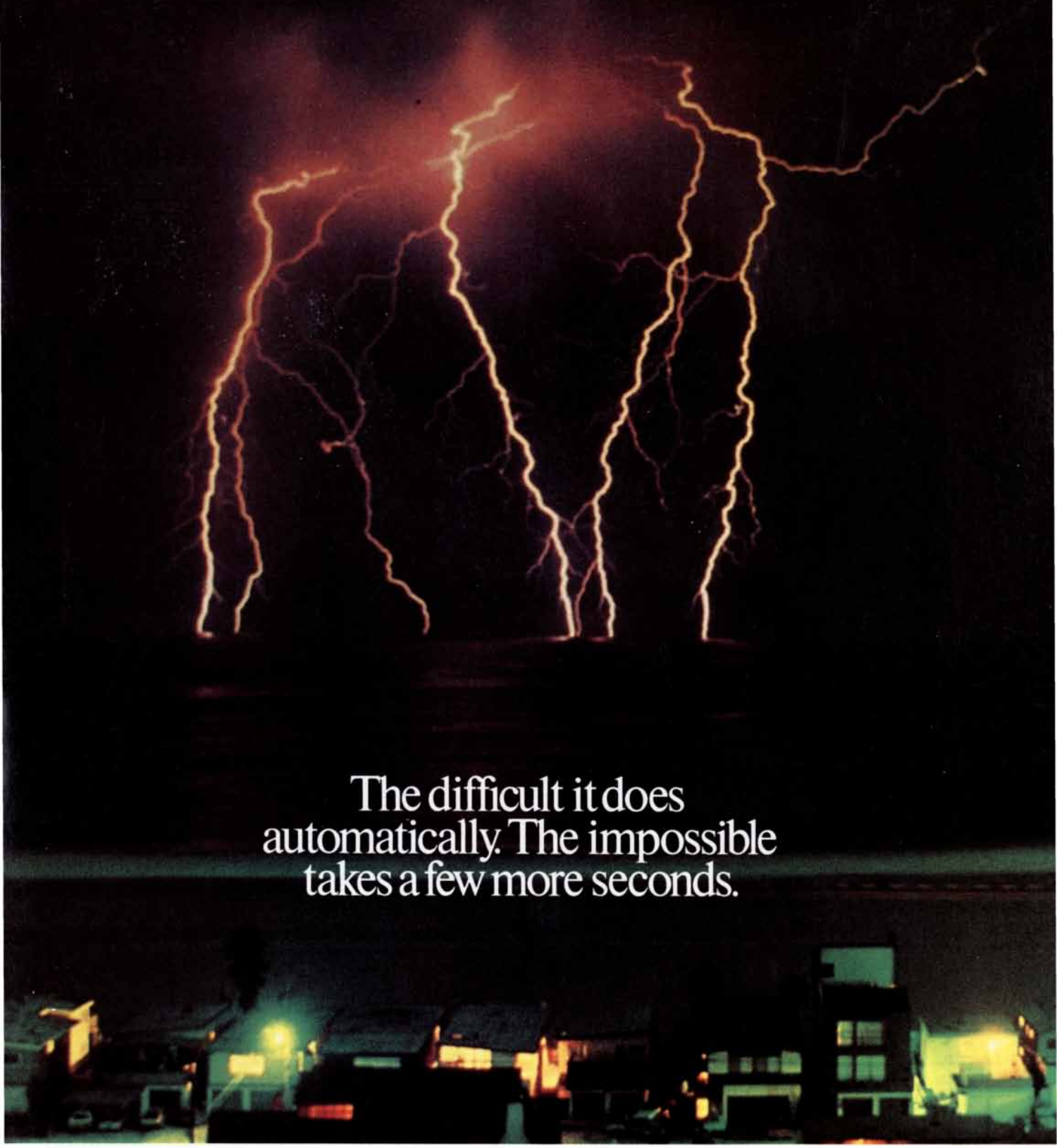
"...borders between technologies are rapidly disappearing, as evidenced by the fact that optical engineering and electronics are merging and creating new possibilities. Amid these currents, companies must avoid competition with one another both inside and outside this country..."

At present, semiconductor manufacturing equipment such as steppers accounts for about 40% of our total sales, surpassing sales of the camera department. It was only in 1980 that we completed the first commercial product in our stepper line, and in the past ten years our product mix has undergone dramatic change. We are sure that the growth of the microelectronics industry will continue for some time to come and that hereafter there will be stronger requirements for the automatization and precision improvement of optical measuring instruments. In addition to this industrial equipment field, the image information area, where silver-salt films are being replaced by magnetic disks, and the health and medical equipment realm involving diagnostic/treatment equipment for the opthamologist, will be our future strategic business fields.

The key words common to all of these areas are "light and micro." Regarding micro control technology, Japan has completely caught up with the advanced industrial countries, reaching a level we can be proud of. Large possibilities are still untapped, however. Under the "Yosida Nanomechanism Project," which is being promoted by the Research Development Corporation of Japan and is headed by me, we are endeavoring to establish super-micro control technology on the order of nanometers (1/1,000 micron). Such micro technology is the supporting basis for the technological development not only of microelectronics but also of a wide variety of engineering fields including the design of new materials. It is believed that "those who can govern the micro world can also control the macro fields."

Research and development expenses at Nikon are equivalent to about 4% of our total sales, but our total R&D investments, including expenditures for development of production technology and for product development, exceed our equipment investments. Increasing R&D investments are a trend witnessed throughout the manufacturing industries. Nikon also has been placing top priority on R&D in tapping our human resources, while continuously trying to secure a variety of good employees. One example of this is that Nikon Precision, Inc., which is engaged in sales of steppers and related technological services in the United States, has started to employ R&D staff members there.

Although we are placing emphasis on "light and micro," we have no intention of being excessively or exclusively attached to that concept. It is also necessary to absorb peripheral technologies and thereby expand business fields. When cooperating with other companies in technological development, "give and take" relationships must be the premise. All the more because of this, we intend to proceed with the development and accumulation of unique Nikon technology.



Catching a bolt of lightning used to be a shot in the dark.

Take the picture you see here, for example. Ordinary exposure control systems could be fooled by the dark black sky and overexpose the lighted skyline.

But with the Nikon N8008, all you do is select Matrix Metering (our unique multi-segment computer-controlled light meter), set the exposure control for Aperture Priority Automatic and, if your timing is right, lightning will strike.

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Hitoshi Aoike

**Senior Managing Director,
General Manager of Research and
Development Division,
General Manager of Central R&D Center**
VICTOR COMPANY OF JAPAN LTD.

Business in Japan's audiovisual industry is currently undergoing cataclysmic change. Broadly classified, the change is occurring in the form of interdisciplinary business advancement, internationalization and software orientation.

"...it will become necessary to adopt a global strategy for conducting research and development at the places of consumption throughout the world."

Regarding interdisciplinary business advancement, industrial boundaries are disappearing due in large part to the introduction of computers. In turn, the industries handling information, such as the AV, computer, printing, and photographic industries will become mutually interrelated. If you remain idle, someone from another industry will advance into the market; on the other hand, you will have increased opportunities for entering other fields. At any rate, the arena for business will change, with rules for competition being altered as a result.

Regarding internationalization, it will become necessary to adopt a global strategy for conducting research and development at the places of consumption throughout the world. Software orientation is difficult to define, but the times have changed so that things should be considered through an approach based on application, rather than on hardware as in the past. In the past, hit products for general consumers emerged from among those targeted at nonspecific masses. Now, however, they are among those products for specific large groups of consumers. The undercurrent of this phenomenon is the shift toward software.

Corporate strategy in the 21st century must be worked out in light of the major changes mentioned above. A setup must be established that allows integrated business operations, ranging from the manufacture of hardware to sales, to be conducted with user applications uppermost in mind. With regard to internationalization, production at places of consumption is expected to increase. But without adapting product designs or application development to local needs, it will be impossible to become really rooted in the local economy. In implementing R&D, in addition, personnel resources must be utilized on a global scale. The time has come for Japanese corporations to shake off their past attitude of pure defense and grapple with these matters positively, in accordance with an appropriate corporate strategy.

We've set up the goal of "continuously fostering specialized technologies for use in countries around the world," a goal we will pursue as we prepare to take on the challenges of the 21st century. Accordingly, we thoroughly restructured our research organization in February of this year. The conventional R&D setup in which activities were conducted for each hardware product, like VCRs and TV sets, was replaced with a system under which each researcher will completely master the specialty areas involved. At our general research laboratory, researchers are divided into groups of 10 to 30 persons, to work in such specialized fields as image processing and audio psychology. Researchers in such groups also belong to "horizontal" groups formed on the basis of rough classification of products, such as memories and displays. Thus our research structure has been turned into a kind of vertical and horizontal matrix-shaped organization. From now on, researchers who can understand the world of sensitivity, for example, will be required. As an AV equipment manufacturer, where many researchers have long been tackling problems relating to sensitivity, Victor Co. of Japan would like to develop more engineers excelling in sensitivity in the framework of a new organization.

Multimedia and information compression technology are key technologies for the coming years. Multimedia, which unifies images, sound, text, and graphics, can be considered the embodiment of interdisciplinary business advancement. As for information compression technology, common worldwide standards have yet to materialize. Conventional compression technology has negative aspects such as the degradation of image and sound quality. But it will become important to achieve compression without lowering the quality level of the information. Times are again heading toward the use of analog signals, and away from the reliance on digital signals that is engendered in computers.

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Toshio Nakatsubo

Senior Managing Director, Executive Director Corporate Research

OLYMPUS OPTICAL CO. LTD.

Olympus Optical plans offensives in the following three areas as the 21st century approaches:

(1) video and information
(2) medical treatment and biotechnology
(3) semiconductor-related fields

These are not new areas for our company, which is accomplished at the precision technology required for cameras, endoscopes, and microscopes. Our posture is to put our managerial assets, such as the personnel and technology we now hold, into full play and further develop them.

"...it is our policy to reposition cameras, which have been used only as hardware in the realm of images, as the core of an image information system, including software."

In the field of images and information, we have undertaken the work of reviewing the concept of the camera. We now believe that a solid-electron camera is the ideal camera for the near future. This will be a camera designed to be free of the mechanical aspects of existing cameras to the fullest extent possible. It will be an improvement over the electronic still camera with magnetic memory that has just appeared on the market. Instead of using film or a floppy disk, the new camera will use an IC card and will be equipped with an electronic button for a shutter. The reproductivity of the images stored in the IC card will make possible various applications, such as television displays, transmission through telecommunications circuits, and hard copy printouts through video printers. Thus, it is our policy to reposition cameras, which have been used only as hardware in the realm of images, as the core of an image information system, including software. This will create new business opportunities.

The point of our work in this area is to attain the technology for enhancing the density of information storage. Existing magnetic disks and IC cards are insufficient for large-volume information storage on a micro scale. We believe that optical IC cards or optical disks, (to be developed through the application of optoelectronics) will be required for this purpose. Our Hachioji Research Laboratory, completed last year at a total construction cost of about ¥15 billion, is now striving to develop short-wavelength light sources, memory materials made mainly from organic pigments, and pickup devices.

Even in the future, such auxiliary medical equipment as endoscopes, microscopes, and biotechnological analysis equipment will surely remain the basis for our medical equipment operation. The conversion of endoscopes into electronic scopes and the electronic filing of medical information are future tasks to be tackled. In addition, support equipment for research on cerebral nerves has recently loomed large as a new development theme. With the graying of society accelerating in the next 10 years, diseases of the aged or related to mental stress will increasingly need to be addressed, and the number of cerebral researchers is expected to grow. For this reason, we dispatched our researchers to the United States and are now making preliminary preparations for full-fledged research and development in this area. As for semiconductor-related pursuits, we are endeavoring not to manufacture semiconductors themselves, but to provide semiconductor manufacturers with experimentation- and development-supporting equipment. And we have already developed, as a commercial product, an acoustic microscope for IC inspection.

The ratio of research and development expenditures to total sales is 9%. As high as 30% of our employees are R&D staff. In our pursuit of high added-value products, we plan to further raise this proportion in the future. Also, to deal with the increasing complexity of technology, we are now thinking of widening the scope of new university graduates we hire to include agronomy and biology majors in addition to engineering graduates. We are also going ahead with the improvement of the software side of our research environment by adopting a system to encourage researchers' voluntary selection of study themes and initiating budgetary steps for promising ones. We are also arranging the complete introduction of a flex-time system that does not use time cards.

Takashi Oka

General Manager, Product Planning and Marketing Group No. 3

NISSAN MOTOR CO. LTD.

Nissan Motor Company has put on sale its "Infiniti," a luxury automobile that embodies many new concepts that presage the future. This car is the realization of our long-cherished dream to produce a "flagship car" that represents Nissan. The recent high yen rate has prompted some people to favor developing high value-added products, including high-class cars. The production of our Infiniti, however, originated from totally different concepts.

"We hope to make a unique car. Not an imitation of an existing car, but a car of global appeal."

Throughout the world, there are a number of luxury cars and classic cars. If we were to absorb all the strong points of these cars, then manufacture a car with Japan's advanced technology, and market it at a low price, Nissan could make a profit. In that case, however, Nissan would be unlikely to become a corporation respected throughout the world. In undertaking the development of a new car, we want to produce one not inferior to Mercedes-Benz, BMW, Jaguar, or Cadillac, thereby adding to the choice among luxury automobiles.

We hope to make a unique car—not an imitation of an existing car, but a car of global appeal. The basis for such a car, however, is the indigenous nature of the country of origin. Thus, the answer to the question, "Is it all right if only Japan's cultural tradition is put to the fore?" is "Not exactly."

We determined that it was most important to incorporate Japanese traditional features that would be evaluated highly worldwide, and clearly represent the future direction of the best in Japanese technology. This was an attempt to materialize a Japanese concept of a high-class car that would be appreciated throughout the world, by means of leading-edge technology and in a form that will endure into the future.

For Japanese cars, three characteristics—fuel economy, good quality, and high reliability— have become tradition. It was a matter of course for us to further promote these qualities, but we also thought of incorporating highly advanced technology where necessary to create a high-class car that would harmoniously serve the driver's intuitive or personal sense and thus further enhance the quality of the driving experience.

It is generally believed that driving stability and riding comfort are mutually opposed. A major characteristic of this car, however, is that the levels of both are raised through the incorporation of high technology. For instance, the Infiniti has a 4.5-liter DOHC engine. Conventional DOHC engines have insufficient torque at medium and low speeds, but with this engine that problem was solved by changing the valve timing between the medium- and low-speed ranges and the high-speed range. Through this and other novel ideas, improvement of fuel economy was also vigorously pursued, to produce an engine that by far surpasses others of similar size in terms of fuel economy.

A supercomputer was used to analyze engine vibration characteristics. Based on the results we studied how to make an engine produce a "comfortable" sound. That is, we utilized sound, not noise, as an accurate indicator of the condition of a car.

For the suspension, too, we adopted a totally new concept. Under the four-wheel multi-link suspension formula we employed, the most appropriate position of the wheels within the parameters of their location is computed, and precise changes are made accordingly. For example, the suspension will control the optimum location of the tires when they are pushed upward or when the car is turning.

It is a matter of common knowledge to be cautious in applying the brakes when the car is being turned. This car, however, will maintain its course even if the brakes are slammed on while turning. The changes in the suspension caused by the application of the brakes were determined in preliminary studies, producing this effective suspension design.

It is also important that the tires maintain a positive grip on the road surface when the car is turning. Therefore, we developed a four-wheel steering system of the phase-reversing control type—the first one of its type in the world. The combination of this steering system and the above-mentioned multi-link suspension provides driver-friendly handling characteristics. We believe that this represents the world's foremost automotive technology.

A major characteristic of the car is to skillfully use a nonlinear control region so that control movement becomes driver-friendly. This type of technology is also expected to be applied to other industrial products and become an outstanding quality of Japanese industry.

Not only Nissan but all other car makers as well are diligently striving to improve the reliability of control systems. In effect, car makers are producing an aircraft-class vehicle at one-hundredth of the price of an aircraft. In the 21st century, these sophisticated mechanisms will not be limited to luxury cars but will be part of all passenger cars.

JAPANESE. LUXURY.

From the days of the gilded coach, the concept of luxury has been one of costly indulgence and material abundance. And today, in the field of luxury cars, that definition is mostly accurate.

But in Japan, centuries ago and today still, where true luxury is a spare, natural idea and beauty is a personal experience, there's no such definition.

The Japanese idea of what a luxury car should be is different from the Western concept.

In Japan, luxury trends are seen as temporary and transient—the idea of luxury has more to do with a deeper set of values than with ornamentation or technical gadgetry.

Japanese luxury is not a showy badge or a symbol of accomplishments, it is an experience of ownership based on long-lasting quality.

That is the Infiniti philosophy.

Infiniti is primarily a driver's car—where the driver is more important than the car itself. Designed to please the driver while he's driving it. Designed to provide an experience of ownership that will not diminish over time.

This experience isn't something you can pick up from the pages of a magazine—a picture with a list of specifications will contribute marginally to understanding what it is that makes the Infiniti experience different.

The real experience comes from driving an Infiniti—which you'll be able to do later this year.

If you can wait, we promise you won't be disappointed.

For additional product literature, call 1-800-522-0990.

Thank you.

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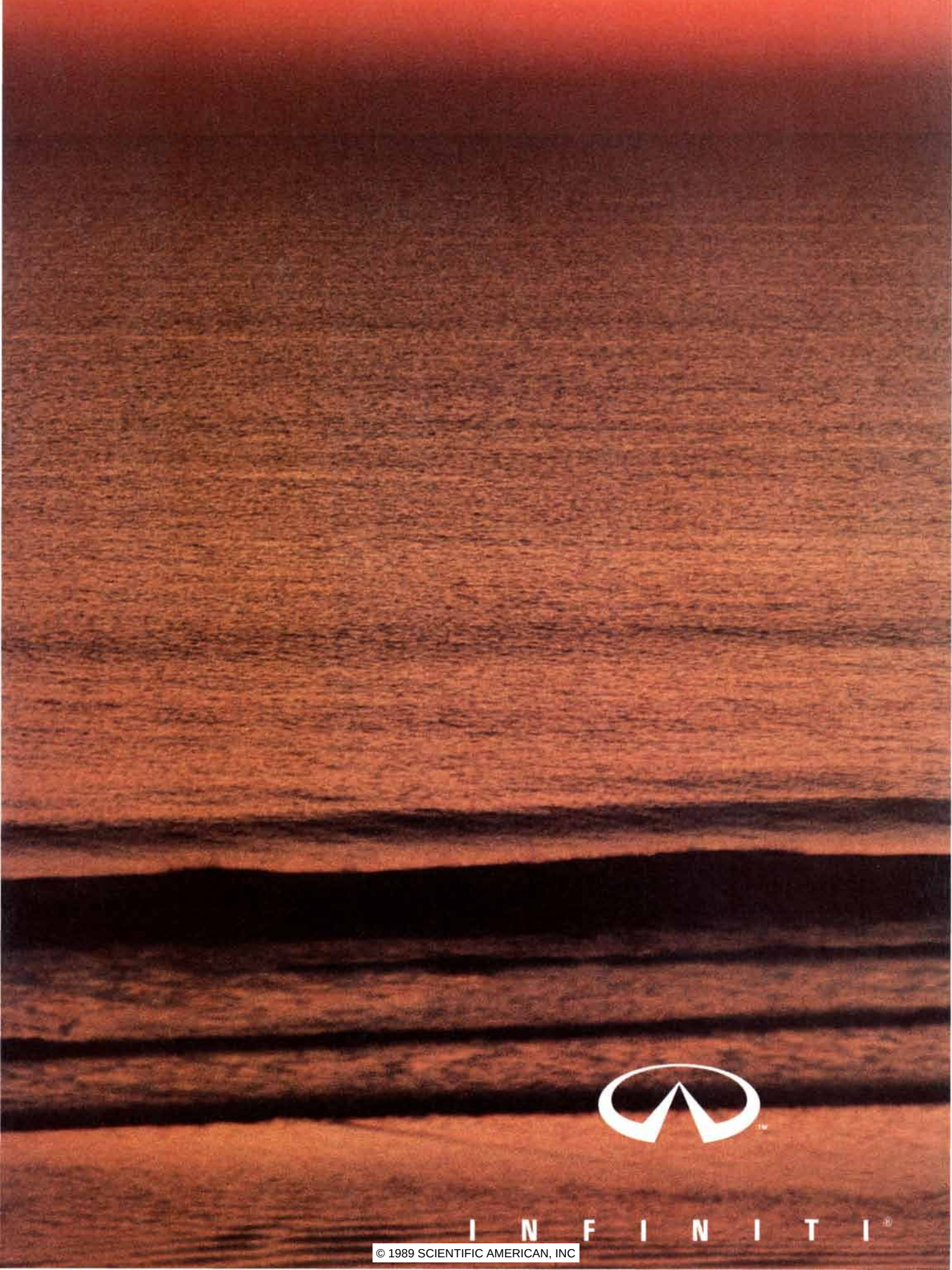


Dr. Yoshinori Ito

Senior Managing Director, General Manager of Research and Development Division

SUMITOMO METAL INDUSTRIES LTD.

Not long ago, the steel industry was in a very difficult situation, but its business base was strengthened by restructuring efforts and the crisis in the industry was successfully overcome. With domestic demand still propelling the nation's economic expansion, favorable conditions for the industry are expected to continue for some time. The technology of the industry and international competitiveness of its products are at high levels. But with the United States, European nations and Asian countries making efforts to match the level of the Japanese steel industry, we can by no means let our guard down. And, taking the long view, there are many steps that should be taken now. Technological development is the most important one. It must be pursued regardless of the overall economic situation or the state of the steel industry.

"advanced technology can be a decisive weapon in responding to the competitive surge of the developing nations."

In its technological development endeavors, Sumitomo Metal Industries is now giving priority to reducing production costs and adding high value to products. The former is important in the upstream stages of steel production, such as the selection of raw materials, and the latter is important downstream, where products such as sheets and pipe and tubes are manufactured.

Needless to say, in raising the international competitiveness of corporations and their products, cost reduction is essential. And advanced technology can be a decisive weapon in responding to the competitive surge of the developing nations. Already, we have the good prospect of accomplishing the technology for achieving significant cost reductions without substantially changing the existing production line. We undertook this effort about two years ago, and the new technology is expected to become operational around 1995.

The addition of high value has various facets. An example is a surface treatment technology for overcoming the susceptibility of steel to corrosion. We were certainly delayed in our efforts at first, but now we are confident of our position among the leaders in the industry.

Steelmakers commonly recognize that they cannot survive if they continue to depend solely on steel. The question then is, what fields should the steelmakers advance into? Each company is formulating its own unique answer. Electronics is the most attractive area, and some steelmakers are registering steady achievements, as in LSI production.

It is true that we are also trying to develop semiconductor-manufacturing equipment. However, electronics is a field where competition is very keen, so it is not easy to survive in that arena. Consequently, we are looking at biotechnology, not that area in which active research and development is currently being conducted, but a field that is more directly related to human health. We have termed this field focussed on heath, the "high-quality life." Particular areas with strong technological development potential are health foods and pharmaceuticals.

Our first endeavor in this field was in the development of herbal medicine. Herbal medicine is for preventing diseases and maintaining health rather than curing diseases. However, the herbal medicines currently available are not of equal quality, since the cultivation of herbs is often adversely affected by weather. We therefore hope to raise herbs in an artificially controlled environment and thus provide high-quality herbal medicines. As our first step, we opened an herbal culture and research laboratory in Eniwa City, Hokkaido, this year.

The base for our full-scale research and development activities will be the High Quality Research Institute. This institute, scheduled to be completed in the Kansai Cultural and Academic Research City in October 1991 at a total construction cost of ¥10 billion, will engage in various studies, among them research on herbal medicine and health foods; research on life science synthesizing medical science, pharmacy, sports physiology, and psychology; research on new medical systems unifying Oriental and Occidental medical science; and development of new medical equipment.

Our present staff will not be sufficient to conduct these research and development efforts. Therefore, we will have to bring on board about 100 people through various methods, including recruiting. Our success in attracting these people will be the key to the ultimate completion of these projects.

We would like to raise the company's ratio of high value-added product sales to total sales to 30% by the beginning of the 21st century.

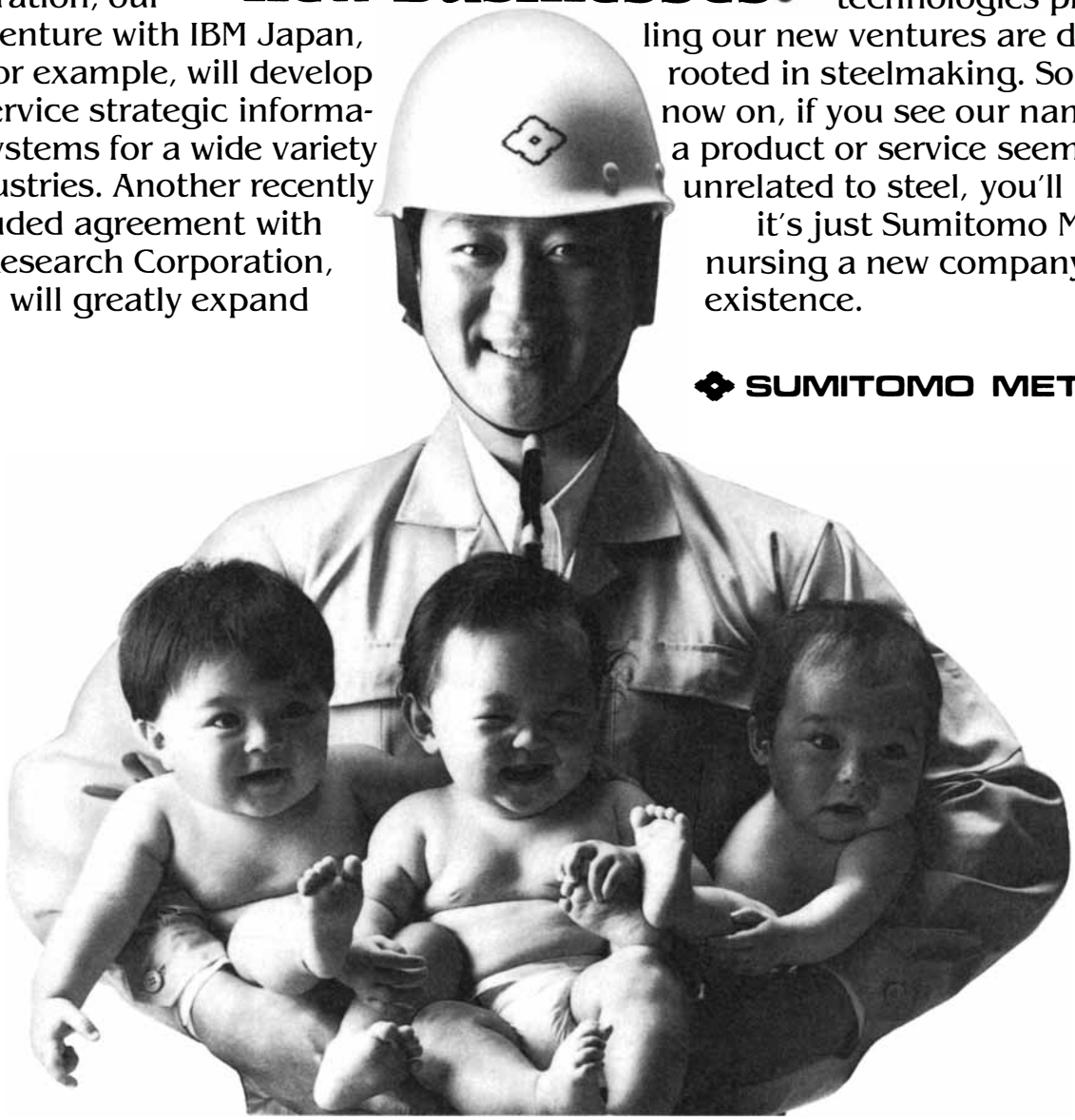
Who'd have expected a steelmaker to provide a fertile environment for creating new businesses?

Most people know Sumitomo Metals as one of the world's leading steelmakers. But what isn't often widely known is that Sumitomo Metals also has a reputation for nursing new companies into existence – many as joint ventures – in a wide range of fields that include health care, information, communications and electronics.

Sumitomo Metal Information Systems Corporation, our joint venture with IBM Japan, Ltd., for example, will develop and service strategic information systems for a wide variety of industries. Another recently concluded agreement with Lam Research Corporation, U.S.A., will greatly expand Sumitomo's semiconductor equipment operations. And we've also moved into the medical and biotechnology business by establishing SMI-Bristol Co., Ltd., a competitor in the rapidly growing field of clinical testing in Japan.

But don't misunderstand. Sumitomo Metals hasn't forsaken the steel business. Our search for steelmaking excellence will continue. In fact, many of the technologies propelling our new ventures are deeply rooted in steelmaking. So from now on, if you see our name on a product or service seemingly unrelated to steel, you'll know it's just Sumitomo Metals nursing a new company into existence.

SUMITOMO METALS



SUMITOMO METAL INDUSTRIES, LTD. Tokyo & Osaka, Japan

TOKYO HEAD OFFICE: 1-3, Ohtemachi 1-chome, Chiyoda-ku, Tokyo, Japan Phone: Tokyo (03) 282-6111 Telex: J22865 Fax: (03) 282-6224

Hideharu Takemoto

President

CANON U.S.A. INC.

As we approach the 21st century, we see image information as a driving force in future business technologies. Canon's growth is very closely predicated on this vision with the goal to making information handling more effective and efficient. In R&D, Canon is focusing on three essential aspects of this technology: image quality, speed, and interfacing capabilities.

The new Canon Color Laser Copier 500 is a recent example of our ability to produce significant breakthroughs in these three areas by integrating digital image processing and laser imaging technologies. The result is a very unique and powerful copier that has no rival in the industry. Our new copier delivers full-color output of uncompromising quality and offers a variety of creative capabilities as well as connectivity to digital and analog input sources, including computers, still video, and video systems.

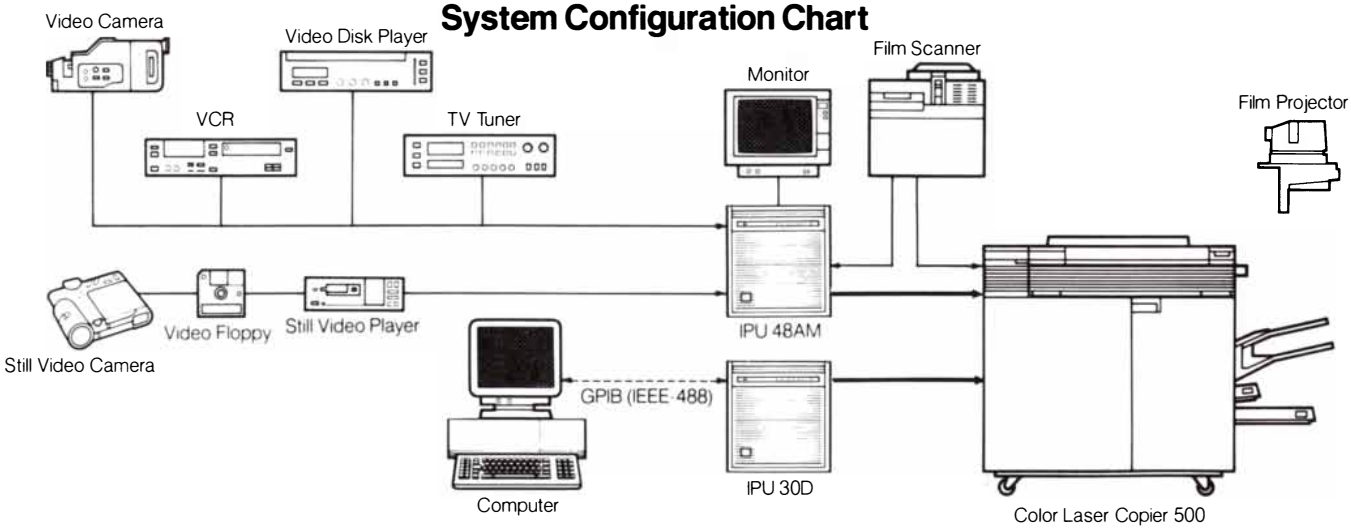
It took more than 10 years of R&D in plain paper copying technology and laser beam imaging technology before we were able to market the CLC-500. The result of our efforts is quality comparable to professional printing. At a very high resolution of 400 dots per inch with 256 gradations of tone per color, the CLC-500 distinguishes text and half-tone images for accurate reproduction of black monochrome characters and four-color images. Through our unique digital image processing system, an original image is scanned and then converted into digital signals, enabling the user to manipulate the image in a variety of creative ways. For instance, the user can merge images with text and graphics, rearrange and manipulate the format until satisfied, change colors and texture, isolate whole or segmented images, make negative and positive reversals, and finally create an original print.

Another unique aspect of the CLC-500 is its connectivity feature, offering customers a wide range of applications, especially in the "computer graphics" field. In today's multimedia age of television, video, photography, and computers, businesses have a wide variety of imaging sources available to them, but each source is employed as a non-assimilated entity that must be processed and produced separately. The connectivity feature makes the CLC-500 a viable technology for decades to come, because the user can integrate these various image sources to create new dimensions in creative design.

Another Canon technology that will have a significant impact on full color reproduction technology of the future is our new bubble-jet color copier. Canon's expertise in production engineering was employed to create an ultrafine bubble-jet printhead, a manufacturing process similar to that used for semiconductors. The printhead is comprised of 400 nozzles spanning a one-inch length. Within each ultrafine nozzle is a tiny heater that produces several thousand sudden temperature rises in the ink per second through a pulse-electric current. Microscopic bubbles are then formed until enough pressure is exerted to eject a single ultrafine droplet of color. This ultrafine printhead produces brilliant colors at 400 dots per inch resolution and will be a powerful tool for large-format, full-color reproduction.

Concerning R&D of future systems, Canon is focusing on highly-advanced communications technologies, developing a new integrated information network system that will change our method of communications. As with all future R&D, Canon will employ its expertise first in image data technology, concentrating on quality, speed, and widespread applications for higher productivity.

System Configuration Chart



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Dr. Hisao Oka

Executive Vice President

MITSUBISHI ELECTRIC CORP.

Today, things should be considered in global terms. Accordingly, "internationalization" is a key word for our company. However, there are many instances in which individual currents are not sufficiently grasped, although overall ones are. For a company, it is necessary to recognize the base reality of present trends and make future predictions accordingly. So, "why" and "what" are more important questions than "how." It is essential for a company to create its own scenario. Resources, energy and environment increasingly concern technology. Furthermore, correlations between humanity and technology cannot be overlooked.

"...it is necessary to recognize the base reality of present trends and make future predictions accordingly. So, 'why' and 'what' are more important questions than 'how'."

Our company is, basically, an electrical and electronic equipment manufacturer. In the field of production technology, Japanese producers are the strongest in the world. With the approaching footsteps of the NIEs that follow us and the counter-offensives of advanced countries using their intellectual property rights, however, the era of low-cost mass production has come to an end. From now on, we will be required to develop highly individual, diversified products with independent intelligence and significant high added-value, as well as system-inclined products rather than single ones. Our company now manufactures a wide variety of products ranging from heavy electrical machinery to household electrical appliances, but hereafter the relative weight of the information and telecommunications fields will increase. Under our medium-range plan up to 1992, information and telecommunications-related products, such as computers, semiconductors, and telecommunications equipment, are expected to account for 50% of our total sales. And in 10 years their share is likely to rise to 70%. This is because, for instance, electric power companies, which are the largest users of heavy electrical machinery, are themselves expected to become highly information-oriented and will require automatic gauge examination systems and a high degree of network build-up. In the realm of household electrical appliances, there will be a growing demand for personal information equipment. Therefore, it will become increasingly important to anticipate such latent needs and to be ready to satisfy these needs as soon as they materialize.

Our research and development investments have more than doubled in the past ten years. Of a present total of 50,000 employees, about 3,200 are involved in research and development, but we intend to increase the number to 5,000 in ten years. Since the total number of employees will remain at the present level, about 10% will be engaged in R&D. The ratio of R&D expenditures to total sales is now about 7%, but it is expected to surpass 10% in the year 2000.

In October of last year we established the Development Division, thereby establishing a system for seeing the 21st century in perspective. The point of this move was to build an R&D organization designed to emphasize basic research and to cater to trends for increased system inclination. With regard to the importance of basic research, we decided to reinforce and expand efforts at our Central Research Institute, leaving 30% of the research work up to the discretion of researchers themselves. At present we are constructing a Basic Technology Research Building within the compound of the Central Research Institute. Basic research for a corporation, however, is not pure research without a purpose, but research having some broad direction. Therefore, we have reorganized our research institutes for conventional household appliance and industrial equipment systems into new institutes for conducting R&D on systems such as life equipment and industrial equipment systems.

There are three kinds of technologies that we emphasize. One is the technology for putting functions into full play; new materials, semiconductor devices, and biotechnology fall under this category. A second is systems and computer software. The third is advanced processing technology. Processing technology that challenges existing limits, such as molecular and atomic-level surface processing, will be required hereafter. Since a shortage of engineers is anticipated in the future, supporting technology for enhancing intellectual productivity, such as computer-aided engineering, will become necessary in the years ahead.

Sakae Shimizu

Senior Executive Vice President

TOSHIBA CORPORATION

"...our globalization efforts can be cited. It is no longer sufficient to look at the domestic market only. Markets and business resources must be sought throughout the world. We have thus far tapped markets through exports, but hereafter we would like to promote globalization by 'rooting ourselves in overseas areas' and operating in local markets."

It is difficult to foresee the state of the world ten years in the future, but one thing is certain: it will be further along the road toward an increasingly information-oriented society. Since electronics and information services are the most promising fields for tomorrow, Toshiba intends to give top priority to information processing and telecommunications technology. As for such traditional business fields as heavy electrical machinery and household electrical appliances, we would like to respond to market needs and conduct our operations more efficiently. Now with the issue of the trade imbalance front and center, we intend to deal with it through efforts symbolized by "C" (Cooperation), "C" (Complementariness), and "C" (Competition)—namely, competing where competition is appropriate, cooperating where cooperation is possible, and complementing others where there are "complementable" conditions.

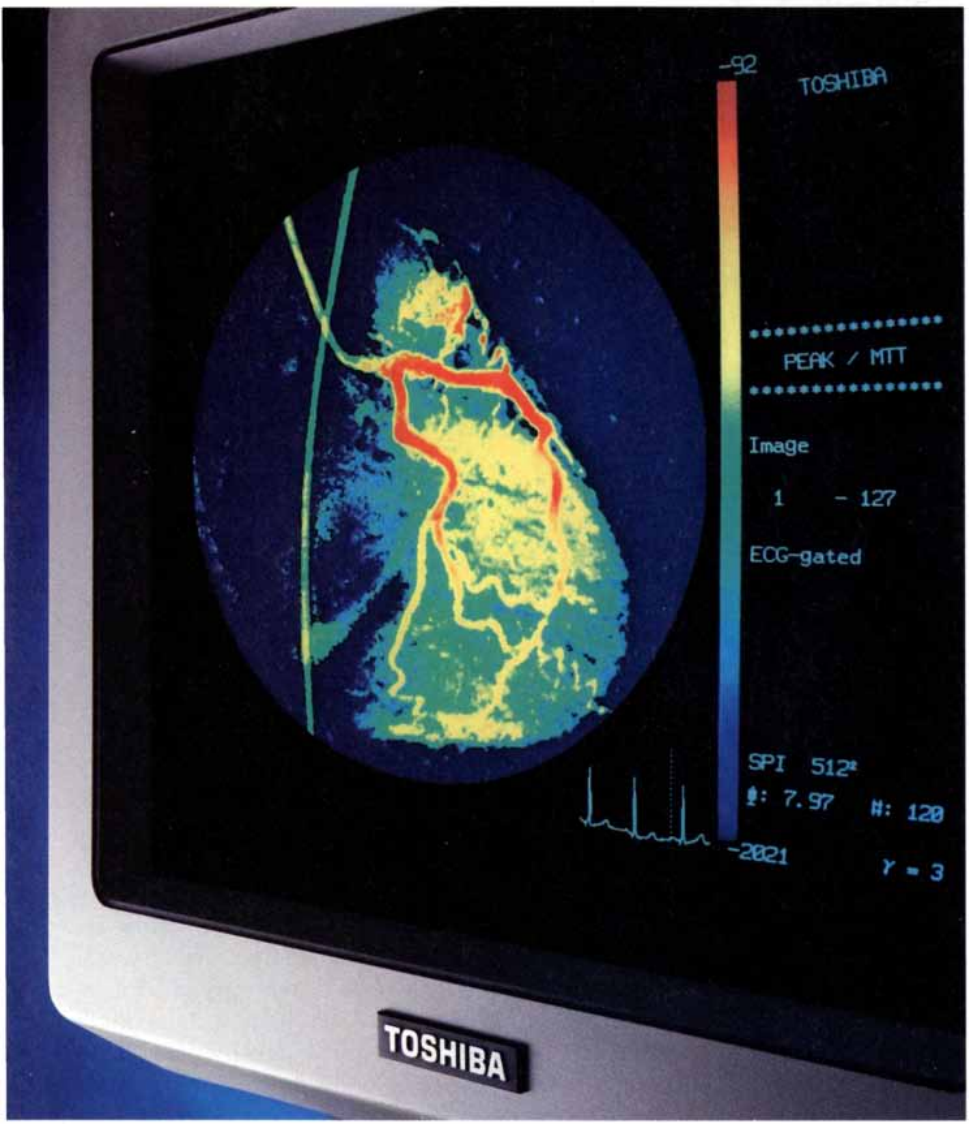
As for specific steps toward the 21st century, our globalization efforts can be cited. It is no longer sufficient to look at the domestic market only. Markets and business resources must be sought throughout the world. We have thus far tapped markets through exports, but hereafter we would like to promote globalization by "rooting ourselves in overseas areas" and operating in local markets. Toward this goal, in October of this year we plan to establish a regional headquarters in London, thereby completing a four-polar system based in the United States, Europe, Southeast Asia, and Japan. In line with internationalization, we must also proceed with transfers of technology. At any rate, it is essential for Japan, which is not blessed with an abundance of natural resources, to raise and maintain our levels of technology.

Toshiba engineers in the future must be adept at not only "innovation," but "invention" as well. Many engineers in the past were of the innovative type, capable of solving existing problems. In the future, we would like to develop engineers that can "anticipate problems." Even so, there is a shortage of engineers at present, and we have recently begun to employ female engineers. In Japan, this resource has been vastly underutilized. Since women are skilled in problem-solving, we hope to actively tap their abilities in the future.

Our research and development expenditures in 1989 will total ¥230 billion, equal to 7.8% of our total sales. Since R&D spending in 1981 amounted to ¥84 billion, the R&D investment almost tripled in eight years. A breakdown indicates that priority investments have been made in information and electronics fields, which have accounted for more than 70% of R&D expenditures during the period. The day is not far ahead when R&D spending will surpass 8% of our total sales. Of course, R&D investment amounts vary with the product line. "White goods," or household appliances, require R&D spending equivalent to 3% to 4% of sales, but the figure rises to 15% for semiconductors of ICs.

Future key technologies will involve microelectronics and information processing and telecommunications. Microelectronics has been responsible for the onset and advance of the information society. Toshiba is the top producer of 1MB memories, and we intend to further emphasize this area in the future. In order to embark on studies in such special fields as new materials and biotechnology, and thereby provide for the future, we established a basic research laboratory within our general research institute last year. All new materials produced by the general research institute are subjected to careful toxicity testing. We have taken thorough steps to handle industrial wastes discharged from our semiconductor plants, and further intend to address environmental and other social issues in earnest.

THE PICTURE OF HEALTH.



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Now doctors can see multiple images simultaneously. Images can be enlarged. And computer-enhanced color can be added to increase information and diagnostic capability.

Throughout all our medical-related technologies, from X-rays and computer tomography scanners to magnetic resonance imaging and imaging processing, Toshiba's vision has always been clear: to build the most sophisticated diagnostic equipment in the industry.

Not just for the health of our business, but, more importantly, for the health of the people who need it.

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Dr. Norio Tashima

Executive Director
System Equipment Operations
MINOLTA CAMERA CO. LTD.

At Minolta, the export ratio is extremely high for all of our main products, such as cameras and office equipment. For this reason we are better off if the exchange rate shifts toward a cheaper yen. When the yen appreciated, we tried to raise selling prices, but there were limits to such moves, and accordingly we were unable to completely offset the impact of the yen's appreciation with price hikes. As a corporation Minolta has always strived to reduce costs, but when the burden of the higher yen was added, we were quite distressed. If the yen appreciates gradually over a period of five years, for instance, we can somehow cope with it. A rapid change, however, creates a difficult situation.

"...if Japanese corporations are to maintain their business leadership, it will be necessary to further refine their R&D potential. As one step in achieving this goal, reinforcement of cooperation with government and academia should be pursued."

The fundamental reason for the strong yen lies in the strong competitiveness of the Japanese economy, which has caused intensifying trade frictions. From a long-term point of view, Japanese companies must work toward coexistence and mutual prosperity with local business communities overseas. So-called local production is an effective means of avoiding friction, but we have not made a rash move to expand our overseas operations. This may have given the impression that we are a conservative company. In building a toner plant for copying machines in the United States, we spent two years from the initial planning stage. We will also have to effectively cope with the planned EC unification. Our company acquired controlling rights of a West German copying machine maker, through equity participation, and we will engage in such M&A activities from time to time in the years ahead.

In any case, if Japanese corporations are to maintain their business leadership, it will be necessary to further refine their R&D potential. As one step in achieving this goal, reinforcement of cooperation with government and academia should be pursued. Since we cannot engage in all activities at our own research laboratories, we want to effectively utilize outside resources. Research on fuzzy engineering, which is essential for the future development of our company, belongs in this category, and we are now strengthening our collaboration with others in this field.

The ratio of R&D expenditures to our total sales has remained at about 5% for some time. Of course, we are always working to improve our in-house R&D, but the fact is that no matter how many people we may have, more will still be needed. Therefore, we would like to secure an increasing number of capable personnel through various methods, including mid-career recruitments. We are also actively assigning young people to important posts. This is because we think we can vitalize the company by changing the present seniority-based system.

The main themes for R&D activities will be in electronics and optoelectronics, as in the past, in addition to fuzzy engineering. In the energy field, we would like to speed the progress of research on batteries, since this area should not be overlooked. We cannot neglect research on micromechanisms, either, to improve the mechanical details that are relatively prone to failure. Faster development has become more important than ever. To move ahead of other companies or to catch up with early starters, speed is required. We would like to meet this requirement by further employing CAD/CAM in the future.

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MINOLTA

Dr. Yasutsugu Takeda

Executive Managing Director

HITACHI LTD.

"It is a matter of course for private companies to engage in research serving their own interests. But from now on, it will become important to go beyond such corporate borders and open untapped horizons for new industries."

The nearly 45 years of Japan's post-war history can be divided into ten-year periods. The first, beginning in 1945, was a phase of confusion; the next ten-year period from 1955 was a phase of learning; the period from 1965 to 1974 was a high-growth phase; the ten-year period from 1975 was the time when the industrial structure substantially changed to become an intellectually intensive one; and the period since 1985 has been characterized by a huge trade surplus. During these years, the United States and Western European countries developed "sharp" technologies such as are embodied by transistors, computers, and so on, thereby creating new industries. In the future, Japan must play such a pioneering role.

It is a matter of course for private companies to engage in research serving their own interests. But from now on, it will become important to go beyond such corporate borders and open untapped horizons for new industries. We can already see the beginnings of this. Hitachi has been exerting efforts in the field of optoelectronics. In 1960 Dr. Meyman at the Hughes Research Institute succeeded in laser oscillation. At that time, research in this field was so risky that those engaged in research and development were regarded by U.S. and European scientists as trying to develop a technology with dim prospects. But prior to the industrialization of the technology, Hitachi and private research institutes and universities in Japan pushed for its development, and the effort has born abundant fruit in the form of such technologies as optical disks. Similarly, Hitachi would now like to strive to further develop new technologies and nurture new industries.

It is also important to consider international relations. Hitachi's Central Research Institute has a program for accepting overseas researchers, and a cumulative total of about 100 of them have been involved in R&D activities there. Previously, studying in the United States was the general practice, but now it is time for reciprocity. Therefore, foreign researchers are joining and experiencing research activities at the Institute so that they will understand Japanese culture as well as our R&D methods.

We believe it is vital to be accepted overseas as "insiders" in the true sense of the word. Our overseas plants have already adopted "localism," and we would like to completely realize locally-based activities ranging from research to sales, and then return their positive results to the local community. In the spring of this year, we established satellite laboratories in San Francisco and Detroit in the United States, at Cambridge University in the United Kingdom, and at Dublin University in Ireland. Satellite laboratories are basic research insititutes where people with cultures and characteristics different from those of Japan cooperate in an effort to yield new achievements. About half the members of these institutes are local university or college professors, and half are employees of European or U.S. Hitachi organizations. All of the satellite laboratories have advisory committees to discuss budgets, personnel, and research themes. Research results will naturally be retained and utilized by local Hitachi companies. For university or college professors, the laboratories offer the possibility of expanding students' job opportunities, and the professors are willing to cooperate as evidenced by their proposal to hold lecture meetings once a year at local universities.

In the years to come, corporations should contribute to the support of environmentally sound communities on a global scale. It is impermissible to seek corporate development at the sacrifice of the environment. Furthermore, close attention needs to be paid to resources and international relations. Hitachi intends to endeavor vigorously in this direction, thereby meeting its responsibilities to the world.

The painting on the opening page depicts "Shinkai 6500", a deep sea survey bathyscaph which has just set the new world diving record of 6,257 meters for an existing deep submergible vehicle.

Scientists at the Hitachi Central Research laboratory recently made a historic breakthrough: A superconductive, microcomputer chip so advanced, it's decades ahead of the computers that will eventually use it.

This chip contains 22,000 Josephson junctions. These permit processing speeds that will make today's fastest computers seem as slow as abacuses in comparison.

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*US$48,496 million; net sales for the year ending March 31, 1989. US$1=¥132.

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SCIENTIFIC AMERICAN December 1989 Volume 261 Number 6

Getting Out of the STARTing Block

Verification issues should not obstruct an agreement that achieves major reductions in strategic arms. An effective verification regime should deter militarily significant acts of noncompliance

by Sidney N. Graybeal and Patricia Bliss McFate

Although a Strategic Arms Reduction Talks (START) agreement is clearly on the foreign policy agenda of the Bush Administration, until recently it seemed to carry less urgency than in the last year of the Reagan presidency. The Bush Administration went through a much needed full review of U.S. national security policy objectives and of the strategic forces and the force-modernization efforts required to meet those objectives. It did not definitively decide on the status of mobile intercontinental ballistic missiles (ICBM's), of sea-launched cruise missiles (SLCM's) or of the relation between START and the Antiballistic-Missile (ABM) Treaty. The first negotiating session under this administration did not begin until June 19 of this year, and in mid-September President Bush stated he felt "no rush on that subject."

Shortly after making this statement, however, the President received a letter from General Secretary Mikhail S. Gorbachev of the Soviet Union, brought by Foreign Minister Eduard A. Shevardnadze on the eve of Shevardnadze's meeting in Wyoming with Secretary of State James A. Baker III. The letter presented a series of arms-control proposals; some of these have resulted in agreements that will expedite the START negotiation process.

What has been blocking progress on START? Part of the answer is that one of the barriers to completing a START agreement under the Reagan Administration still exists: verification problems seem intractable to those concerned about Soviet potential for noncompliance and military gain. A recent emphasis on negotiating and implementing specific verification procedures in parallel with negotiating the basic provisions of an arms-control treaty is an attempt to remove this barrier. This new approach is best illustrated by the plan, disclosed by the Bush Administration on June 16 of this year, to confront several verification problems during START negotiations. In essence, the plan replaces Ronald Reagan's slogan—"Trust, but verify"—with "Verify, then agree."

Verification is only part of the arms-control process, which is in turn only one of the many instruments used to pursue the goal of national security. Arms-control agreements should be judged primarily by their military and political significance and not solely by their verifiability. Although verification must not be sacrificed in the name of arms control, we believe seemingly intractable verification problems must be addressed constructively; they should not impede arms-control agreements that would otherwise be of military and political benefit. It is not our intention here to prescribe a verification regime for START. Instead we wish to review some of the major problems presented by START verification and, where appropriate, offer constructive approaches to the problems.

Verification regimes should deter, prevent or warn of Soviet noncompliance, particularly any acts of noncompliance that would let the U.S.S.R. gain a significant military advantage or let it rapidly "break out" of an agreement with such an advantage. Breakout may be achieved through illegal, covert actions or through steps permitted by a treaty (sometimes referred to as legal circumvention). Under some arms-control agreements, a legal military buildup occurs because the agree-

SIDNEY N. GRAYBEAL and PATRICIA BLISS MCFATE are, respectively, deputy director and program director at the Center for National Security Negotiations of the Science Applications International Corporation. Graybeal is a former director of the Office of Strategic Research of the Central Intelligence Agency. For 12 years he worked in the Arms Control and Disarmament Agency, and he was also the first U.S. Commissioner of the Standing Consultative Commission. He has received the President's Award for Distinguished Federal Civilian Service. McFate currently serves on the Committee on Science, Arms Control and National Security of the American Association for the Advancement of Science. She has written extensively on arms-control verification and compliance issues.

ments cannot anticipate weapon systems based on new technologies—as is the case with the ABM Treaty. In other cases, the participants in an agreement may see it as mutually advantageous not to limit some weapon systems too stringently—and some not at all. One side may wish to preserve its superiority in a weapon technology; the other side may also want to enhance its own capabilities in that or similar areas.

When designing a verification regime, the U.S. must consider both the legal and illegal capabilities of the Soviet Union to circumvent or break out of a treaty. If the Soviets can legally exceed START warhead limitations by several thousand, it would be a waste of effort and resources to seek the ability to monitor the provisions of the agreement with sufficient precision to ensure that the U.S.S.R. could not cheat by adding dozens or even hundreds of warheads.

Representative Les Aspin of Wisconsin addressed the issues of verification and breakout in a report of the Defense Policy Panel of the House Committee on Armed Services, dated May 24, 1988. The report pointed out that under START, in addition to the limit of 6,000 weapons, the Soviets could and probably would legally deploy "another nearly 3,000 weapons and could 'legally' have available nearly 11,000 additional weapons that are a source for a sudden breakout from START." The report concluded that "more intrusive verification is not the answer to the problems posed by the Soviet potential to deploy many more than 6,000 weapons.... Better verification cannot dispel this threat."

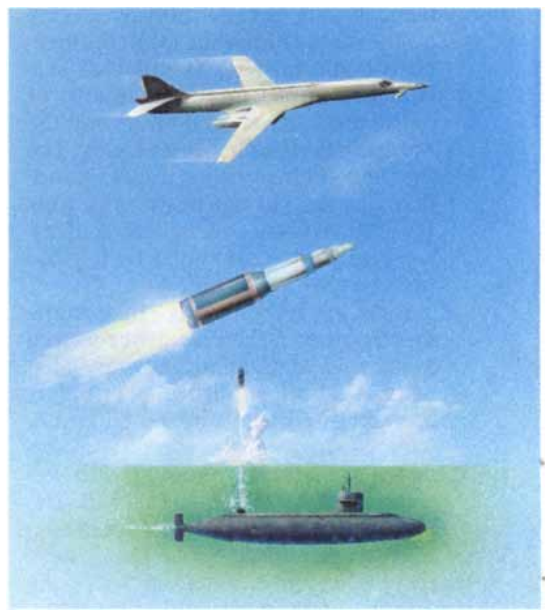
Verification regimes are often judged by three criteria—military, political and legal—that describe the nature and impact of the violations they may discover. Military significance speaks to the issue of risks that affect the strategic balance under an agreement and that could require a timely military response. Both Secretary of Defense Harold Brown in the Carter Administration and Ambassador Paul H. Nitze in the Reagan Administration focused on military significance when describing the quality of verification. During the ratification hearings on the second phase of the Strategic Arms Limitations Talks (SALT II), Brown explained that under an adequate verification regime, "any Soviet cheating [that] would pose a significant military risk or affect the strategic balance would be detected by our intelligence in time for the United States to respond effectively." In testimony given before the Senate, Nitze described the Intermediate-Range Nuclear Forces (INF) Treaty verification regime as "effective," meaning that "if the other side moves beyond the limits of the treaty in any militarily significant way, we would be able to detect such violation in time to respond effectively, and thereby deny the other side the benefit of the violation."

The political yardstick for verification recognizes that arms-control agreements are fundamentally political instruments and that any violation, major or minor, real or perceived, takes on political significance. The legal criterion underlines the contractual aspects of the agreements and also deems any violation unacceptable. During the Reagan Administration, reports to Congress emphasized Soviet noncompliance with existing arms-control agreements, citing the political and legal criteria, and found great significance in those real and purported violations regardless of their military consequence.

Determining the proper balance between Soviet breakout capabilities and U.S. monitoring requirements will be difficult, but it will be a necessary step toward achieving a START verification regime. What constitutes effective or adequate verification will always be controversial. There will also be an ongoing dilemma resulting from two conflicting objectives: the desire to have direct access to a broad range of Soviet facilities and activities and the requirement to protect sensitive U.S. facilities, technology and operational information. We believe that military significance—rather than political or legal significance—is the most important test that should be applied in judging the effectiveness of a START verification regime. The criterion of military significance is consistent with U.S. security needs and will prevent verification requirements from becoming unrealistic and costs from becoming excessive.

The foundation for monitoring a strategic arms-control agreement has always been the intelligence-gathering and analytical capabilities that are generally known as National Technical Means (NTM). These include all of a nation's resources for collecting intelligence, such as reconnaissance satellites, peripheral radar systems and satellites for intercepting communications and electronic signals. NTM was sufficient by itself to verify the SALT I and SALT II limitations, which focused primarily on heavy bombers and launchers for ICBM's and submarine-launched ballistic missiles (SLBM's). The recently completed INF Treaty and the START negotiations cover total inventories of deployed and nondeployed nuclear weapon systems and their launchers, and NTM has not been considered adequate for effective verification of these agreements. As a result, extensive cooperative measures such as on-site inspections were included in the INF verification regime and will be part of the START verification regime. In our view, NTM supplemented with cooperative measures can provide the basis for effective verification.

The INF Treaty contains the most extensive and rigorous verification regime ever successfully negotiated. The Joint Summit Statements, which include the framework for START verification, build on the provisions of the INF Treaty. At a minimum, START will include the following: exchanges of information about the weapon systems; "baseline" and "elimination" inspections to determine whether weapon systems have been eliminated according to the terms of the treaty; continuous monitoring of critical weapon production and support facilities; short-notice inspections, in accordance with agreed-on procedures, of declared locations and other sites where either side suspects covert activities involving strategic arms could be occurring; on-site inspections and other procedures for confirming the



STRATEGIC ARMS Reduction Talks (START) Treaty will reduce by about 50 percent the Soviet aggregate throw-

number of warheads on deployed ballistic missiles; provisions prohibiting concealment or other activities that might impede treaty verification by NTM; and other cooperative measures for enhancing NTM.

Because START reduces the number of weapons rather than eliminating entire classes of them as the INF Treaty did, the verification problems and issues will be far more complex and difficult to resolve. When weapons are banned, then the discovery of even one such weapon is a violation. Proving violations under a treaty that limits numbers of weapon systems depends on counting the weapons and monitoring their whereabouts.

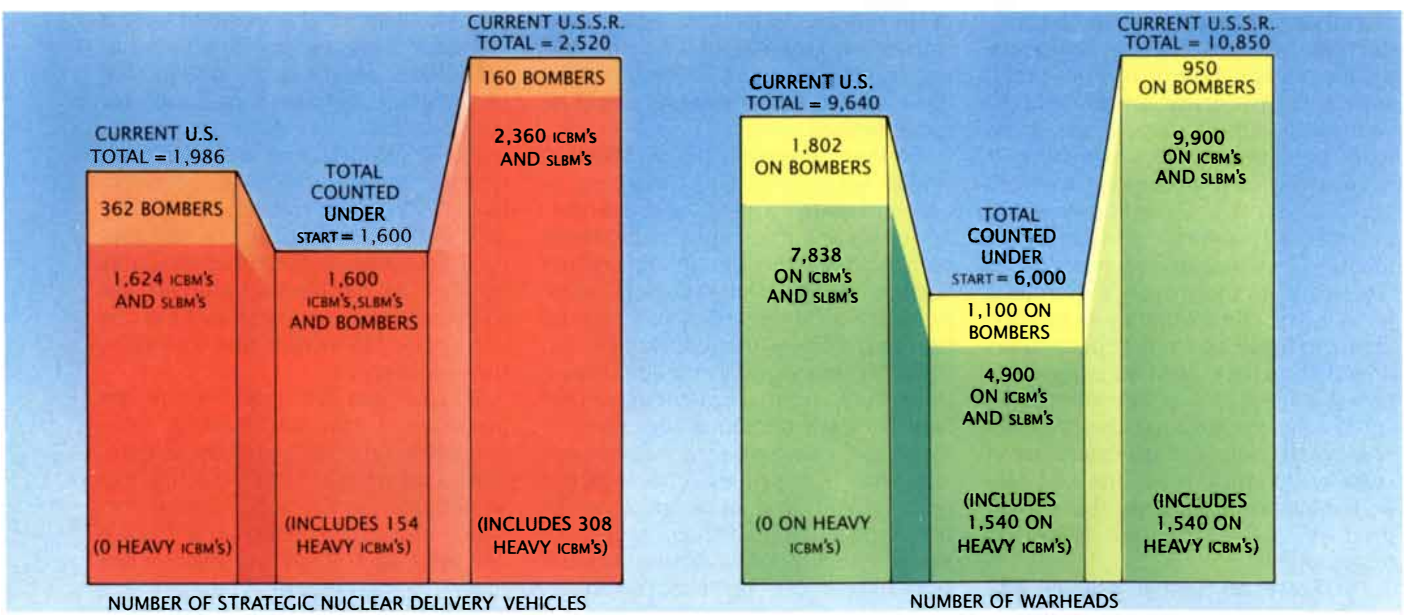
Last June, the Bush Administration put forth a new plan to negotiate and carry out some specific verification measures before completing a START agreement. Secretary Baker has emphasized that the verification plan is not a precondition to agreement and that "it is intended to accelerate and enhance the negotiation of a START treaty." The verification and stability measures were presented in detail in Geneva and were subsequently discussed in Washington before the Wyoming ministerial meeting. In Wyoming, the Soviets agreed in principle to the proposed measures, which included the following: an early, comprehensive exchange of data on strategic forces; a halt to the denial (including encryption) of ballistic-missile telemetry data during flight tests; the establishment of on-site portal-perimeter monitoring of certain missile-production facilities (such as the final assembly facilities for the Soviet SS-24 mobile ICBM's) and production facilities for solid-fuel rocket-motor boosters; steps to address the problem of SLBM's that have "short times of flight" or depressed trajectories; familiarization with procedures for inspection of numbers of warheads on ballistic missiles; and the demonstration and information exchange on techniques for the identification ("tagging") of mobile ICBM's. An agreement on strategic exercise notification was signed.

In our view, this new approach—pursuing the design and implementation of specific monitoring techniques while negotiating START Treaty provisions—makes eminent sense as long as conflicts over verification issues are not allowed to obstruct progress on arms control. Settlement of verification issues should not be a precondition for negotiations, and the difficulties with verification that are certain to arise should not be permitted to undermine START. This approach permits both sides to identify the strengths and weaknesses of various verification techniques and to formulate treaty language that minimizes the problems in these areas. A more workable agreement could be reached without much delay.

The difficult questions confronting the planners of START verification are: Do the U.S. verification requirements exceed the nation's monitoring capabilities, and Is the gap between the two widening or narrowing? The answers depend primarily on the administration's adoption of military significance as the criterion used to judge effective verification, on technological advances in U.S. NTM and on the administration's assessment of Soviet incentives and capabilities to violate the agreement. Four major problem areas have been at the focus of START verification: SLCM's, mobile ICBM's, air-launched cruise missiles (ALCM's) and the ABM Treaty.

Although SLCM's are not covered by the current START draft agreement, their growing significance as strategic weapons dictates that some understanding between the major powers on SLCM limitations will be necessary before the START negotiations can conclude. The U.S. and the Soviet Union have already agreed that SLCM's will not count against the overall ceilings on strategic delivery vehicles and warheads; this agreement allows the U.S. to retain the advantages of its lead in cruise-missile technology yet also leaves the U.S.S.R. free to bolster its SLCM strength.

Both sides have agreed to discuss SLCM's further, but there are major divergences in their approaches. The current U.S. position is that only nuclear-armed SLCM's should be limited. Last July 13, Colonel General Nikolai Chervov, chief of the arms-control directorate in the Soviet military's General Staff, indicated that the Soviets



weights of intercontinental ballistic missiles (ICBM's) and submarine-launched ballistic missiles (SLBM's), ballistic-missile warheads and heavy ICBM's (SS-18 missiles). U.S. strategic forces will also be reduced significantly. Many nuclear weapons will not be charged against the START limits, including warheads on sea-launched cruise missiles (SLCM's).

IDENTIFICATION "TAGS" could be placed on some weapon systems to verify that they have been made at declared, monitored production facilities. One type of tag would consist of a sparkle-containing epoxy that could be applied to features of weapon systems such as solid-fuel rocket motors. When the tag is viewed under special lighting, it shows a unique reflectance pattern that cannot be duplicated; a weapon system could be "fingerprinted" by photographing this pattern. Notice the differences between the two sparkle patterns spread over similar lettering.

are willing to give up all deployed nuclear-armed SLCM's if the U.S. will do the same. The U.S. has not yet responded to this suggestion and has yet to be convinced that existing verification capabilities can distinguish between nuclear-tipped and conventionally armed SLCM's or can keep track of deployed SLCM's.

Monitoring any limitations on SLCM's poses extremely challenging problems. SLCM's are small, pilotless aircraft that can be deployed on submarines and surface ships in large numbers. The launchers for SLCM's need not be visible, as those of larger ballistic missiles are. SLCM's can be produced and stored in numerous types of facilities that lack unique identifying features, unlike the production facilities for the solid-propellant rocket motors in ICBM's and SLBM's. Today nuclear-armed and conventionally armed SLCM's are externally indistinguishable; moreover, it is relatively easy to convert warhead types on SLCM's. Conversions would be extremely difficult to detect and identify. It may also be possible to convert ALCM's into SLCM's by adding jet-assisted takeoff units and modifying them for firing from torpedo tubes or rail launchers. Another problem is posed by the U.S. policy of neither confirming nor denying the presence of nuclear weapons on board naval vessels. On-site inspections and other verification measures that would disclose this information would be unacceptable.

There are no simple, reliable and currently acceptable solutions to SLCM verification problems; nevertheless, certain approaches are worthy of further exploration. One such approach involves tagging and sealing all SLCM warhead compartments. The tags and seals could be applied to conventionally armed or nuclear-armed SLCM's, or both, at declared production facilities. The tags would then be inspected as the SLCM's were being loaded on designated ships and before testing at agreed-on test sites. Any untagged SLCM or one bearing a tag that showed signs of tampering would constitute a violation.

This approach, however, would not preclude the covert production and deployment of illegal SLCM's, and it could run counter to the U.S. policy against revealing whether naval vessels have nuclear weapons on board. Many additional issues—such as who will apply the tags, how the reliability of the tags can be guaranteed and how to eliminate the risk of sabotage during tagging procedures—would need to be settled before tagging could be implemented.

Another approach to verification would set accountable numbers of conventionally armed and nuclear-armed SLCM's that could be deployed on specified types of submarines and surface vessels. Unfortunately, monitoring allocations of SLCM's would be impossible without intrusive and probably unacceptable on-site inspections. Both countries might agree that future SLCM's should be designed to make the conversion of conventionally armed SLCM's to nuclear-armed ones difficult and to assure that the two types have distinguishable, observable features. Monitoring such design differences, however, could require intrusive inspections.

The prospects for remote monitoring of SLCM's by other technical means currently look poor, as illustrated by the results of a nongovernmental exercise involving the Natural Resources Defense Council and the Soviet Academy of Sciences. In early July of this year, the Soviets permitted a group of American scientists to go on board the missile cruiser *Slava* in the Black Sea to test the ability of passive gamma-ray detectors to sense the radiation given off by a nuclear warhead on a Soviet SS-N-12 cruise missile. The tests on board the *Slava* successfully detected the presence of nuclear warheads when the sensors were placed next to an SLCM launch cannister; however, the sensors cannot detect nuclear-tipped cruise missiles at a distance. Lead shielding around a warhead could also fool a gamma-ray detector even at close range. In short, the experiments had greater political than practical significance because they highlighted Soviet willingness to invite Americans on board a military vessel containing operational SLCM's. We suggest U.S. government officials should be involved in future cooperative cruise-missile verification experiments with the Soviets.

In our view, significant uncertainties will hinder our ability to monitor any SLCM limitations. Nonetheless, we believe that banning nuclear-armed SLCM's holds the most promise for preserving long-term U.S. security interests and minimizing the problems of verifying SLCM limitations. Future Soviet nuclear-armed SLCM's incorporating stealth technologies for evading radar could be destabilizing and pose serious threats to U.S. security.

The original U.S. position calling for a ban on mobile ICBM's has been reversed, in anticipation of Congress appropriating funds for such systems. The Soviets have already developed and deployed two types of mobile ICBM's: the road-mobile SS-25's and the rail-mobile SS-24's. It appears that the U.S. will proceed with one or the other (possibly both) of two mobile ICBM systems: the road-mobile Midgetman missile or the rail-mobile MX missile, also known as the Peacekeeper.

Senator Sam Nunn of Georgia has proposed a ban on multiple independently targetable reentry vehicles (MIRV) on mobile ICBM's. Such a ban would ease verification concerns, enhance strategic stability and resolve the internal U.S. debate over which mobile ICBM system to pursue. We urge that this proposal be presented to the U.S.S.R. by the U.S. and accepted by both parties.

Baker and Shevardnadze reported to

the press that they had made "progress" on ways to monitor limits on road- and rail-based missiles. Verifying limitations on the numbers of mobile ICBM's, their launchers and their warheads will pose difficult but not insurmountable monitoring problems. Because mobile ICBM's do not require easily detectable launchers like those of fixed ICBM's, the verification regime must focus on the production facilities and the deployment modes and areas for these weapons.

One way to implement continuous monitoring of ballistic-missile assembly facilities and solid rocket-motor production is with "portal-perimeter monitoring" systems. These systems would detect vehicles entering or exiting the facilities and would determine the vehicles' weights, shapes and sizes. Such monitoring systems could reliably count how many ballistic missiles and solid rocket motors were produced at declared facilities.

START will probably limit the numbers of nondeployed mobile ICBM's and their launchers. Although the Joint Chiefs of Staff are believed to oppose limits on nondeployed missiles, civilian Pentagon officials reportedly favor strict limits on these weapons to guard against possible Soviet cheating. We believe there should be strict limits on all nondeployed ballistic missiles and their launchers—both to strengthen verification and to minimize Soviet breakout potential.

Tags, or "unique identifiers," on mobile ICBM's and their launchers would help verify that weapons being flight-tested and those located in rail garrisons or designated deployment areas had been manufactured at monitored, declared production facilities. This approach would help preclude the introduction of covertly produced mobile ICBM's and launchers into the testing and operational infrastructure for permitted forces, thus diminishing the military utility of covert weapon systems and reducing the incentive for cheating.

Several types of tags in development show promise. Tags can be divided into "passive" and "active" types. A passive tag emits no signals. It could be attached to a weapon or a launcher at the factory and read by inspectors at test ranges or entrances to deployment areas and rail garrisons. Sandia National Laboratories is experimenting with tags that display distinctive, complex three-dimensional patterns of small suspended particles; when light shines on these tags, it produces a unique pattern of reflection and diffraction. One verification concern is that the tags must be reliably stable when installed on a weapon system. Ongoing research aims to minimize or eliminate reliability problems.

Active tags, in contrast, can emit unique signals that can be read from a distance. Each tag would contain a small electronic device that broadcasts an identifying signal when it is "interrogated" by a radio command. Research on active tags lags behind that on passive tags, which could be available for operational testing soon.

Monitoring the number of reentry vehicles (RV's) on deployed ICBM's and SLBM's also poses a major verification problem. Nuclear warhead- and reentry vehicle-design information is extremely sensitive, which makes visual inspections objectionable. Innovative covers and sealing mechanisms and procedures may help meet the verification requirements without compromising sensitive information. Such procedures must not interfere with or compromise the operational effectiveness of the weapons.

Today ALCM's are deployed on U.S. B-52 heavy bombers and Soviet Bear H heavy bombers and can also be carried by the new Soviet Blackjack heavy bomber. The two nations agree that long-range ALCM's will be permitted under the START regime and that those that carry nuclear weapons will count against the 6,000-warhead ceiling.

In other matters concerning ALCM's, however, the U.S. and the U.S.S.R. disagree. The U.S., unlike the Soviet Union, believes that conventionally armed, long-range ALCM's should not be constrained by START. The Soviets would define long-range ALCM's as those with ranges of more than 600 kilometers, whereas the U.S. would include only ALCM's with ranges greater than 1,500 kilometers. The two sides also disagree about the "attribution rules" for counting ALCM's on bombers: the Soviets propose charging each bomb-

PORTAL MONITORING system, developed by Sandia National Laboratories to verify the Intermediate-Range Nuclear Forces (INF) Treaty, could also help with START verification. The system can be installed at the exits of declared ICBM-production facilities to preclude the illegal production of missiles at those facilities. When a truck passes through the system, infrared scanners mounted on the posts and the guardrails measure the truck's size while scales embedded in the roadway measure its weight. Trucks carrying suspicious objects would be stopped for inspection.

AIR-LAUNCHED cruise missiles (ALCM's) will be limited by START, but the procedure for counting them has not yet been determined. A counting scheme that attributes specific numbers of ALCM's to various types of bombers could be verified by the intelligence resources known as National Technical Means without intrusive on-site inspections of individual bombers.

er with the maximum number of ALCM's it could carry; the U.S. proposes charging each bomber with a specific less-than-capacity number. Last June, the Joint Chiefs of Staff reportedly suggested each bomber should be credited with the actual number of ALCM's it carries. According to a report that appeared in the *Washington Post* last August, the Soviets have suggested "bombers be counted as carrying no more than the actual number of missiles installed in a given period."

If the U.S. and Soviet Union can agree to count ALCM's by assigning specific numbers to classes of bombers, the verification problem would simply involve identifying and counting the number of U.S. and Soviet bombers—a task that can be accomplished by NTM. Because loading a bomber with more than its attributed number of ALCM's would not be a violation of the agreement, intrusive inspections for counting deployed ALCM's would be unnecessary. Similarly, because there would be no limits on the number of ALCM's that could be produced or stored, monitoring requirements would focus on the ALCM carriers and not on ALCM production or storage.

The U.S. and the Soviet Union have agreed that, in the future, conventionally armed ALCM's will be "distinguishable" from nuclear-armed ones and that heavy bombers equipped with nuclear-armed ALCM's will be distinguishable from other heavy bombers. Unfortunately there is as yet no agreement on what will constitute distinguishable features nor on how they will be verified. As in the case of SLCM's, tagging and sealing warhead compartments of the missiles may help minimize problems of conversion between conventionally armed and nuclear-armed ALCM's.

Since the beginning of the SALT talks, strategic offenses and defenses have been linked. This linkage was underlined by the U.S. in SALT I on May 9, 1972, when Ambassador Gerard C. Smith stated, "If an agreement providing for more complete strategic offensive arms limitations were not achieved within five years, U.S. supreme interests could be jeopardized. Should that occur, it would constitute a basis for withdrawal from the ABM Treaty." This statement has been repeated many times and apparently remains the U.S. position. To date, there have been no ratified treaty limits on strategic offensive-weapon systems, and until this past September the Soviet Union had indicated that it would not agree to reductions in strategic offensive forces in the absence of adequate constraints on ballistic-missile defenses.

At the Washington summit in 1987, the two sides agreed that during a specified period, they would "observe the ABM Treaty, as signed in 1972, while conducting their research, development, and testing as required, which are permitted by the ABM Treaty." There is no agreement as yet on what is meant by "as signed" or on the specified period. There have been reports that the Bush Administration does not plan to advance any compromise proposals in the near future on the testing or deployment of space-based defenses.

At the Wyoming meeting between Baker and Shevardnadze, the Soviets made a proposal that should help break the impasse created by the previous Soviet insistence on the linkage of adherence to the ABM Treaty's restrictions on space-based defenses with completion of a treaty on reductions in strategic offensive weapons. According to an article in the September 24th issue of the *New York Times*, the "Soviet side told the Americans that they would sign and carry out a strategic arms treaty without securing assurances ahead of time that the United States would not deploy a space-based defense shield." The Soviets warned, however, that "if the United States ever broke out of the 1972 Anti-Ballistic Missile Treaty by moving to deploy 'Star Wars' defenses, Moscow would reserve the right to abrogate the strategic arms agreement."

If this Soviet move breaks the existing linkage between START and the ABM Treaty, attention can be focused on the unresolved START issues while deferring the controversies over the ABM Treaty limitations to a future date and separate forum. It will not, of course, remove the more fundamental linkage between overall strategic offenses and defenses, which is essential for national security.

The specific requirements for the START verification regime will be driven by provisions in the final agreement, the results of the various verification experiments recently proposed by the Bush Administration and the criteria used to determine "effective" verification. Whatever those requirements will be, however, they will clearly put a strain on NTM. The task of monitoring Soviet compliance with START, verifying the accuracy of baseline data exchanges and their periodic updates, monitoring weapon reductions and checking the accuracy of the various notifications will require a monumental data collection and analytical effort.

According to an article in the *Washington Times* on December 21, 1988, Central Intelligence Agency Director William H. Webster has stated that verifying START would "require intelligence gathering at more than 2,500 weapon locations throughout the Soviet Union.... The intelligence community will be increasingly asked to assess Soviet motivations and monitor Soviet compliance with the provisions of the agreements.... [The]

amount of support required is tremendous." The May 29, 1989, issue of *Newsweek* alludes to a "frightening" new CIA report that raises serious questions about the U.S. ability to verify any START agreement. According to *Newsweek*, this CIA report is a "secret National Intelligence Estimate" that concludes that Moscow could "secretly deploy up to twice the total of warheads START will likely allow."

Yet according to published statements, the Bush Administration has announced that because of budget constraints, the U.S. may not "plan to modernize the nation's surveillance satellites despite President Reagan's promise to do so." On hearing this news, Senator David L. Boren of Oklahoma, the Chairman of the Senate Intelligence Committee, stated that failure to uphold the former president's promise would "seriously jeopardize our own near-term national security interests and could slow down completion of a strategic arms reduction treaty." He warned that if the administration continued to refuse to seek the necessary money, the Senate would cut other areas of the budget to free money for this vital modernization.

In addition to the stresses placed on U.S. NTM and the intelligence community's analytical resources, there are other little noticed but demanding monitoring tasks necessary for assuring American compliance with all the provisions of an arms-control agreement. This responsibility, which was entrusted to the Department of Defense after the SALT I agreement in 1972, is currently the responsibility of the Office of the Under Secretary of Defense for Acquisition. It requires the establishment of a program to ensure continuing U.S. compliance, which would include procedures for determining the applications of the agreement's provisions to strategic weapon programs and their operations and to specific weapon systems and their supporting equipment; the development and issuance of detailed guidance and instructions for implementing the agreement to all involved government and contractor components; and the provision of specific advice and decisions on request.

Reporting U.S. compliance will require significant resources in view of the nature of the weapon systems to be limited, the extensive elimination procedures, the numerous on-site inspections of various types and the many notifications likely to be required by the START agreement.

On-site inspections under START should be implemented by the On-Site Inspection Agency (OSIA) established within the Defense Department, which has already proved to be effective for the INF Treaty. The U.S. should immediately provide the OSIA with the resources it needs to begin planning for START verification and to participate in the on-going START verification experiments. OSIA should be prepared to conduct inspections in the U.S.S.R. and to escort Soviet inspectors in the U.S., as will be required by START.

Strategic arms-control agreements need a forum to promote their objectives and implement their provisions. In the case of the ABM Treaty, this body was the Standing Consultative Commission (SCC), which proved its effectiveness in handling treaty ambiguities and compliance issues as well as establishing the required dismantling or destruction procedures for ICBM, SLBM and ABM launchers and associated equipment. The INF Treaty established a separate implementing body, the Special Verification Commission, whose functions are essentially identical to those of the SCC. The forthcoming START agreement will probably create another separate implementing body with similar responsibilities. In our view, U.S. interests would be best served by consolidating these three entities into a single implementing forum that would report directly to the director of the National Security Council staff.

Implementation of START will be costly in both dollars and resources. Some observers have questioned whether U.S. officials are generating unnecessary START verification procedures and costs. We believe that the proposed verification regime and its costs are in excess of what is truly required to ensure national security, particularly if the criterion of military significance is adopted and if the U.S. makes its strategic forces increasingly more invulnerable. Even with these excessive costs, however, we believe that the overall benefits resulting from the confidence that both parties are complying with START will outweigh the verification costs.

During the process of treaty ratification, verification uncertainties, "legal" and illegal breakout opportunities and the potential for noncompliance must be recognized and evaluated, and steps must be taken to compensate for them. These goals can be achieved by formulating and adopting specific hedges against these uncertainties.

To accomplish these objectives, we propose that the intelligence community provide a comprehensive assessment of its monitoring capabilities and limitations to Congress and the White House. The Department of Defense should identify specific research and development programs or other appropriate responses, including the timing and costs of such proposals, that would assure continued U.S. security in the event that the Soviets took advantage of one or more of these monitoring uncertainties. These safeguards and their costs should also be provided to the executive branch and Congress. Congress should take this information into account during the ratification process. Thus, when the Senate has ratified the agreement, it will have accepted both the verification uncertainties and the proposal to fund the required safeguards. If either or both are unacceptable, then the agreement should not be ratified. The executive branch and Congress should be prepared to amend, withdraw from or abrogate the START agreement in the event that the Soviets take militarily significant actions inconsistent with the agreement and subsequently refuse to correct these actions in a timely manner. This intention should be made clear during the ratification process, and a decision should be promptly taken if such a serious but unlikely situation were to arise.

Although there are and will remain significant verification uncertainties associated with any probable START agreement, we believe that an agreement along the lines currently being pursued is in the national interest, can be verified "effectively" according to the criterion of military significance and should be completed and ratified by the end of 1990. A mutually beneficial, verifiable START agreement is attainable and will contribute to national security and to a stable environment marked by further constructive international relations.

FURTHER READING

THE LIMITATIONS OF ON-SITE INSPECTION. Sidney N. Graybeal and Michael Krepon in *Bulletin of the Atomic Scientists,* Vol. 43, No. 10, pages 22–26; December, 1987.

BREAKOUT, VERIFICATION AND FORCE STRUCTURE: DEALING WITH THE FULL IMPLICATIONS OF START. Report of the Defense Policy Panel of the Committee on Armed Services. U.S. Government Printing Office, May 24, 1988.

START FINISH. James P. Rubin in *Foreign Policy,* No. 76, pages 96–118; Fall, 1989.

The Evolution of the Earth's Magnetic Field

Molten iron flows through the outer core, creating conditions that generate the earth's magnetic field. Maps of magnetic activity at the core surface link fluid flow to the evolution of the field

by Jeremy Bloxham and David Gubbins

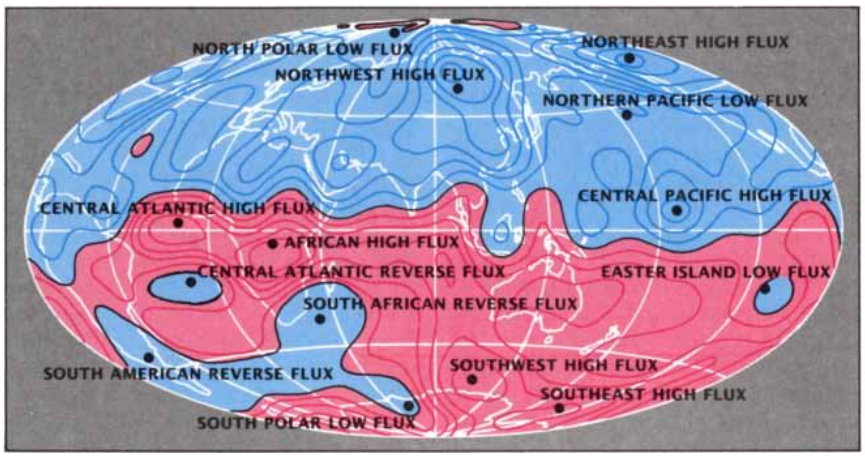
What is the weather like within the outer core, 1,200 kilometers from the earth's center? Temperatures there reach those of the sun's surface (5,800 degrees Celsius); pressures exceed a million atmospheres. The molten iron of the outer core churns around the solid inner core, acting as a dynamo that generates the earth's magnetic field. Magnetic tempests develop from surges in the liquid iron, which flows as readily as water and conducts electricity slightly better than does copper. Even at the earth's surface, 3,000 kilometers from the outer core, the tempests can be detected by the waxing and waning of the earth's magnetic field.

Clearly, geophysicists who seek to explain and forecast changes in the field must understand what happens in the outer core. Unlike meteorologists, they cannot rely on observations made in their own lifetime, however. Whereas atmospheric storms arise in a matter of hours and last for days, magnetic tempests develop over decades and persist for centuries. Fortunately workers have recorded changes in the earth's magnetic field for more than 300 years.

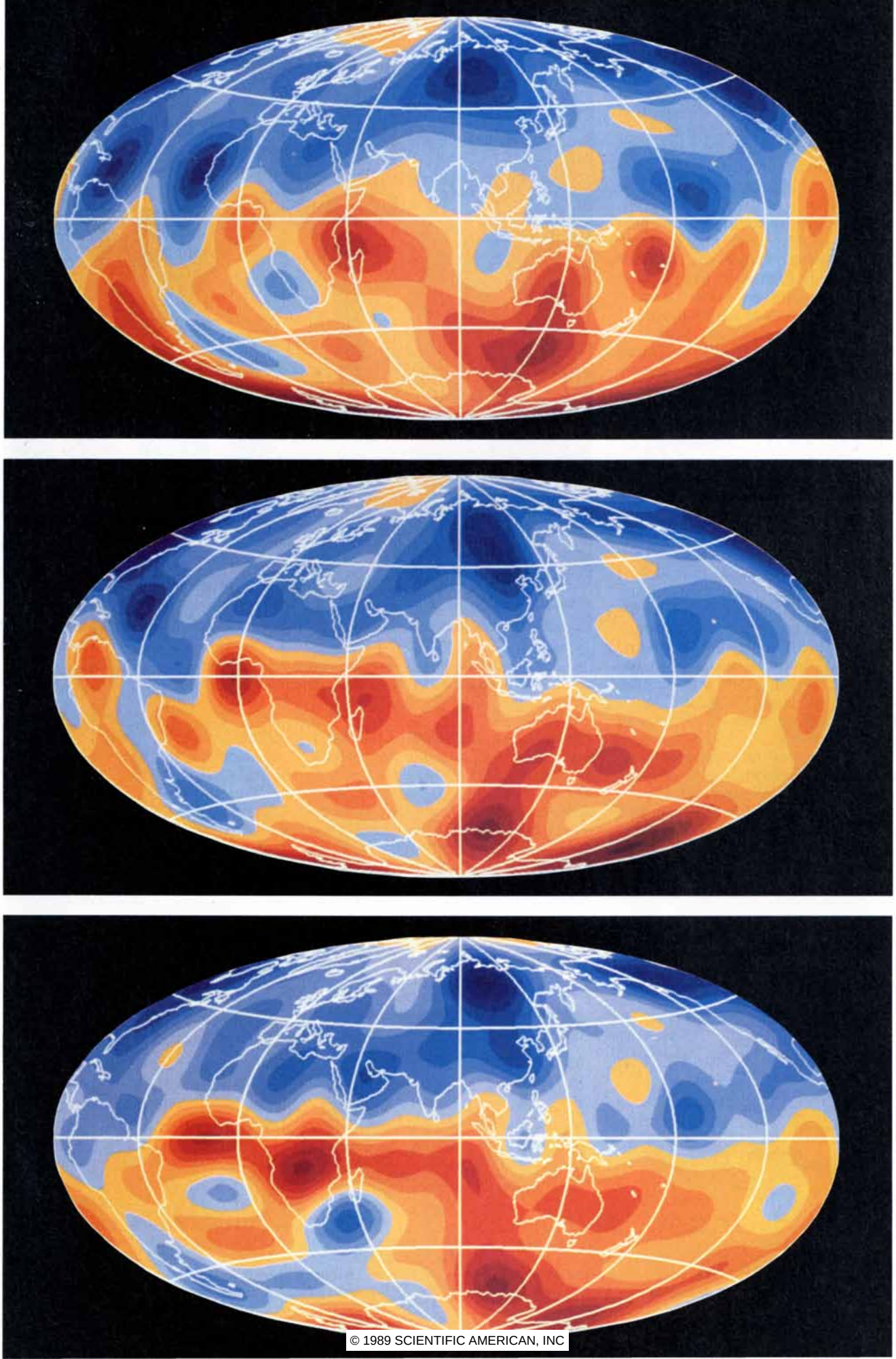
During the past nine years our group, first at the University of Cambridge and then at Harvard University and the University of Leeds, has been working to extract more detail from the historical record. In 1983, by extrapolating from this data, the group succeeded in mapping the magnetic field at the boundary between the core and the mantle [*see illustration on opposite page*]. Since then these maps have revealed remarkable, unknown features of the earth's magnetic field and have elucidated the geodynamo, the process that maintains the field.

The basic characteristics of the geodynamo have been known since the 1950's. The influence of the earth's rotation and heat propels the molten iron in the outer core. As the conducting fluid flows through the outer core, it interacts with the earth's magnetic field, which has been present to some extent throughout geological time. The interaction generates an electric current, just as moving a wire across a magnet creates a current in the wire. Once the electric current is established, it too generates a magnetic field, which reinforces the earth's field. The geodynamo is self-perpetuating. So long as the forces that arise from both the earth's rotation and heat drive conducting fluid around the core, electric currents will materialize, and the magnetic field will develop.

JEREMY BLOXHAM and DAVID GUBBINS have collaborated on investigations of the earth's magnetic field since 1980. Bloxham is assistant professor of geophysics at Harvard University. In 1986 he earned his Ph.D. at the University of Cambridge, where he was one of Gubbins's graduate students. Gubbins is now professor of geophysics at the University of Leeds. In 1972 he obtained his Ph.D. from Cambridge in the laboratory of Sir Edward C. Bullard. He was a member of the department of earth sciences and a fellow of Churchill College when he left Cambridge in 1989. Gubbins and Charles R. Carrigan wrote "The Source of the Earth's Magnetic Field"; SCIENTIFIC AMERICAN, February, 1979.



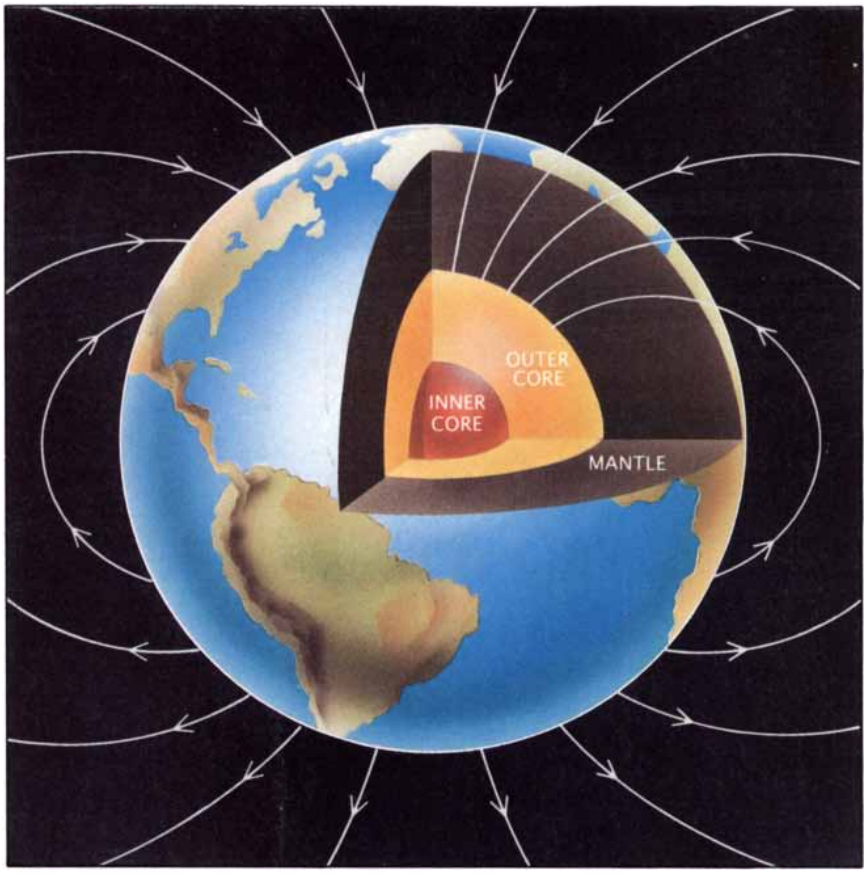
EARTH'S MAGNETIC FIELD at the boundary between the core and mantle (*right*) has been projected from measurements made at the earth's surface in 1777, 1882 and 1980 (*from top to bottom*). Intensity of color represents the intensity of magnetic flux perpendicular to the core surface: the number of lines of magnetic force that enter or exit the core surface. Blue tints represent inward flux; red and yellow tints show outward flux. Several "flux patches" are labeled above. During the past two centuries two high-flux patches near the north pole of the core and two near the south pole of the core have remained stationary. In the Southern Hemisphere three reverse-flux patches accompanied by high-flux patches have drifted to the west and south.



Although these simple ideas about the geodynamo provide an intuitive sense of how the field arises, it cannot explain many of the slow changes that workers have detected. For example, from decade to decade the field weakens by about 1 percent, and in some places its pattern rotates by about one degree relative to the earth's surface. Every million years or so, the field reverses polarity. During the past million years, for instance, the magnetic north pole has migrated from Antarctica to the Arctic [see "Ancient Magnetic Reversals: Clues to the Geodynamo," by Kenneth A. Hoffman; SCIENTIFIC AMERICAN, May, 1988]. Although many aspects of these phenomena remain inexplicable, the maps of the earth's magnetic field at the core-mantle boundary are evoking increasingly detailed theories of geomagnetism; the maps may also lead to a greater understanding of the magnetic fields generated by the other planets and the sun.

The first investigations of the earth's magnetic field date back to 1600, when William Gilbert published *De Magnete*. One century later, Edmund Halley crisscrossed the Atlantic Ocean in an extraordinary effort to chart magnetic declination (the angle between geographic and magnetic north). Other great explorers such as James Cook and James Ross also made detailed records of declination.

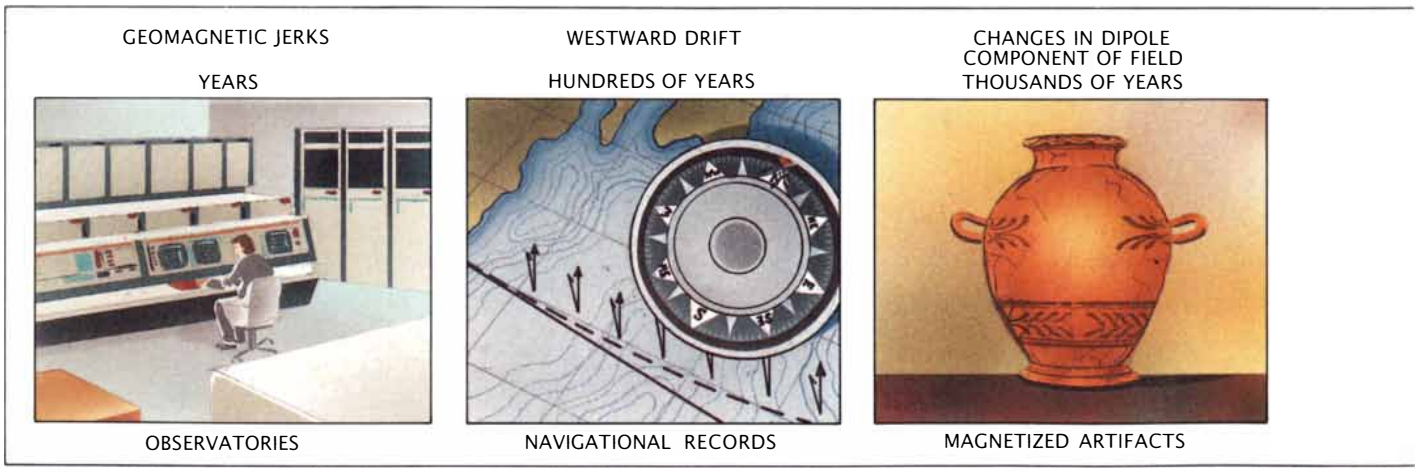
During the past two centuries workers have gradually improved the quality and quantity of measurements of the earth's field and have established geomagnetic observatories around the globe. Efforts to measure the field culminated in 1980 when the MAGSAT satellite was launched into space. The year-long project produced an abundance of high-quality data.



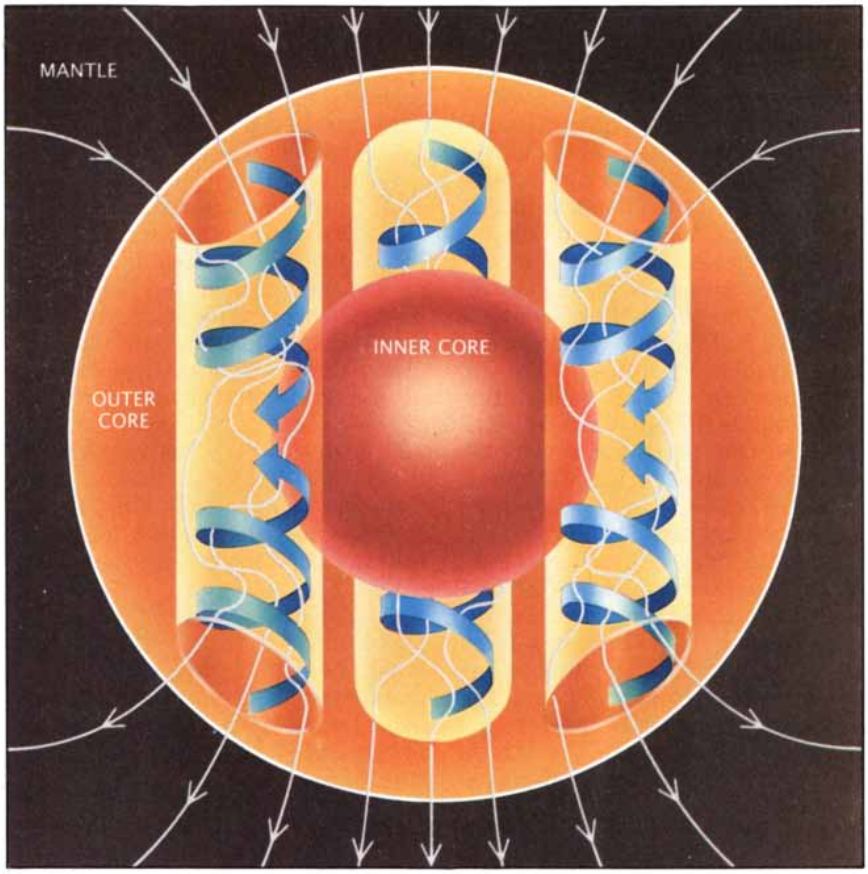
LINES OF MAGNETIC FORCE represent the field outside the core (*left*). A tangent to a field line indicates the direction of the magnetic force. The density of lines shows the

In the same year, one of us (Gubbins) began to collect and analyze records of the magnetic field from both historical and contemporary sources. Soon after, Kathy A. Whaler, Ken A. Hutcheson, Andrew Jackson and one of us (Bloxham) joined the project. David R. Barraclough of the British Geological Survey and Robert A. Langel of the National Aeronautics and Space Administration's Goddard Space Flight Center gave invaluable advice on the data sources. The first stages of the project produced a 380-year record of the field at the earth's surface.

The maps revealed well-known characteristics and features of the surface field. The field looks similar to the field that would emerge from a giant bar magnet aligned with the earth's axis of rotation or, alternatively, from a huge loop of wire carrying current



VARIATIONS in the earth's magnetic field occur over different time scales. Each type of variation can be inferred from the sources of evidence shown at the bottom of the table. The mantle screens some electromagnetic signals that originate in



strength of the force. From maps of the magnetic field, the authors' group has deduced a possible configuration of fluid flow and magnetic field in the core (*right*).

around the Equator. Such a field has two poles where the strength of the field is greatest and hence is known as a dipole field.

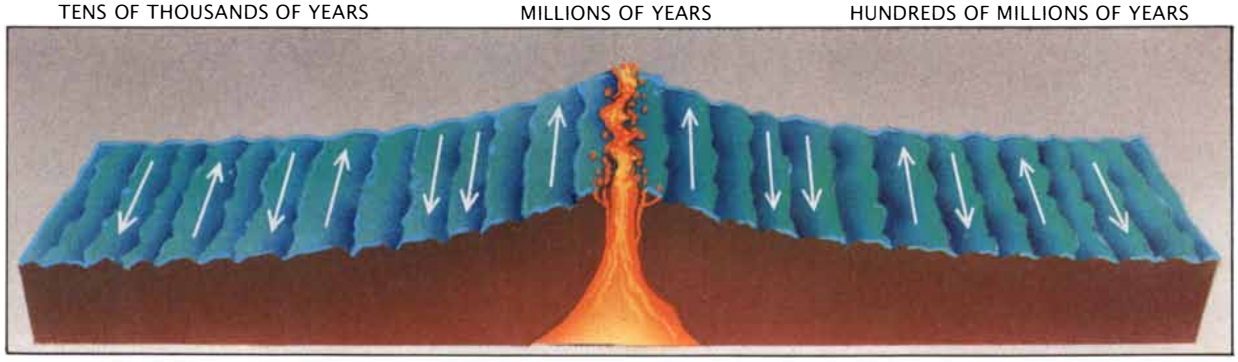
The earth's magnetic field can be represented by lines of magnetic force. These lines trace curved paths, most of which exit near the South Pole and enter near the North Pole. A tangent to a field line indicates the direction of the magnetic force. The density of the field lines represents the strength of the magnetic field.

Maps that show the earth's magnetic field at the surface reveal the "secular variation," a term broadly applied to the changes in the earth's magnetic field that occur over periods of from decades to tens of thousands of years. Among the most striking changes are a decrease in the dipole component of the field and a westward drift of part of the field pattern. The dipole component of the earth's field was considerably stronger 2,000 years ago than it is today. (Dipole decay is evident in Roman ceramic artifacts, which contain iron particles that are magnetized to a greater extent than are those in modern products.) In the next two millennia, if the present rate of decay is sustained, the dipole component of the field should reach zero. Westward drift was first observed by Halley in the Atlantic Ocean. There, the line of zero magnetic declination (the line along which the compass needle points directly at geographic north) has moved steadily westward during the course of several centuries.

To understand the origins of dipole decay and westward drift, one needs a picture of the magnetic field closer to its source, the outer core. The conducting fluid at the surface of the outer core masks the magnetic field in the interior. Yet one can deduce the magnetic field at the boundary between the core and the mantle.

Measurements of the field at the earth's surface can be projected to the core surface by applying mathematical methods devised in the early 19th century. Yet the projection has been performed reliably only in recent years. The complications did not stem from unknown physics: the crust and the mantle conduct electricity very poorly, and so for the most part they neither create nor screen magnetic fields. Instead difficulties arose because small-scale features of the field at the earth's surface, whether spurious or real, tend to blow up into large anomalies when the features are projected to the core.

Our group, in conjunction with Robert L. Parker, George E. Backus and



MAGNETIC FIELD PATTERN OBSERVED OVER THE OCEAN CRUST

the outer core. Therefore, one cannot observe changes there that have a period of less than one year. During a period of more than one year, one might measure a "geomagnetic jerk," a sudden change in the acceleration of the field pattern.

Loren Shure of the Scripps Institution of Oceanography, developed a mathematical method to find the least complicated core-surface map that could be projected from measurements at the earth's surface. In 1983 we first applied the method to the most recent observations because these presented the fewest difficulties. Since then the group has converted virtually all of the data from the past 380 years to create a series of maps of the field at the core-mantle boundary.

The maps show the number of field lines penetrating the core surface, that is, the flux going through the surface. We colored the maps with blue tints whose intensity represented the magnitude of the inward flow of field lines, or inward flux; the intensity of red tints represented the magnitude of outward flux.

If the magnetic field at the core were a simple dipole aligned with the earth's rotational axis, the map would become bluer toward the North Pole and redder toward the South Pole. Such a coloring would indicate that the most intense flux is at the geographic poles. In addition, the equator of the core surface would coincide with the boundary between red and blue shades, because the magnetic equator would coincide with the geographic equator. (The magnetic equator is the line along which the field exerts a force parallel to the surface only. It is called a null-flux curve because no flux enters or exits through the portion of the surface marked by the curve.)

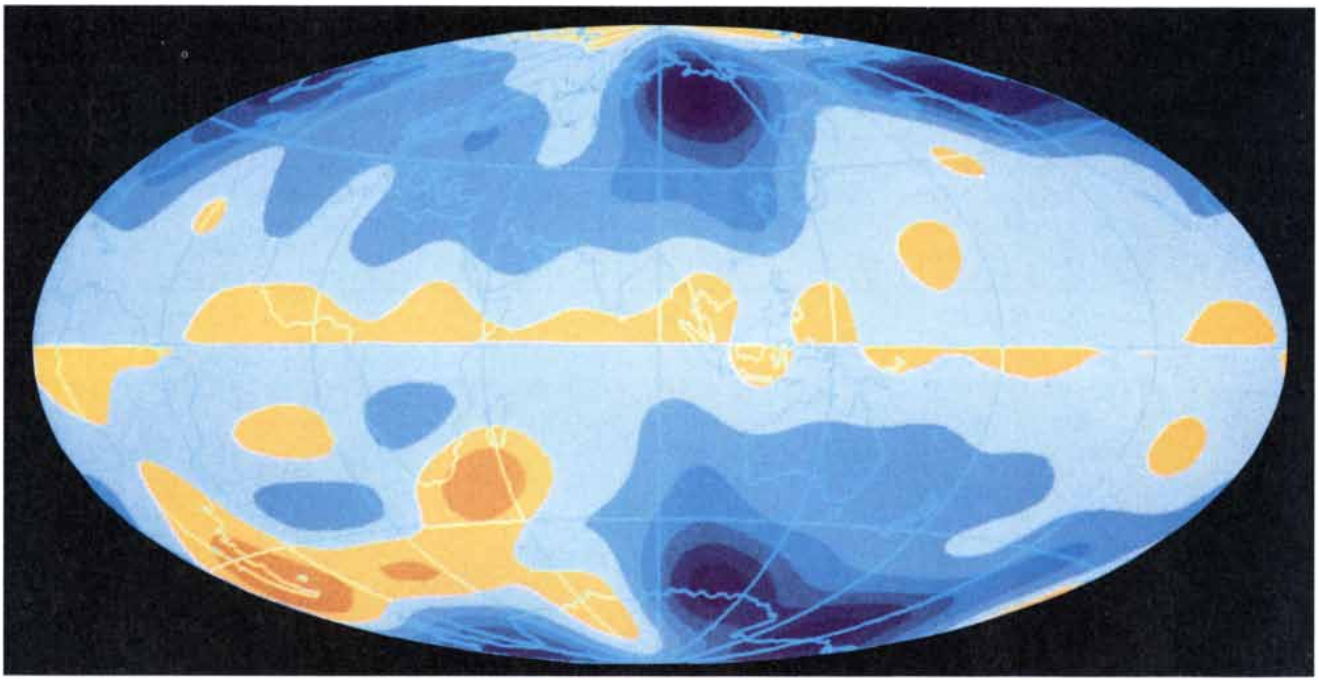
A map based on satellite measurements made in 1980 reveals that the geomagnetic field at the core surface shares some characteristics with a dipole field. The map is mostly blue in the Northern Hemisphere and mostly red in the Southern Hemisphere. Furthermore, the magnetic equator, or equatorial null-flux curve, lies close to the geographic equator.

Yet the core-surface field differs from a dipole field in many respects. The 1980 map illustrates seven null-flux curves in addition to the magnetic equator. These curves appear on the map as borders between blue and red regions (boundaries between the inward and outward flux). A dark-blue patch on the map in a region below the South Atlantic Ocean indicates an intense inward flux. This patch is one example of a reverse-flux feature. The map also shows high- and low-flux features—regions where the flux is either more or less than that expected from a dipole field.

How do such observations of the core-surface field relate to observations at the earth's surface? The question is linked to three mysteries: the origin of the dipole component of the earth's magnetic field, the cause of dipole decay and the forces behind secular variation (including westward drift). By exploring these questions and others, one can begin to understand how information about the core-surface field is shaping a new theory of the geodynamo.

Our group found that the greatest contribution to the dipole field comes from four patches on the core surface [*see illustration below*]. These patches are symmetrically displaced about the Equator. (Their centers lie at the intersection of the lines 60 degrees north, 60 degrees south, 120 degrees east and 120 degrees west.) The locations of the patches have not changed much throughout historical time, which suggests that they have a long-term role in shaping the earth's magnetic field.

The patches are near low-flux polar regions that contribute little to the dipole field. It is interesting to note that these polar regions have the same diameter as the projection of the inner core onto the surface of the outer core. This observation seems to agree with the work of Friedrich H. Busse and his colleagues at the University of California at Los Angeles. In 1973 they built a model that consisted of two spheres: one small sphere rotated inside a second, larger sphere that was filled with water. The workers found that the flow of fluid above and be-



DIPOLE COMPONENT of the field at the core surface is strongest in the regions colored in dark blue. In the Northern Hemisphere inward flux augments the dipole field; in the Southern Hemisphere outward flux contributes to the dipole field. If the earth's field were a dipole field, the map would show areas of dark blue at the poles and would get lighter toward the Equator.

low the rotational poles of the inner sphere was weaker than the flow elsewhere. If the flow in the earth's outer core were similar to the flow in the model, one would expect the field to be weaker around the poles.

From Busse's work and our own, we inferred the general characteristics of the fluid flow inside the core. The four patches that contribute most strongly to the dipole field are, we think, the tops and bottoms of two columns of liquid. It seems likely that these columns (and perhaps a third) touch the inner core and run parallel to the earth's rotational axis [*see top illustration on page 71*]. We believe that fluid spirals down through the two columns and so creates a dynamo process that concentrates flux within the columns. If this theory proves true, we will be able to link the flow of fluid in the outer core directly to the field pattern at the core-mantle boundary.

Although promising, the theory is not complete. It does not explain the secular variation and in particular westward drift. During the past four decades two major explanations have been proposed. In 1950 Sir Edward C. Bullard and his colleagues at the University of Cambridge suggested that electromagnetic forces drive the core westward with respect to the crust and mantle.

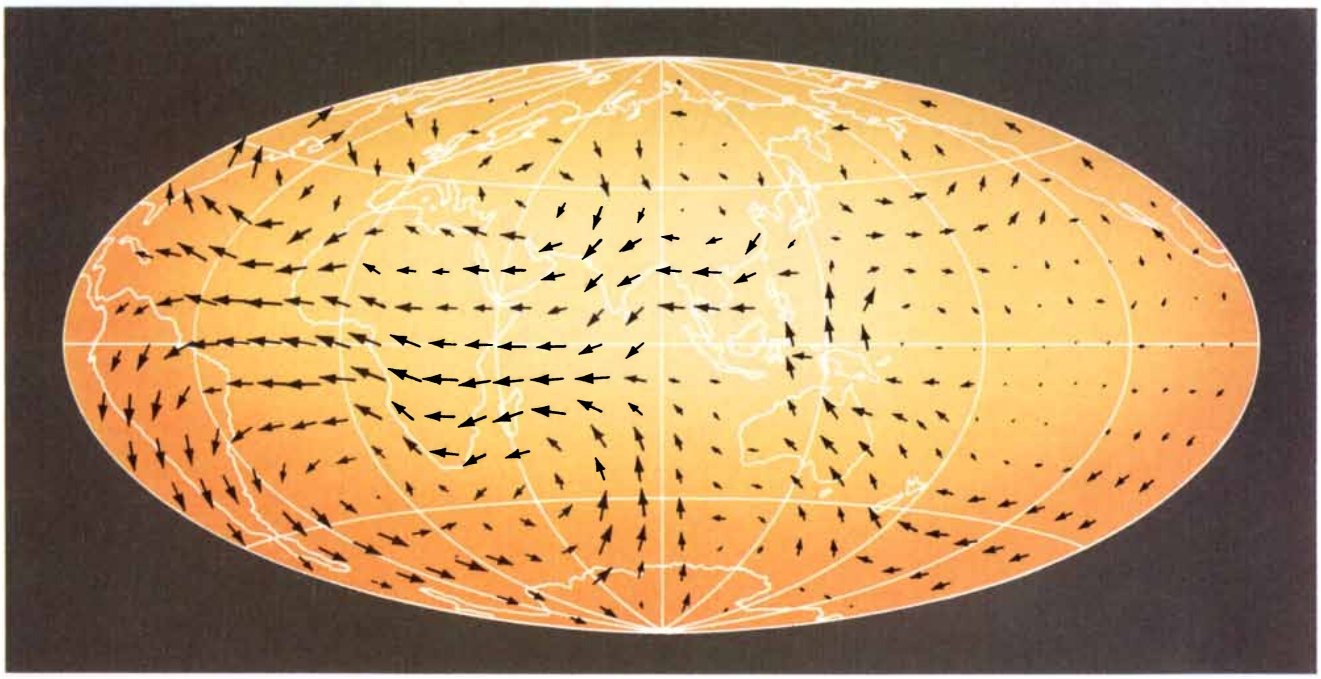
The second theory, commonly attributed to Raymond Hide of the United Kingdom Meteorological Office, posits that the westward drift arises from the wave motion of fluids in the core. Unlike the first theory, the wave theory could explain westward drift even if the core fluid did not rotate relative to the mantle. After all, a wave could form from the upwelling and downwelling of fluid, just as a wave can travel along a string even if the only motion is perpendicular to its length.

Maps of the field at the core surface seem to contradict Bullard's theory in toto and Hide's theory in part. Bullard's theory requires westward drift everywhere. Yet the historical record of the field at the core surface seems to indicate that westward drift is confined primarily to the Atlantic hemisphere (from 90 degrees west to 90 degrees east), where a few core features move west at rates of about 10 kilometers per year. Hide's theory might still be viable if an explanation can be given for why waves of iron fluid do not propagate in the Pacific hemisphere.

To understand the forces that drive westward drift and, more generally, secular variation, we tried to determine the direction of the fluid flow by tracing the movement of the magnetic field at the core surface. Magnetic field lines are "frozen" in the iron liquid of the core. As the fluid moves, the field lines are carried along. If one could tag a field line, one could follow a parcel of fluid circulating around the surface of the core.

In our study we utilized a technique whose history extends back to 1965. Paul H. Roberts and S. Scott of the University of Newcastle upon Tyne had suggested a method to determine fluid flow directly from surface measurements of the field. Soon after, E. H. Vestine and his associates at the Rand Corporation applied the method to produce the earliest maps of fluid flow at the core surface. Roberts had realized, however, that the technique that he and Scott had proposed was ambiguous because in most cases individual magnetic field lines cannot be labeled. For example, the field lines that represent a uniform field cannot be distinguished from one another and cannot be traced from one moment to the next. Then in 1968 Backus at Scripps attempted to understand the ambiguity. He investigated the properties of curves where no flux penetrates the surface (so called null-flux curves). Backus noted that one could follow the passage of a null-flux curve over time and thereby determine fluid flow perpendicular to the curve (but not parallel to it).

Other workers have recently found additional situations that allow one to calculate fluid flow. Coerte V. Voorhies of the NASA Goddard Space Flight



FLUID at the core surface circulates rapidly in two regions: one below Europe, the other below the tip of Africa. (The arrows represent the direction and speed of the flow.) The two flows could account for the westward drift of the magnetic field, as observed on the earth's surface. The flow pattern is consistent with the influence of the inner core and the earth's rotation.

Center showed that the flow can be determined if it remains steady over time. Jean-Louis Le Mouël and his colleagues at the Institut et Observatoire de Physique du Globe du Puy de Dôme in Clermont-Ferrand, France, have proved the flow can be found if it is driven by a balance of rotational and pressure forces. Whaler and David Lloyd at Cambridge showed the flow can be found in regions near the core surface where no upwelling or downwelling occurs. Today investigators are concentrating on combinations of all these plausible hypotheses.

We employed similar methods to determine fluid flow at the core surface. In the Atlantic hemisphere, we found two prominent circulations of fluid: one to the north of the Equator, the other to the south. Near the Equator the fluid from both the northern and southern circulations flows westward. The drift of core features to the west, which was observed in the historical record, appears therefore to be part of a great flow at the core surface.

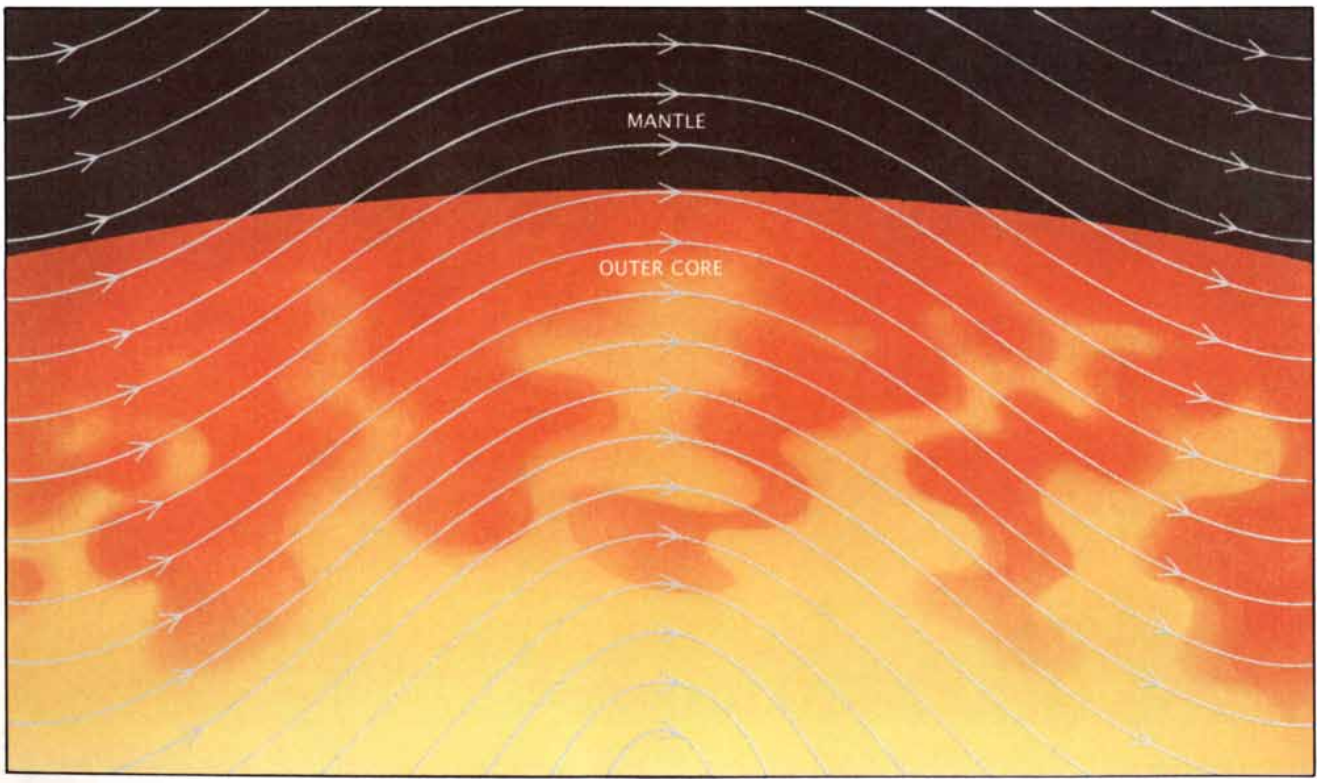
Although the surface flow suggests the movement of the core features, it does not explain their origin. In 1958 Bullard first proposed a mechanism to explain the formation of core features [*see illustration below*]. Bullard maintains that flux enters and exits the core as fluid circulates from deep in the core up to the core surface. In the process the upwelling fluid produces a high-flux feature and an intense reverse-flux feature—a combination known as a core spot because of its magnetic similarity to sunspots. Our maps of the field at the core-mantle boundary support Bullard's mechanism. We have investigated this mechanism further and find that it reasonably explains the formation and movement of core spots.

Some features of the field move and form at a rapid pace whereas others remain stationary. This phenomenon suggests some external influence. As long ago as 1967, Hide proposed that inverted mountains protruding from the mantle into the core could affect fluid flow at the core surface. Hence, the inverted mountains could influence the magnetic field in a manner similar to the way that mountains at the earth's surface affect the weather.

It is also possible that convection of heat through the mantle may cause the temperature at the core surface to vary, influencing fluid flow and the magnetic field. Adam M. Dziewonski and John H. Woodhouse of Harvard University and Robert W. Clayton and his associates at the California Institute of Technology have mapped variations in temperature in the lower mantle. We have found some intriguing correlations between the core-field maps and the inferred lower-mantle temperature. For example, three of the four flux patches that contribute strongly to the dipole field lie under "cold zones," which suggests that the dynamo is "locked" to the mantle in some way. Core spots form below southern Africa, where the mantle is hot and might induce upwelling of core fluid. A low-flux feature in the Pacific Ocean also exists below a hot region of the mantle; possibly, slow upwelling has swept magnetic field lines away from the region. A cold ring around the Pacific Ocean may explain the lack of magnetic features there.

Evidence is mounting that the present dramatic fall in the dipole component of the field is caused by the growth and propagation of the reverse-flux features beneath Africa and the Atlantic Ocean. It seems that the present reduction in the dipole component of the field is caused by the growth of the African core spot and the southward movement of the Atlantic core spot.

The central Atlantic core spot ap-



UPWELLING FLUID crowds field lines up against the core surface. The lines associated with the upwelling fluid diffuse up and down through the boundary. The process creates an outward-flux patch (*left side*) and an inward-flux patch (*right side*).

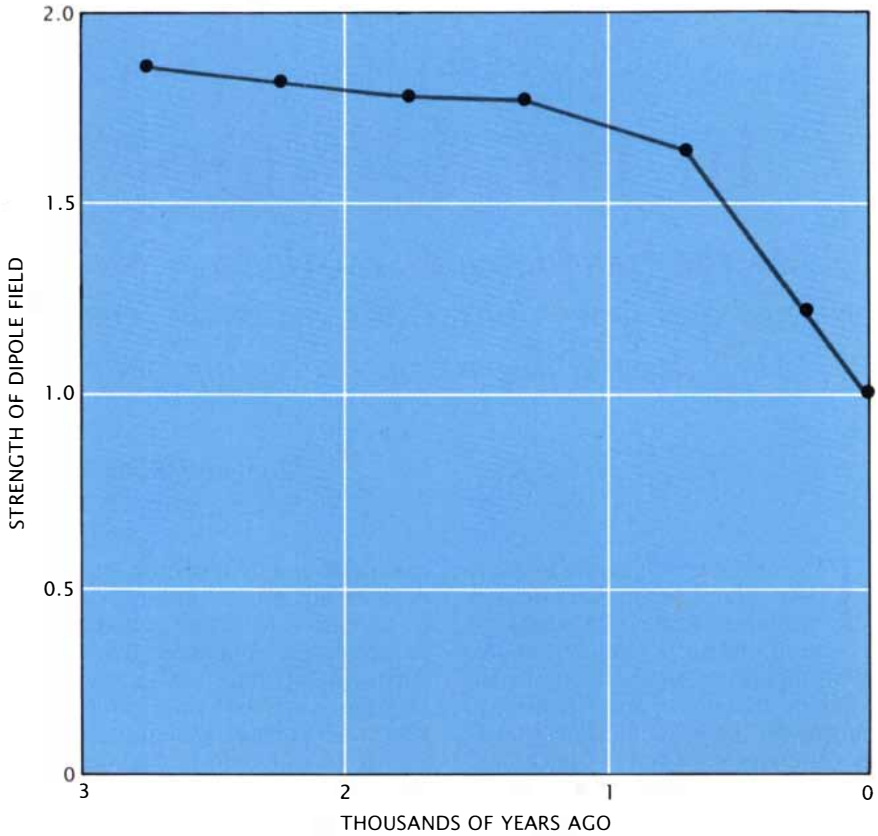
pears in our earliest core-field map, dated at 1650. Since then it has moved westward, and increasingly southward, at about .1 degree of longitude per year. The African core spot may have formed near Indonesia in the late 18th century but did not become prominent until the early 20th century. The African core spot has drifted westward rapidly, at about .3 degree of longitude per year.

The historical record is too short for a proper study of a cycle of these flux features, but we have tried to infer their movement. We suspect that core spots form near Indonesia and drift westward rapidly, at .3 degree per year. When they reach southern Africa, they intensify quickly. They then cross beneath the Atlantic Ocean at the slower rate of .1 degree per year and move increasingly southward. The present-day Atlantic core spot would then have formed 900 years ago and the African core spot some 200 years ago. This account is speculative, but it explains the long-term fall in the dipole component of the field observed in the archaeomagnetic record. As core spots move south, their reverse fluxes reduce the dipole field. If a new feature forms and drifts west, as the Atlantic and African core spots have done, the dipole component of the field will be further reduced and a complete reversal of the earth's magnetic field may occur.

Curiously, the historical record shows that reverse-flux features have formed and intensified but that none has decayed. Evidence suggests, however, that these features do decay during periods of dipole growth. During the past 10 million years the earth's magnetic field has reversed polarity once every 500,000 years or so. Yet the dipole field decays on a much shorter time scale. These facts suggest that the field does not reverse polarity after every period of dipole decay. In many cases a dipole field having the same polarity may emerge as reverse-flux features decline.

The late Allan V. Cox of Stanford University proposed a model to explain the random occurrence of reversals. He assumed that the strength of the dipole component of the field oscillates. On rare occasions, these oscillations would be so large that the polarity of the field would be reversed. We agree and add that the oscillations might originate from the movement of core spots.

Yet the formation of core spots cannot explain a puzzling aspect of field reversals. The magnetic field has reversed polarity at different intervals during different geological periods. During the Cretaceous period 90 million years ago and the Permian period 170 million years ago, we know that no reversals occurred because the rocks that formed during those periods share the same polarity. During the past 90 million years reversals have steadily become more frequent. The core changes too rapidly to account easily for such long-term behavior. Changes in the solid mantle might be involved: they exhibit 100-million-year cycles. If the temperature increased in the deep mantle, particularly beneath southern Africa or Indonesia, the formation of the reverse-flux features could accelerate, thereby precipitating reversals.



DIPOLE PORTION of the earth's field has decayed rapidly over the past millennium. The graph shows the strength of the dipole component divided by its strength measured in 1980. Michael W. McElhinny and W. E. Senanyake of the Australian National University compiled the data from historical and archaeological sources.

Geophysicists are now in a position to construct more detailed theories of geomagnetism. Further study will require a continuous stream of observations. Data from the MAGSAT satellite has advanced our knowledge appreciably. Despite the tremendous success of that mission, no firm commitment has yet been made for future missions. Lack of funds also threatens to close important magnetic observatories. Ironically, fewer observations are made today than were made 25 years ago.

We think data collection is now the overwhelming priority for the study of geomagnetism. It is essential that scientific agencies around the world maintain magnetic observatories and that they contribute to new facilities and satellite missions. It would be a shame indeed to miss the discovery of a new flux feature, the evolution of a magnetic tempest or the birth of a core spot.

FURTHER READING

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Synapse Formation in the Developing Brain

As the brain develops, existing synapses between nerve cells are refined and new connections are made. The changes are not automatic; they depend in part on the young neurons generating impulses

by Ronald E. Kalil

The development of the mammalian brain is an extraordinary achievement. From a single collection of immature, undifferentiated cells emerges an organ so structurally complex that most other natural or human-crafted systems seem simple by comparison. In spite of such intricacy, neurobiologists have managed in the past century to learn a great deal about how the brain's electrical circuitry is formed and refined in the course of embryonic and postnatal development.

Most investigators would agree that genes determine which neurons are initially wired together to establish the basic circuits of the brain. Yet for years there was much disagreement over whether genes control every aspect of neuronal maturation. Many workers suspected that experience—in particular, the flow through neuronal circuits of impulses known as action potentials—helps to control such details as the number, distribution and efficiency of synapses, which are the sites of communication between neurons.

In the past 25 years a host of studies have shown that atypical activity in the immature brain can certainly give rise to abnormal wiring. What is perhaps more intriguing, recent work has demonstrated that brain activity does not merely influence synaptic development; action potentials are, in fact, essential to several aspects of such development. For example, my colleagues and I at the University of Wisconsin at Madison and at the University of Colorado at Boulder have shown that when young neurons are prevented from generating action potentials, their synapse-forming structures known as axon terminal bulbs become "frozen" in an immature state: they fail to grow, to form new synapses and to change in a variety of other important ways.

The cessation of change is actually desirable at some point in many brain systems—in a major sensory pathway that has fully matured, for example. Indeed, certain pathways established during gestation remain plastic for only a limited time after birth, during which their wiring is fine-tuned. (The timing of these so-called critical periods varies from one part of the brain to another.) Once such honing is complete, however, the pathways essentially lose their ability to change, which ensures that a mature system will respond in a consistent way to a given stimulus (such as a flash of light).

On the other hand, in some brain systems the ongoing ability to alter the wiring of neurons is crucial. For instance, the systems responsible for learning presumably remain plastic indefinitely; otherwise, new knowledge could not be stored.

Studies of how plasticity is maintained by the learning centers of the brain are yielding what may be important clues to some of the molecular events mediating the effects of brain activity on synaptic development. Certain of the findings suggest that critical periods may simply be epochs in which young neurons in widespread areas of the brain temporarily share the molecular characteristics that enable the learning centers to perpetually alter their neuronal connections. There is even some reason to suppose that closely related mechanisms may help mediate the effect of brain activity on synapse strength, control the timing of critical periods and enable learning to continue throughout life.

Although the brains of various mammals differ in size, shape and detail, all are built on a common plan and share a similar history during growth and maturation. Early in gestation, a number of cells aggregate to form the neural tube, which then gives rise to discernible layers and clusters of cells; these groupings will later become the specialized parts of the mature brain.

Once the cells are organized into groups, they differentiate by extending projections: a single axon and many dendrites. The axon, which can grow to be tens of centimeters long, typically transmits signals, whereas the dendrites, which usually are shorter, generally receive signals.

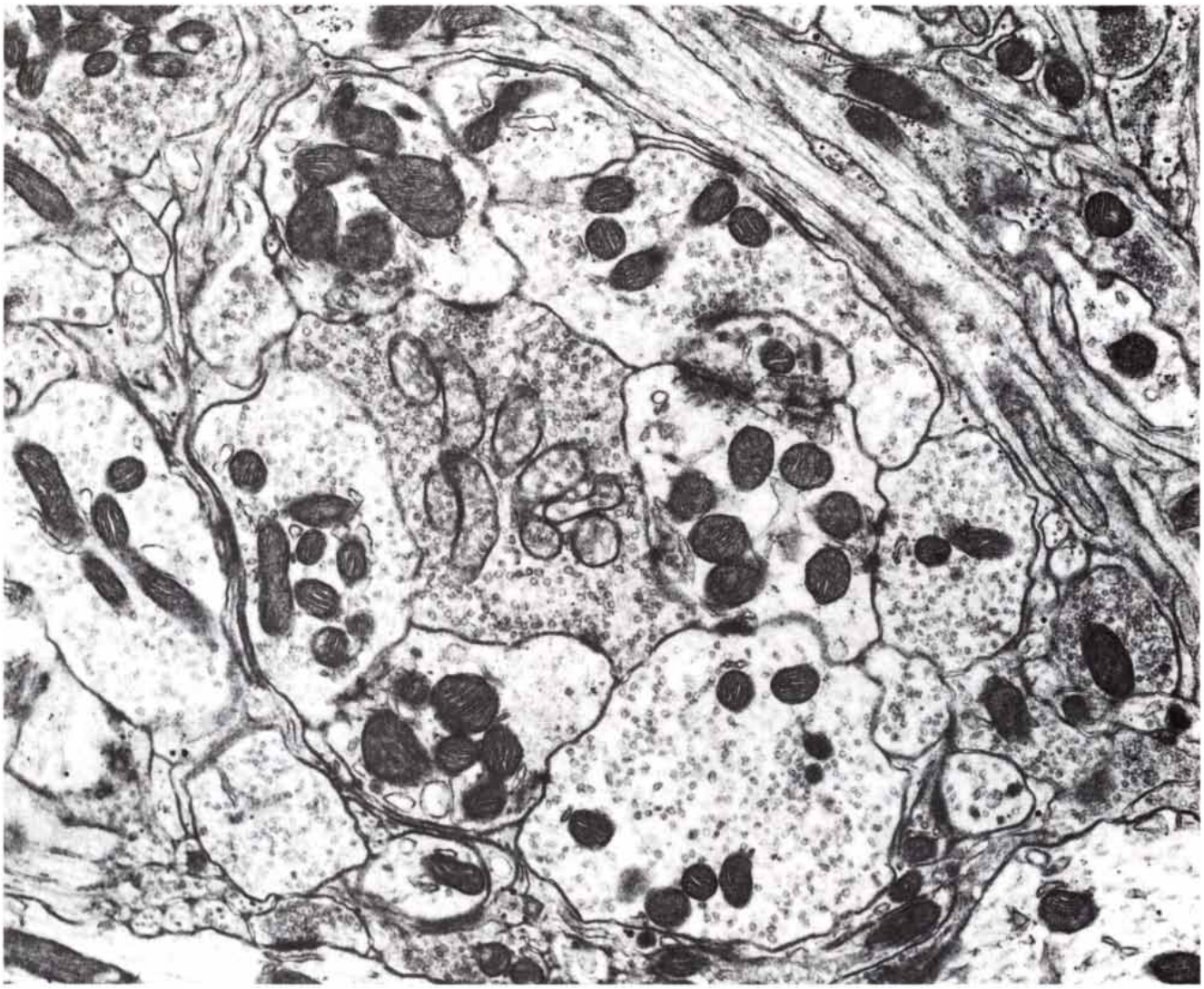
Growing axons are thought to make their way to specific parts of the rudimentary brain by following a chemical trail whose production is probably determined genetically. After the leading tip of an axon reaches its destination, it elaborates an arbor of branches, each of which has a bulbous terminal. The bulbs, in turn, make synapses with dendrites or other receptive regions on selected target cells. Most synapses consist of a specialized region on a presynaptic axon bulb, a receptive region on a postsynaptic dendrite and a narrow cleft between the two regions. (An axon can make contact with a number of cells, each of

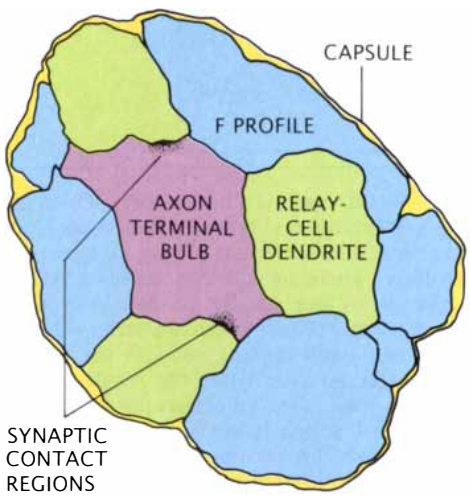
RONALD E. KALIL was educated at Harvard College and the Massachusetts Institute of Technology. In 1973 he joined the faculty of the University of Wisconsin-Madison, where he is now professor of ophthalmology and Director of the Center for Neuroscience. In addition to studying the role of experience in directing the formation of synaptic connections in the brain, Kalil is interested in the mechanisms by which the brain's visual circuits recover from injury.

which may receive input not only from that particular axon but also from many others.)

Once synapses are established, signals can be passed from neuron to neuron. Transmissions in most places in the mammalian brain take place chemically. The presynaptic bulb releases a neurotransmitter, which diffuses across the synaptic cleft and binds to receptor molecules in the cell membrane of the postsynaptic cell. The binding causes the receptors to change their shape and thus activate channels through which selected ions flow into or out of the cell.

The net change of ions in the cell body (which can receive many signals at once) determines whether a neuron will be inhibited or else stimulated to generate an action potential, or nerve



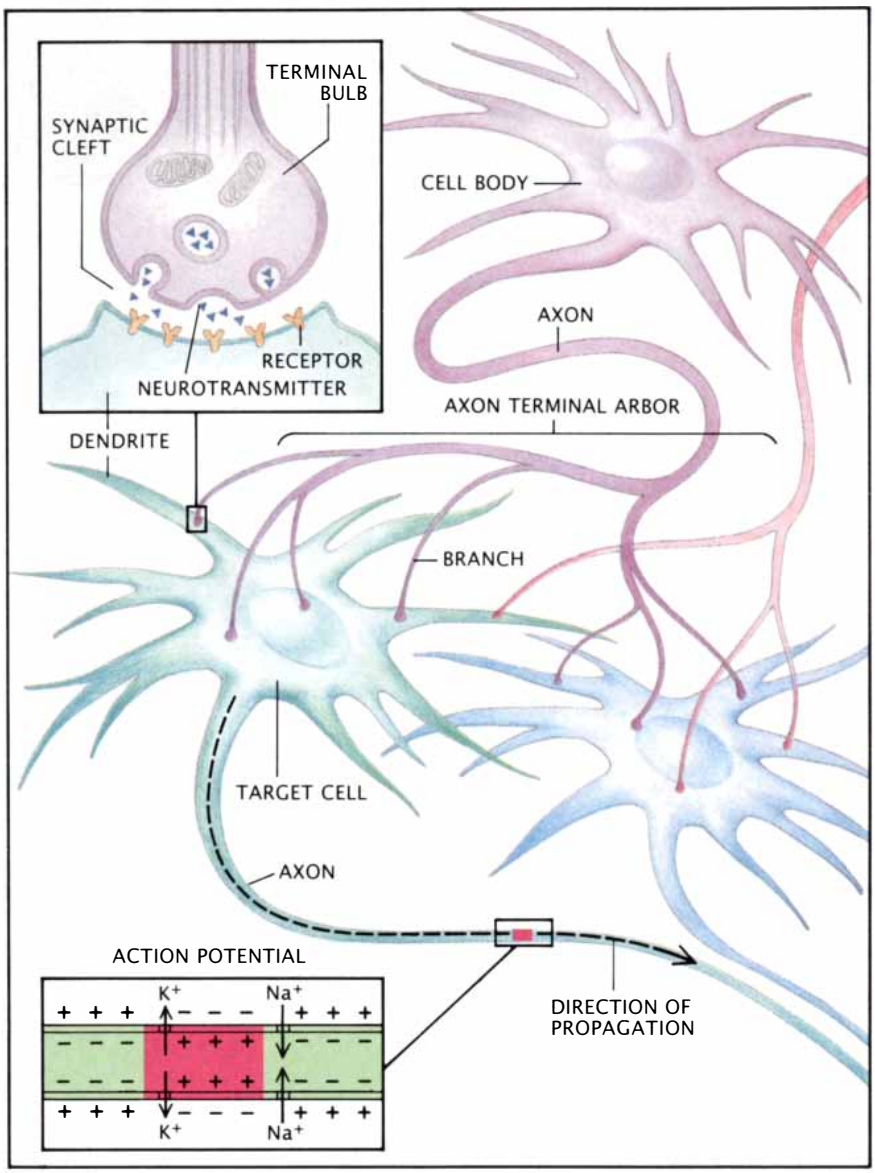


COMPLEX SYNAPTIC ZONE in the part of the brain known as the lateral geniculate nucleus is one of many such zones that normally form during the first eight weeks of a cat's life. In the center is a terminal (*purple on map*) of an axon (a long, signal-transmitting projection) that extends from a ganglion cell in the retina of the eye. At birth such terminals, which are bulbous, are about half their mature size and have already formed some synapses (sites of communication) with the dendrites (relatively short projections) of what are called geniculate relay cells (*green on map*). During the next eight weeks the bulbs grow and also form synapses with F profiles (*blue on map*), specialized appendages of the dendrites of the geniculate cells known as interneurons. The bulbs and their surrounding dendrites then become enclosed in a capsule (*yellow on map*) that defines the complex synaptic zone. The author has found that all of this anatomical development in the first eight weeks of life depends on the generation of nerve impulses known as action potentials. The zone shown in the electron micrograph is magnified some 18,000 diameters.

impulse. These impulses propagate down the length of the cell's axon and, if many of them are fired, can trigger the release of the cell's own neurotransmitter molecules, which then act on a new set of neurons.

What exactly is an action potential? Such impulses, which last less than a thousandth of a second, are essentially momentary, self-limiting reversals of the transmembrane potential—the difference between the charge inside and along the external surface of the cell. In a resting cell the transmembrane potential is 70 millivolts (.07 volt), with the inside of the cell negative relative to the outside. Action potentials arise in a resting cell after the net ionic flux (the average of all inputs from the presynaptic cells) increases the positive charge in the cell body enough to reduce the transmembrane potential by about 40 millivolts.

When that voltage threshold is attained, the cell membrane in a specialized region known as the axon hillock (where the axon joins the cell body) becomes extremely permeable to sodium ions, which are positively charged. These flood into the cell and for an instant make the charge of the interior positive relative to that of the exterior; a concomitant outflow of other positive ions restores the resting voltage almost immediately, as the action potential continues to travel down the axon.



EXCITATORY SIGNALS received by a target cell can give rise to an action potential—a momentary, self-limited reversal of the charges along the inside and outside of the cell membrane. Action potentials propagate down the length of a cell's axon (*broken arrow*) and thus constitute a nerve impulse. Signals are generally passed across synapses chemically (*top detail*): an axon terminal bulb from one cell releases a neurotransmitter that diffuses across a narrow cleft and binds to receptor molecules on the target cell. Such binding renders the postsynaptic cell membrane locally permeable to selected ions. When the result (*bottom detail*) is a sufficiently large influx of sodium ions (Na^+), an action potential (*red block*) is generated. Then the interior of the cell, which is normally negative relative to the exterior, becomes positive, and the exterior becomes negative—for an instant. A concomitant outflow of potassium ions (K^+) helps to restore the original charges almost immediately.

The suspicion that action potentials might be critical to brain development grew to a great extent out of several studies done in the 1960's and 1970's, mainly involving the visual system of the cat. This system is much studied, in part because a great deal of its maturation is delayed until the first two months after birth, which makes the last stages of development relatively easy to examine and manipulate.

The cat's neuronal pathways for vision begin with the ganglion cells in the retina. These cells convey information received from the retina's photoreceptors to way stations known as lateral geniculate nuclei in the thalamus of the brain. As is true for many mammals, the ganglion cells in the right side of each eye (which receive input from the left side of the visual field) send axons to the lateral geniculate nucleus in the right hemisphere of the brain; the ganglion cells in the left side of each eye send axons to the nucleus in the left hemisphere [*see illustration on opposite page*]. So-called relay cells of the lateral geniculate nucleus, in turn, transmit the information to the visual cortex in the same hemisphere for processing.

Carla J. Shatz, David W. Sretavan and Marla B. Luskin of the Stanford University School of Medicine have uncovered much of what is known about the prenatal development of these pathways. The embryonic axons from the retinal ganglion cells normally arrive at the lateral geniculate nuclei about midway through gestation, which in the cat lasts for a total of about 63 days. At this point, each lateral geniculate nucleus consists of a cluster of randomly arranged cells.

The nuclei are transformed greatly during the second half of gestation. Their constituent cells become organized into layers, each of which will eventually be sensitive to signals from only one eye. This specialization of the layers is accomplished by the gradual stratification of the retinogeniculate axons coming into the thalamus from

the retinal ganglion cells. Axons receiving input from the right eye ultimately terminate in specific layers of geniculate cells, whereas the axons receiving input from the left eye terminate in adjacent layers.

About 10 days before the cat is born, axons from the relay cells of the lateral geniculate nucleus enter the visual cortex. These geniculocortical axons end primarily in the fourth of six primitive layers there. At first, axons associated with the right eye overlap with axons receiving input from the left eye; the axons often terminate on the same cells, which means that the target cells can be stimulated by activity in either eye.

That state of affairs is temporary, however. Simon D. LeVay, Michael P. Stryker and Shatz showed while they were at Harvard Medical School that during the second month after the cat's birth, the geniculocortical axons become segregated by eye. They appear to retract some of their terminal branches, so that individual cortical cells remain in contact with geniculate cells responsive only to the left or only to the right eye. (Presumably the axons also increase the strength, or efficiency, of the remaining synapses, although this has not yet been proved.)

The net result of the segregation is the establishment of alternating, similarly proportioned ocular-dominance columns in the cortex: some columns of cortical cells respond only to signals from the right eye, whereas the alternating columns respond only to signals from the left eye.

Several of the most important studies showing that normal visual experience is critical to such developmental changes were done in the 1960's by Torsten N. Wiesel and David H. Hubel of Harvard Medical School. These early studies involved suturing closed the lid of one eye in newborn cats. The studies demonstrated that limiting the activity of one eye in this way severely interferes with the development of ocular-dominance columns. Measurements of electrical activity in the fourth layer of the visual cortex revealed that virtually all of the cells there responded exclusively to signals from the open eye.

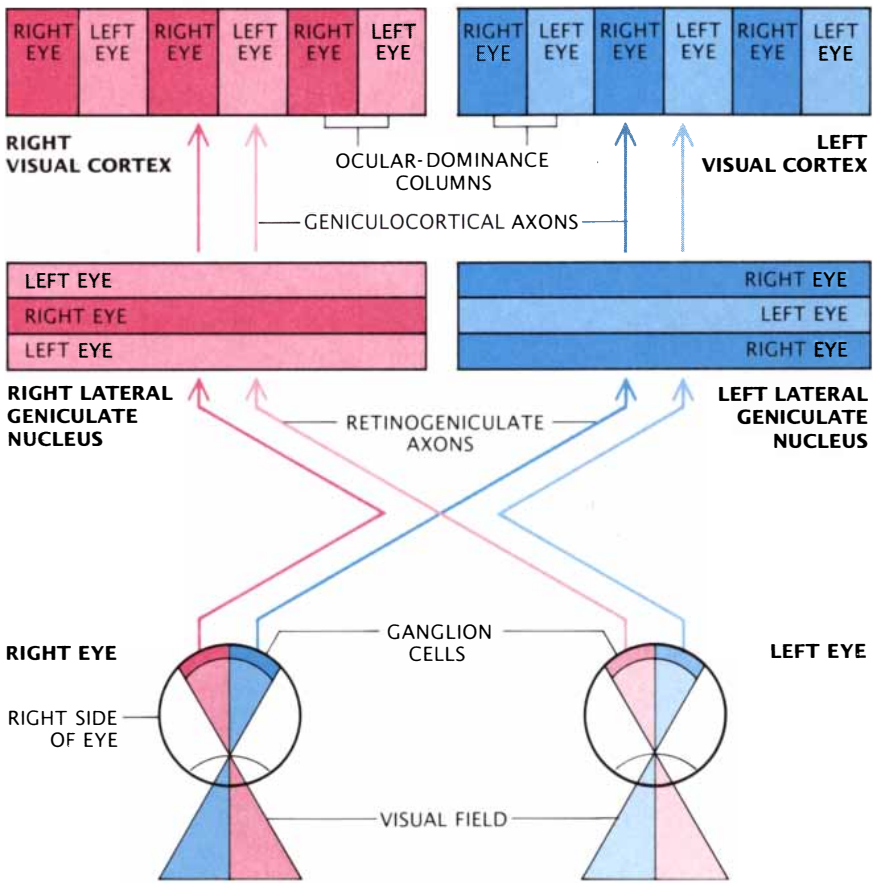
Much of the explanation for the cortical abnormality rests with the axons extending from the lateral geniculate nuclei. By staining these axons, Shatz and Stryker showed in cats, and Hubel, Wiesel and LeVay showed in monkeys, that the geniculocortical axons of animals raised for many weeks with one eye closed do not segregate into the usual eye-specific domains. Instead those axons associated with the open eye elaborate new terminal branches, thereby expanding their territory in the cortex and crowding out axon terminals carrying information from the deprived eye.

Once it became clear that atypical neuronal activity during brain development could distort the usual wiring of the visual system, attention turned to the issue of whether neuronal activity is necessary for wiring to proceed. The possibility existed that some amount of synaptic development could occur even in the absence of action potentials, which would mean that some aspects of the development were under genetic control.

The only way to resolve the issue was to eliminate action potentials. Investigators initially attempted to do that by raising cats in complete darkness from birth. The suturing of both eyes closed would have been insufficient because some light would have entered the eyes through the closed lids. (The absence of visual stimulation does not seem to disturb kittens: they remain vigorous and playful, and they grow at a normal rate.)

The visual system of dark-reared subjects developed abnormally but did develop somewhat. In contrast to the ocular-dominance columns of normal animals, those of the dark-reared cats were imprecisely defined, and the spacing between adjacent patches of the columns was often uneven. In other words, the postnatal eye-specific segregation of geniculocortical axons must have begun but was incomplete.

Initially the finding that some development took place seemed to imply



NEURONAL PATHWAYS important for vision in the cat resemble those of other mammals that have forward-facing eyes. Retinal ganglion cells in the right side of both retinas transmit visual information to the lateral geniculate nucleus in the right hemisphere of the brain; the axons from the right eye terminate on cells in the middle layer of the nucleus, and axons from the left eye terminate on cells above or below that layer. Similarly, ganglion cells in the left side of both retinas project to the lateral geniculate nucleus of the left hemisphere, again with the axons segregated into eye-specific layers. Relay cells in each lateral geniculate nucleus, in turn, convey visual signals to the visual cortex of the same hemisphere. In each hemisphere the axons associated with the right eye terminate on specific columns of cortical cells, and the axons associated with the left eye end on the alternating columns. Such segregation gives rise to what are called ocular-dominance columns in the cortex.

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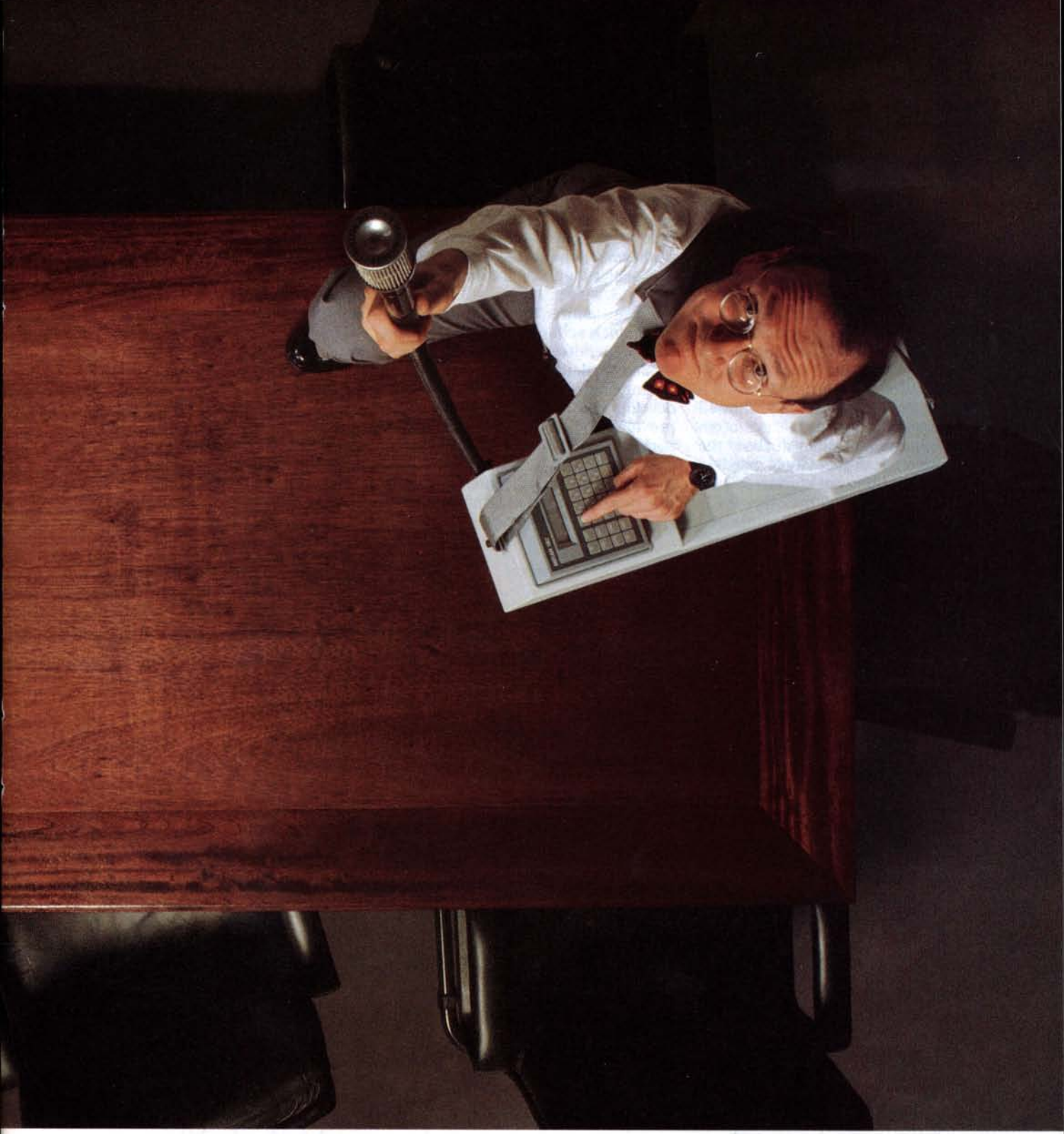

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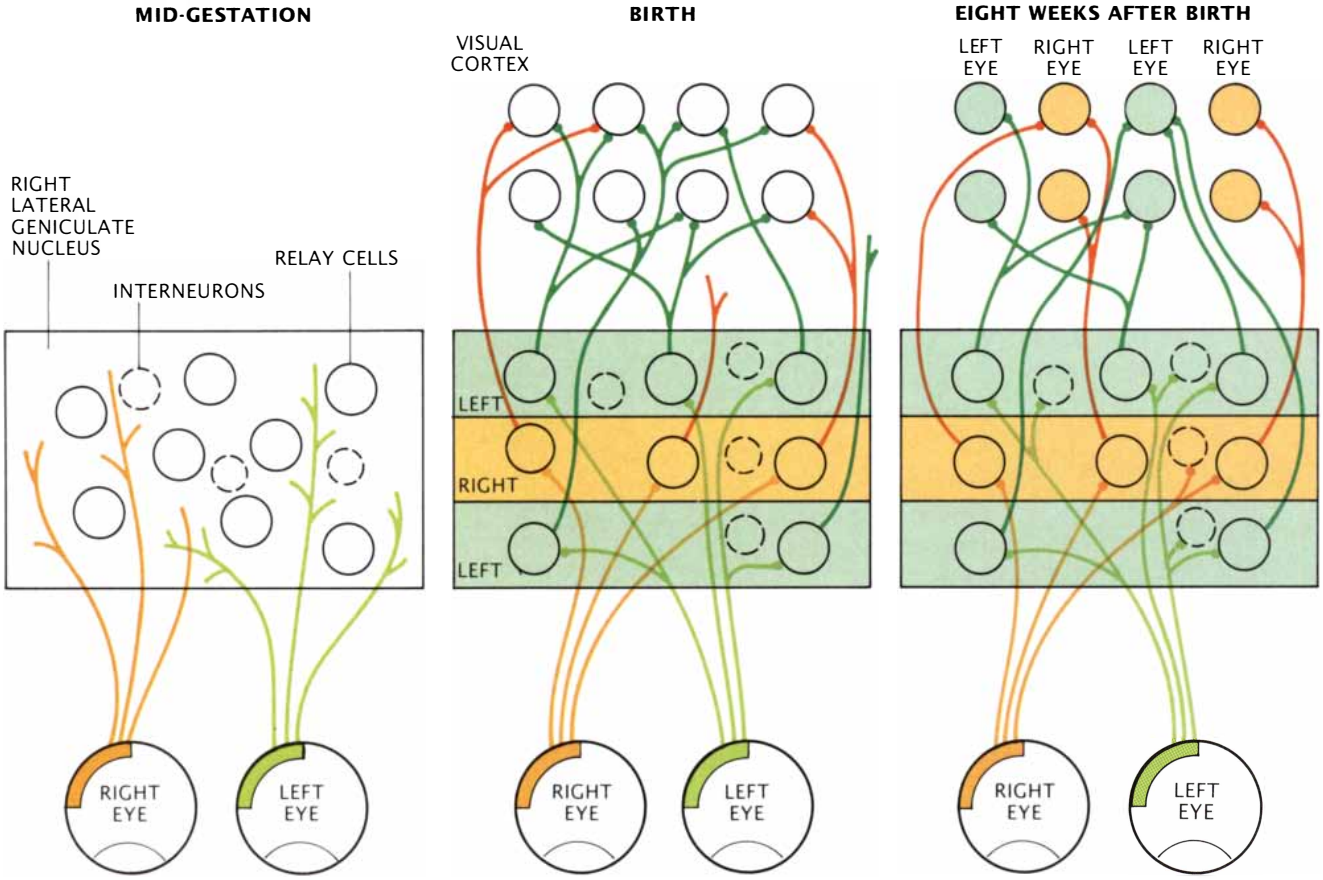
that maturation could proceed at least partially even in the absence of activity in the visual pathway. Other work showed, however, that action potentials had not been fully eliminated, which meant that alternative explanations were possible. For example, William Burke and William R. Hayhow of the University of Sydney showed that a total lack of visual stimulation does not completely silence retinal ganglion cells; the cells discharge action potentials spontaneously even in the absence of light. In addition, Robert W. Rodieck and P. S. Smith, while at the University of Sydney, and David N. Mastronarde of the University of Colorado at Boulder separately showed that ganglion cells in one eye often discharge spontaneously at about the same time, but the activity of ganglion cells in one eye is not correlated with the activity of cells in the other eye.

Collectively these results suggested that the correlated, spontaneous firing of impulses by ganglion cells within each eye might have accounted for the observed development. In particular, it seemed reasonable to suspect that the distinct patterns of spontaneous ganglion-cell activity in the right and left eye could have acted as signatures that enabled developing geniculocortical axons to be sorted into rudimentary ocular-dominance columns.

The failure of dark-rearing to block action potentials made it imperative to find a different approach to determine whether action potentials are necessary for synaptic development. Fortunately nature has provided a toxin, tetrodotoxin, that is perfectly suited for the task. The substance, which is found in the ovaries of the Japanese puffer fish and also in a newt common in California, prevents action potentials from arising but does not destroy nerve tissue. It works by binding to voltage-sensitive sodium ion channels and thereby blocking the crucial ion's entry into the cells. Unfortunately the circulation in the blood of just a few millionths of a gram of tetrodotoxin per kilogram of body weight is lethal for most mammals, and so until recently the substance was not an appropriate research tool. (The drug rapidly arrests such nerve-dependent functions as breathing.)

About 10 years ago methods were developed for injecting the toxin into the eye so that it would essentially remain confined there, unable to circulate. A painless injection every two or three days is enough to prevent retinal ganglion cells from generating action potentials.

With the new method Stryker, who had moved to the University of California at San Francisco, and William A.



DEVELOPMENT of the cat's visual pathways normally follows a standard course. Axons growing from the retinal ganglion cells arrive at the lateral geniculate nucleus about midway through gestation. Initially the axons are too immature to form synapses with the geniculate cells, which are randomly arranged in the nucleus. By the time the cat is born the geniculate cells have been parceled into layers, and the entering retinogeniculate axons have been segregated, so that each geniculate layer receives input from only the right eye (*light orange*) or the left (*light green*). The retinogeniculate axons have begun to establish synapses with relay cells, but synapses with interneurons have not yet been formed. At this point, too, axons from many relay cells have made synapses with cells in the visual cortex. These axons overlap, however: those conveying information from the right eye (*dark orange*) often terminate on the same cortical cells as axons from the left eye (*dark green*). By the end of the first eight weeks of life, the retinogeniculate axons have made synapses with both relay cells and interneurons; the geniculocortical axons have become segregated by eye, and ocular-dominance columns can be identified.

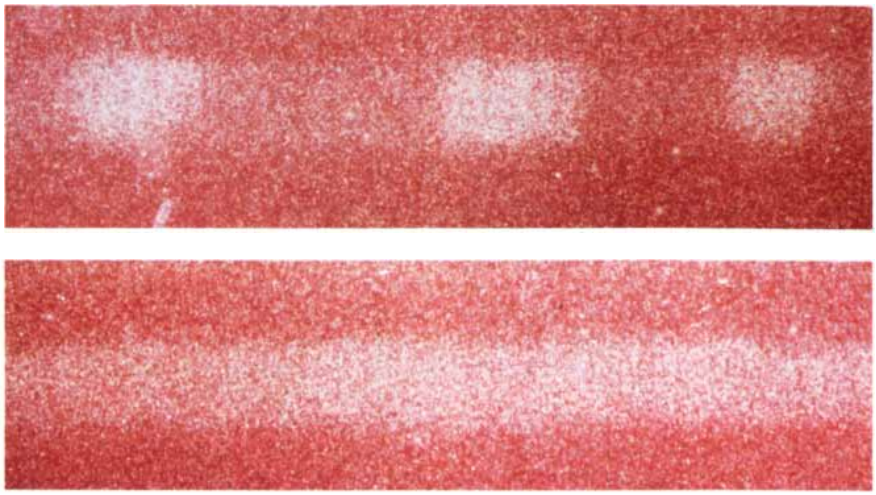
Harris of the San Diego campus were able to eliminate the ambiguity of the dark-rearing results. By treating both eyes of newborn cats with tetrodotoxin until the cats were six weeks old, they blocked the formation of ocular-dominance columns in the visual cortex. They thereby demonstrated that action potentials are needed for the columns to arise.

By staining geniculocortical axons associated with each eye, Stryker and Harris further showed that, as might be expected, the stalled cortical development derived from a failure of the geniculocortical axons extending into layer four of the visual cortex to segregate into eye-specific patches; instead axons representing the right or the left eye often made synaptic contact with the same cells. As a result, when the toxin wore off, most cortical cells responded almost equally to input from both eyes. These properties are typical of the visual cortex of neonatal kittens but are unusual for animals that are six weeks old.

At about the same time as Stryker and Harris were doing their studies, Mark W. Dubin, Louisa A. Stark and Steven M. Archer of the University of Colorado at Boulder examined the neurophysiological effects of ganglion-cell blockade on the lateral geniculate nucleus. They injected tetrodotoxin into one eye of a group of cats for the first two months of life and then recorded the electrical activity in geniculate cells a few days after the drug wore off.

Their recordings showed that eliminating action potentials in ganglion cells during that period prevents an important change from taking place in the lateral geniculate neurons. Normally by the end of a cat's second month of life, its geniculate neurons not only have been parceled into eye-specific layers but also have become specialized in another way: some cells fire action potentials only when a spot of light at the center of their receptive field flashes on, whereas some cells fire only when the spot disappears. (The receptive field is the part of the visual field about which a cell receives information.) This specialization results from the segregation of retinogeniculate axons in such a way that the axons of ganglion cells responsive to the flashing on of light end on different geniculate cells than do the axons of ganglion cells responsive to the light's disappearance.

In the treated animals, however, most of the geniculate cells associated with the treated eye could be excited by both the turning on and the turning off of a spot of light. The cells were unable to distinguish between the two conditions.



SEGMENT OF VISUAL CORTEX in a normal eight-week-old cat is strikingly different from a comparable segment in a cat of the same age in whom input from one eye was eliminated experimentally during development. In the normal cat (*top*) the presence of ocular-dominance columns is revealed by the alternation of white and pink patches. (The white patches were produced by radioactive tracers that traveled to the cortex after being injected into one eye.) In contrast, a corresponding stretch of cortex in the treated cat has no such patches (*bottom*); the bright band indicates that the region is sensitive throughout to inputs from the eye that received visual information (*solid white band*). Clearly, a flow of impulses through the visual pathways from both eyes is needed if ocular-dominance columns are to develop.

This group of studies exploiting tetrodotoxin, then, enabled investigators to gather strong evidence that when action potentials in the visual system are silenced, synaptic development does not proceed normally: geniculocortical axons do not segregate into eye-specific domains, and the on-off segregation of retinogeniculate axons does not proceed properly in the lateral geniculate nucleus. Yet these studies could say nothing conclusive about what was happening structurally at the level of the synapse. For instance, it was unclear whether eliminating action potentials in ganglion cells interfered with the anatomical development of their axon terminal bulbs.

Direct evidence relating to this problem could be obtained only with electron microscopy, and so I undertook such studies with Dubin, Stark and Grayson L. Scott, a colleague of mine at Wisconsin. This effort was facilitated by earlier work Scott and I had done, in which we identified many aspects of normal retinogeniculate synaptic development.

The earlier work had demonstrated that the terminal bulbs of retinal ganglion cells normally change in several specific ways in the two months after a cat is born. For instance, their cross-sectional size typically doubles, and the length of the regions specialized for synaptic contact shrinks by about a third. (The shrinkage may help focus the flow of released neurotransmitter molecules.)

We also had learned that beginning about the third week after birth the bulbs begin to increase the number of contacts they make with the dendrites in the lateral geniculate nucleus. The bulbs retain any existing contacts they have established with the dendrites of the geniculate relay cells and also form new synapses with specialized appendages (called F profiles) of the dendrites of cells known as interneurons. Interneurons, which emit inhibitory messages in the lateral geniculate nucleus, are important in fine-tuning the behavior of the relay cells.

Another change generally occurs by the end of the second month. At that point about 30 percent of all retinogeniculate terminal bulbs are situated in what are called complex synaptic zones, which typically consist of the bulb surrounded by a cluster of dendrites and F profiles. Each complex synaptic zone is encapsulated by protoplasmic extensions from what are called glial cells, which help to give the brain its structure. Although the function of the complex zones is not understood precisely, they may help to isolate the internal synaptic connections from external influences.

When we injected one eye of a group

of cats with tetrodotoxin for the first eight weeks of life, we found that the synaptic connections made by ganglion cells in the treated eye remained identical to those found in cats at birth. Development had been stopped completely. In the absence of action potentials, the bulbs did not grow in size, did not exhibit a decrease in the length of their contact regions and did not make synaptic contacts with F profiles. Essentially all synapses were made with the dendrites of relay cells, and virtually no complex synaptic zones could be found.

Although our studies demonstrated that the elimination of action potentials halts the maturation of the axon bulbs in ganglion cells, the results did not exclude the possibility that retinal blockade simply produces a moratorium on development that can be undone if neuronal activity is restored. The results also did not indicate whether development can proceed in the usual way if a newborn kitten is given normal stimulation for some amount of time before action potentials are blocked. We tried to settle these issues with two additional sets of experiments.

In the first set we blocked action potentials in the retinal ganglion cells of one eye for the first four or 10 weeks after birth; then we discontinued the drug to allow for several months of normal activity. If we found that retinogeniculate connections developed normally even with belated activity, we could conclude that action potentials, although necessary for development, need not be present during a specific period.

In the second set of experiments, we allowed the animals to have normal visual experiences until the third or fifth postnatal week before we initiated the tetrodotoxin injections. If we found that retinogeniculate connections developed normally, we could conclude that action potentials are required to initiate synaptic development but not to sustain it.

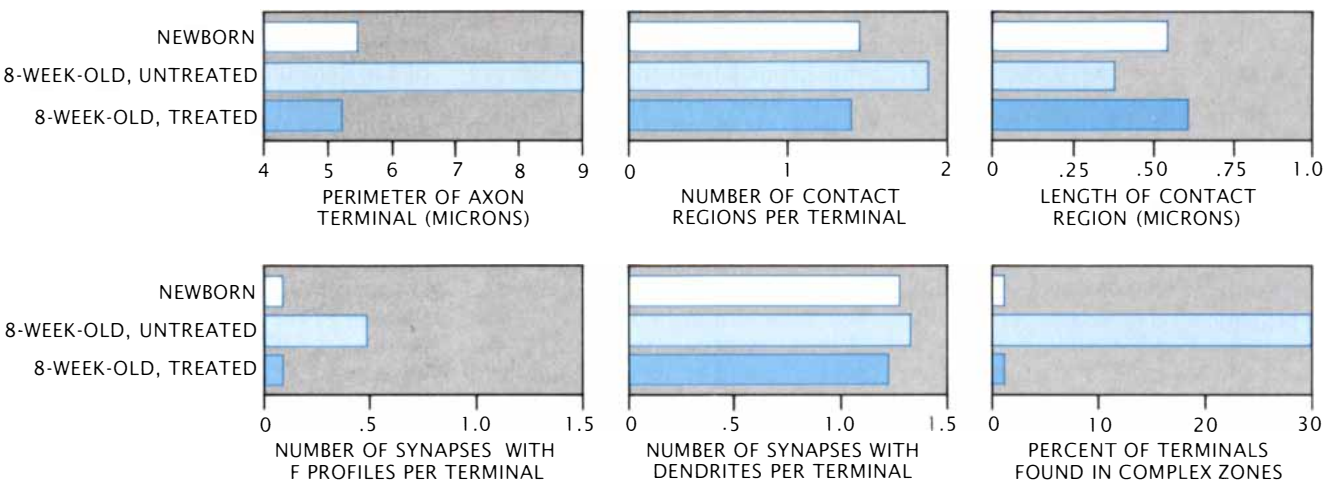
Under none of these conditions did retinogeniculate connections develop properly. We saw the closest approximation to normal development in the first set of experiments, when retinal blockade was discontinued earliest (after the first four weeks of treatment). Then the size of the axon terminals and the number of synapses they formed were close to normal (75 percent of normal), but the number of complex synaptic zones was markedly decreased.

The second set of experiments demonstrated that early visual experience prior to the onset of retinal blockade cannot initiate the usual synaptic development. Even when action potentials are allowed to occur throughout the first postnatal month, retinogeniculate connections look almost the same as they do at birth. Our combined results show, then, that action potentials are required throughout the first two months of life (and particularly in the second month) if ganglion-cell terminal bulbs are to mature and establish new synaptic connections. If action potentials are blocked at any time during this period, normal development will be prevented.

The problem of mechanism remains. By what sequence of molecular events might the flow of impulses from neuron to neuron during brain development trigger the maturation of axonal terminal bulbs or alter the distribution or strength of synaptic connections? These questions still await answers.

Theoretical and experimental work on learning may, however, illuminate the issue of synaptic strength. Studies of learning are potentially applicable to development because learning, in common with development, involves assembling and strengthening some synaptic connections and weakening and eliminating others. A prescient assault on the problem of how synaptic connections might be altered by activity was made by Donald O. Hebb of McGill University in 1949. He suggested that when one cell "repeatedly or persistently" succeeds in activating another, metabolic or structural changes in one cell or both of them increase the efficiency of the connection between the cells. (Random or occasional activity, then, would not be sufficient to strengthen synapses.)

Hebb's ideas could not be tested at



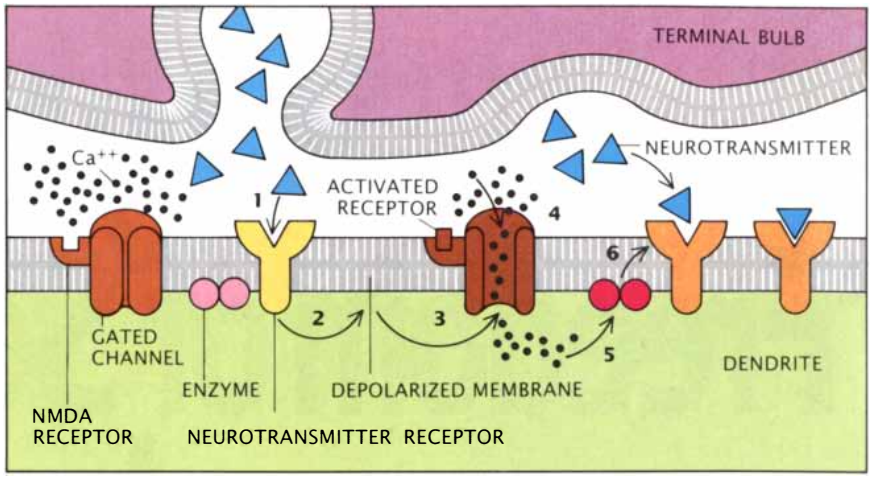
GRAPHS summarize much of the data demonstrating that retinal ganglion cells have to generate action potentials if their axon terminal bulbs are to mature. Electron micrographs were made of single cross sections through the lateral geniculate nucleus of newborn cats, normal eight-week-olds and "treated" eight-week-olds in whom ganglion-cell action potentials were silenced in one eye from birth. The collected images revealed that the axon terminal bulbs of the silenced ganglion cells in the treated eight-week-olds were virtually identical with those of the newborns. Compared with the bulbs of normal (untreated) eight-week-olds, those of the newborns and of the treated cats were smaller, made fewer synaptic contacts and had longer contact regions (regions specialized for the release of neurotransmitter); they also made essentially no synapses with F profiles. Virtually none of the axon terminal bulbs of the newborns or the treated animals were in complex synaptic zones, whereas approximately 30 percent of the terminal bulbs of the normal, mature cats were in such complex zones.

the time. More recently, though, studies of the molecular basis of a phenomenon known as long-term potentiation have suggested a mechanism by which extensive activity across synapses might strengthen them. Long-term potentiation, which was first described by Terje Lømo of the University of Oslo in 1966, is the increasing of synaptic efficiency for days, or even indefinitely, in response to controlled bursts of stimulation. In mammals long-term potentiation occurs most readily in the hippocampus, a part of the brain that is critical to learning and memory.

Exposure of a neuron in the hippocampus to a particular pattern of excitatory stimulation—brief, high-frequency electric currents—can within seconds produce a long-lasting increase in synaptic efficiency. For many years no one understood how that critical pattern achieved long-term potentiation, but an important clue was gained when a molecule known as the NMDA (*N*-methyl-D-aspartate) receptor was found to be activated specifically by that pattern. The receptor acts as a gate, regulating the activity of a channel through which calcium (a ubiquitous intracellular messenger) enters the cell. The receptor's name derives from the fact that the associated channel, which normally is voltage sensitive, can be opened under experimental conditions when it is exposed to NMDA; presumably the effect is mediated by the binding of NMDA to the gating molecule.

The brief, high-frequency stimulation of a postsynaptic cell in the hippocampus gives rise to an inflow of positively charged ions and, in turn, lowers the membrane potential below a set threshold. This change activates NMDA receptors, causing their associated calcium channels to open. Calcium ions then flood into the cell through the open channels and activate intracellular enzymes, probably including enzymes that are major constituents of the part of the postsynaptic membrane specialized to receive transmissions. The events that follow have not been identified in detail, but the enzymes may effect a reorganization of membrane proteins, leading to a subsequent improvement in the efficiency with which the postsynaptic cell responds to specific patterns of stimulation [see "Memory Storage and Neural Systems," by Daniel L. Alkon; SCIENTIFIC AMERICAN, July].

It is tempting to suppose that a similar mechanism may also participate in the strengthening of synapses during the development of the brain.



MECHANISM by which NMDA receptors might effect long-term potentiation—a persistent change in the strength of synaptic connections—in the hippocampus of the brain has been partially deciphered. When input from a presynaptic cell is patterned and timed appropriately (*1*), the stimulation depolarizes the cell membrane (*2*) enough to activate NMDA receptors, causing them to open NMDA-receptor-gated channels permeable to calcium ions (*3*). As the ions flow into the cell (*4*), they activate various enzymes (*5*), presumably including some that help to reorganize the membrane's proteins in a way that improves the efficiency of the synapse (*6*). The systematic activation of one neuron by another in the developing brain may well strengthen synapses by a mechanism similar to the one described here.

For instance, the repeated activation of cortical cells by geniculocortical axons associated with one eye might be detected by a voltage-sensitive receptor, such as the NMDA receptor. The detection of the change could then trigger a calcium-mediated reorganization of the postsynaptic membrane, which would lead to the strengthening and ultimate stabilization of the active synapses.

This mechanism is particularly attractive because it suggests a fairly simple model for the control of the beginning and end of critical periods for activity-dependent development in different brain systems. The timing of the periods could be efficiently controlled in given groups of neurons if their biochemical machinery were genetically instructed when to start and stop synthesizing molecules that, like the NMDA receptor, are sensitive to particular patterns of incoming stimulation. Such a model seems plausible because the inclusion of the start and stop commands in the genes would not require very much coding.

An added advantage of the model is that it can also account for protracted plasticity in other parts of the brain. All that would be required is that neurons be genetically programmed to produce NMDA receptors or functionally related molecules indefinitely instead of halting production at some specified time. Thus, variation on a single biochemical theme could account for relatively brief periods of activity-dependent plasticity, such as is found in the developing visual cortex, as well as for the apparently lifelong plasticity found in other parts of the brain, such as the hippocampus.

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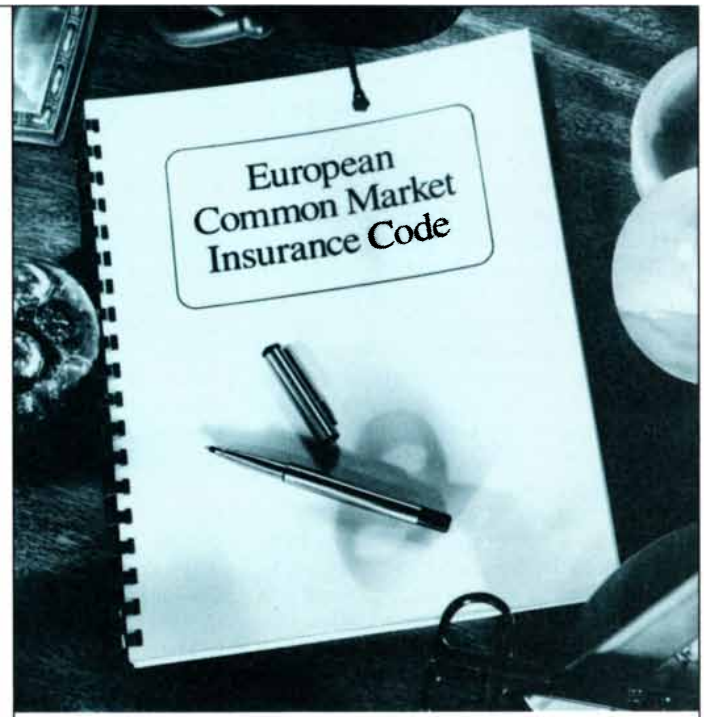

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The First Color Photographs

The earliest schemes for capturing color images were elaborate and unwieldy—but ingenious nonetheless

by Grant B. Romer and Jeannette Delamoir

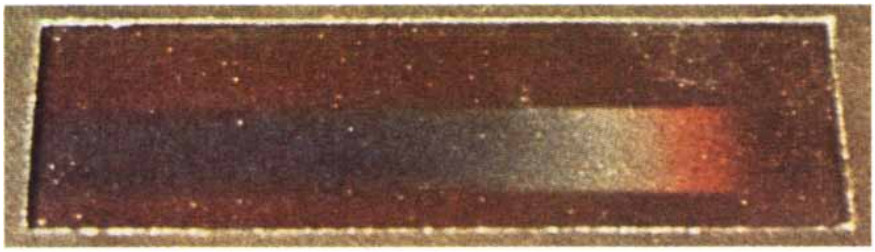
Color photography is often assumed to be a modern achievement, largely because the examples of 19th-century photographic images commonly encountered are more or less monochromatic. Yet modern color photography owes its existence to investigations performed in the 1800's. Indeed, the beginnings of color photography antedate even the commercial debut of the daguerreotype, whose 150th anniversary is being celebrated this year.

The first conceptualizers of photography assumed that photographic images would be in color. A lens projected a color image; why should the resulting image be any different? Hence, the earliest attempts at color photography tried to achieve direct color reproduction, that is, the use of a single light-sensitive compound to record directly the full range of the visible spectrum. Many substances were known to change color during exposure to light, and some even took on the actual colors of light.

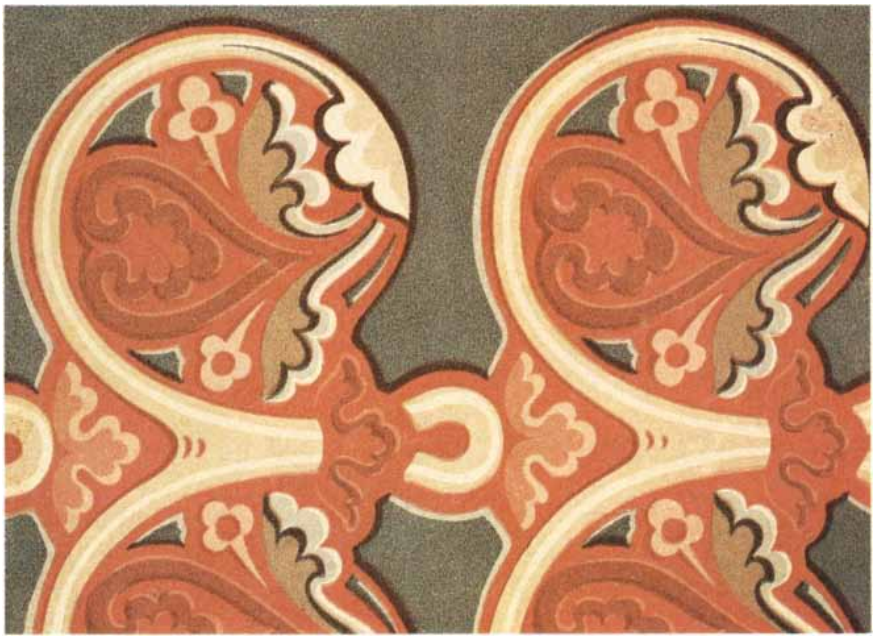
In 1810 Thomas Johann Seebeck, a German physicist who worked closely with Goethe in the polymath's investigations of color, published observations of the response of silver chloride to a projected image of the spectrum. Seebeck spread damp silver chloride on paper and then exposed the paper

GRANT B. ROMER and JEANNETTE DELAMOIR worked together at the International Museum of Photography (IMP) at George Eastman House in Rochester, N.Y. Romer, conservator of photographic collections at the museum, is a specialist in 19th-century photography and spent the past few months making daguerreotypes for the Musée Carnavalet in Paris to commemorate photography's 150th anniversary. Delamoir worked as a cataloguer at the IMP between January and August of this past year.

***MATURATION OF COLOR PHOTOGRAPHY** is represented by this juxtaposition of an 1845 hand-colored daguerrotype* **(above)** *and a color photograph from 1907* **(right)**. *Whereas daguerreotypes met with immediate success on their introduction in 1839, few of the first color processes were commercially viable. The color photograph here was made by a commercial technique called the Autochrome process, which involved screening light through potato-starch grains dyed red-orange, green and violet* **[see top illustration on page 95].**



COLOR SPECTRUM produced in 1848 by the French physicist Edmond Becquerel is preserved at the Science Museum in London. Becquerel deposited silver chloride on a daguerreotype plate and exposed it to light from a prism; the compound took on the refracted hues. Such direct methods of color reproduction dominated early experiments in color photography.



CONTACT IMAGE **(top)** *illustrates another method of direct color reproduction. The Frenchman Claude Niépce de Saint-Victor produced the image in the mid-1800's by exposing a chlorinated silver plate that was in contact with a graphic design* **(bottom)**, *probably a piece of wallpaper.*

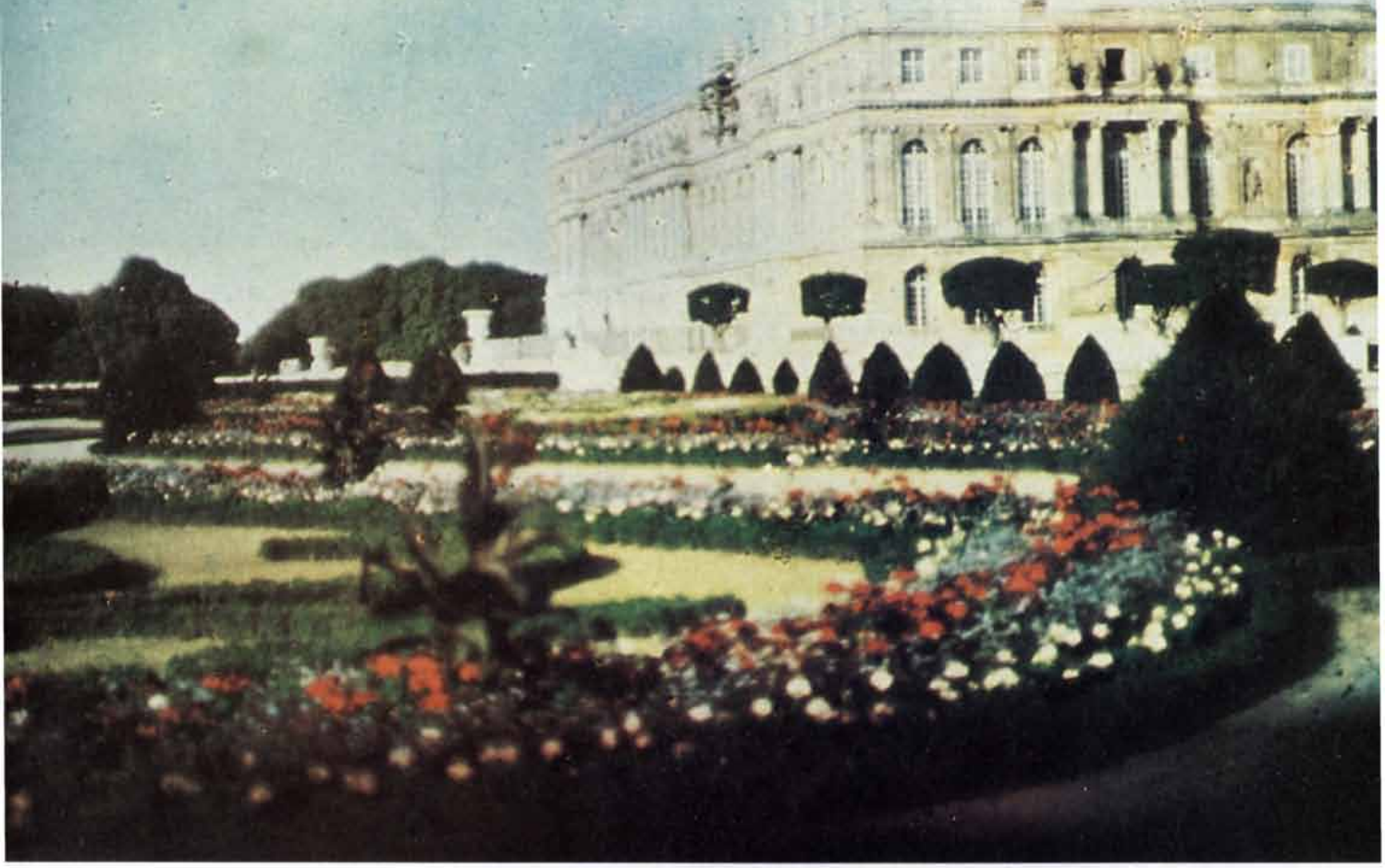
for 15 minutes or more to light that had passed through a prism. The exposed silver chloride took on some of the spectrum's colors, albeit faintly. Seebeck could not explain the phenomenon. (Neither could anyone else until 1868.)

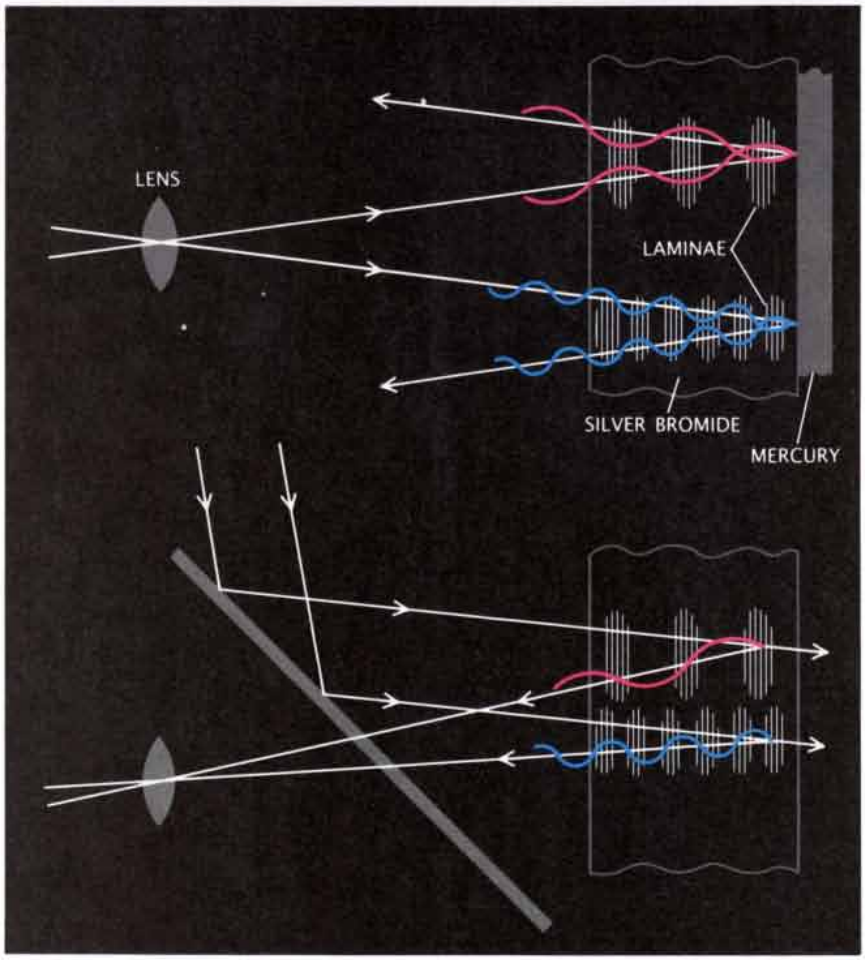
Louis-Jacques-Mandé Daguerre, a scene painter by profession, began his experiments in the 1820's with the hope of reproducing color by means of various phosphorescent minerals. In 1826 a French inventor named Joseph-Nicéphore Niépce made what is now the earliest surviving photograph, a picture of a barnyard he recorded on a pewter plate coated with an asphalt solution; light made the asphalt insoluble, yielding a monochromatic image.

Daguerre and Niépce became collaborators and began experimenting with silver-surfaced plates exposed to fumes of iodine. Four years after Niépce's death in 1833, Daguerre established the procedure for making daguerreotypes, a secret he kept until 1839. At roughly the same time, the English amateur scientist William Henry Fox Talbot laid the groundwork for negative-positive photography on paper with the invention of a system he later called calotypy.

The daguerreotype was the first truly practical photographic process. Images were produced by exposing in a camera a silver-surfaced copper plate that had been treated with iodine fumes. The latent image on the plate was brought out with fumes of metallic mercury, which formed an amalgam with the silver wherever the plate had been exposed; the scattering of light by the amalgam and the reflection of light by the silver substrate combined to create a positive image. The process was improved several years after its introduction by the use of halogens other than iodine, such as bromine and chlorine, to accelerate the speed at which the plate was exposed. Silver chloride also figured in Talbot's paper process. Talbot used paper saturated with the compound to make contact prints from paper negatives.

With these procedures Daguerre, Talbot and their colleagues and customers got sometimes highly colored but nonetheless monochromatic results; that is, the daguerreotype surface would reflect one color quite vividly, but no others. The lack of color reproduction was often compensated for by hand-coloring, which could be exquisitely subtle and effective [*see illustration on page 88*]. The desire to register the colors of nature, however, remained quite strong among the ex-





***LIPPMANN PROCESS** was the last significant attempt to use direct color reproduction. The French physicist Gabriel Lippmann invented the system in the 1890's to exploit new theories of light waves and new kinds of emulsions. He coated a glass plate (not shown) with silver bromide and placed the plate in a camera so that the coating came in contact with a sheet of liquid mercury. The light entering the camera passed through the emulsion and bounced off the mercury; the "standing waves" that were formed caused the silver in the emulsion to segregate into laminae one wavelength apart* (top right). *When the plate was viewed at a certain angle, the laminae reflected light of the same wavelengths (or colors) that had created them* (bottom right), *giving rise to vivid hues such as those in Lippmann's 1890 photograph of Versailles* (above).

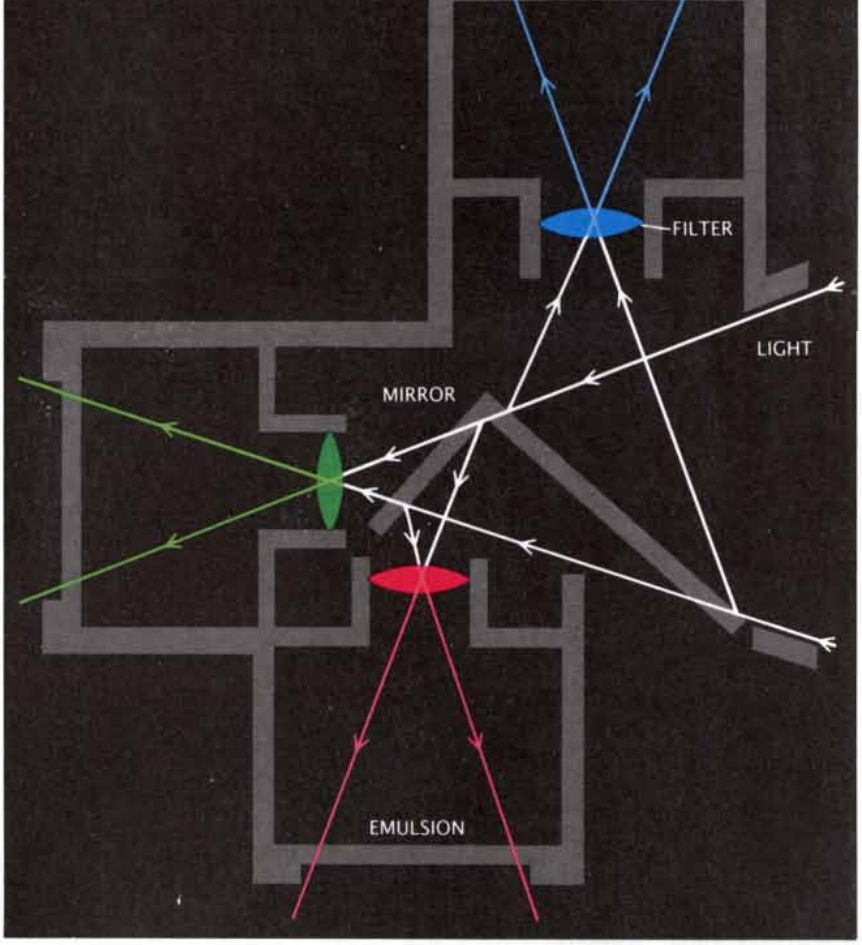
perimenters who sought to extend the boundaries of photography.

Consequently, there was a resurgence of interest in Seebeck's color experiments. In 1840 the English astronomer Sir John F. W. Herschel repeated them, noting the spectral properties of various silver salts. His work caught the attention of the French physicist Edmond Becquerel, who in 1847 began to record color spectra with a thin, even coating of silver chloride on a daguerreotype plate instead of on paper. Becquerel's results were quite encouraging; one of his color records is preserved at the Science Museum in London [*see upper illustration on page 90*].

Claude Niépce de Saint-Victor, a nephew of Joseph Niépce, took up Becquerel's work in 1851 and improved on it by changing the deposition of the silver chloride and by preserving the colors with varnish. One of his brilliant spectral reproductions is on display at the Conservatoire National des Arts et Métiers in Paris. Niépce de Saint-Victor proceeded to capture camera-produced still lifes on his silver chloride–coated plates. He also made contact images on paper from colored graphic designs [*see lower illustration on page 90*].

Niépce de Saint-Victor's process was not commercially viable, because the images could not be adequately fixed and because the exposure times required to register all the colors were unduly long (up to one hour). Yet there is an interesting aside to this work. In 1851, the same year Niépce de Saint-Victor started his color experiments, an American minister and commercial daguerreotypist named Levi L. Hill claimed to have discovered a process for making color daguerreotypes. Hill managed to raise $15,000 from curious subscribers, but no one could replicate his results, and he was ultimately dismissed as a humbug. Recently, however, a present-day daguerreotypist, Joseph W. Boudreau of Paier College of Art in Hamden, Conn., produced color images by following Hill's published instructions. Furthermore, the examination of several of Hill's images has shown that their color resulted at least in part from the photographic process. In fact, Hill's process appears to have been quite similar to the ones Becquerel and Niépce de Saint-Victor used.

In 1868 the German physicist Wilhelm Zenker proposed that the interference of light waves in the photographic medium was responsible for the ability of silver chloride plates to reproduce color. Zenker theorized that light waves interacted with the refractive silver chloride and the reflective surface of the polished silver plate to form so-called standing, or stationary, waves: waves whose peaks and troughs coincide in space but alternate with time [*see illustration on preceding page*]. Where the peaks and troughs coincide, he maintained, the silver chloride is exposed, thereby cre-



DUCOS DU HAURON CAMERA* (above) *captured colors indirectly by means of red, green and blue color records. The French inventor Louis Ducos du Hauron designed the camera with partially transmitting mirrors, which split the light into three different pathways, and with filters to isolate each primary color's contribution. The emulsions available in the 1870's were not sensitive enough to be used in the camera, but with more cumbersome procedures Ducos du Hauron was able to produce color photographs such as the 1877 still life on the left.

ating silver layers; where the nodes between the peaks and troughs coincide, it remains unexposed. Viewed later with white light (light incorporating all visual wavelengths), the silver laminae would reflect only the wavelengths of the light that had created them; that is, they would reflect only the particular color to which the silver chloride had initially been exposed.

Zenker's theory of standing light waves was confirmed by the German physicist Otto Wiener in 1889, and Wiener's work led to the realization of fixable, direct color photography in 1891. The ingenious system was devised by a French physicist named Gabriel Lippmann. Lippmann took advantage of photosensitive emulsions introduced in the 1850's that could adhere to glass plates. He placed a glass plate covered with a fine-grained silver bromide emulsion in a holder that brought the emulsion into contact with a sheet of liquid mercury. The mercury served as a mirror, just as the silver daguerreotype plate had in Niépce de Saint-Victor's experiments.

Lippmann put the holder in a camera and exposed the emulsion. Light traveled through the glass plate and the emulsion, struck the mercury mirror and bounced back onto itself, giving rise to standing waves. In the course of development, silver laminae half as wide as the wavelengths of light that had created them formed from the silver bromide.

The developed image looked like a normal negative image—until it was viewed at a certain angle. At that particular angle, light reflecting off the image's surface gave rise to brilliant colors, true to the natural hues. Even though Lippmann's process entailed long exposure times and difficulties in handling the mercury, the fixed colors were so beautiful that it enjoyed some commercial life until 1907.

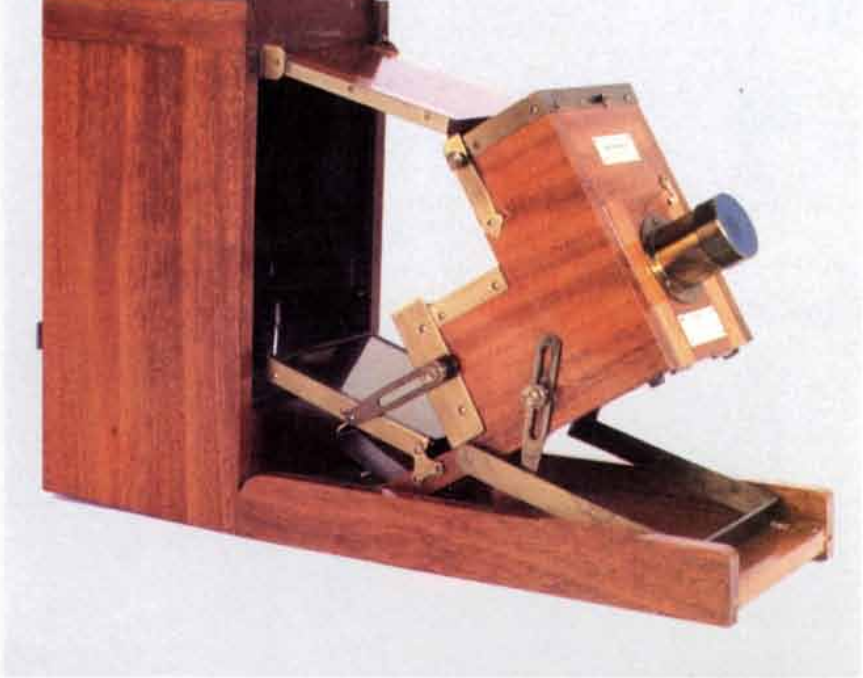
In that year Lippmann's technique was supplanted by indirect methods of producing color images: methods that reconstruct the spectrum of color through the combination of the primary colors red, blue and green. The indirect methods established in the 1800's became the basis of modern color photography. To understand the evolution of those methods, it is necessary to go back once again to the days before the daguerreotype.

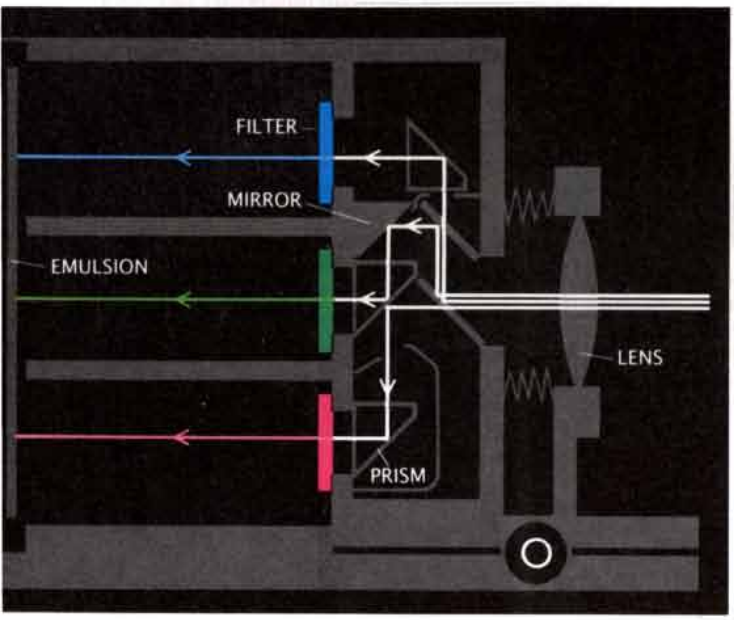
In 1801 the English physician and physicist Thomas Young presented to the Royal Society of London a theory of color vision that predicted the existence within the human eye of three types of color receptors, each sensitive to one of the three primary colors. In varying proportions, the primaries would stimulate the appropriate combinations of receptors to give rise to the perception of any and all colors. Young's presentation marked the first time color was identified as a physiological phenomenon rather than as a material substance. His theory, along with advances in color printing by the superposition of three or more colors, paved the way for photographic experiments with indirect color.

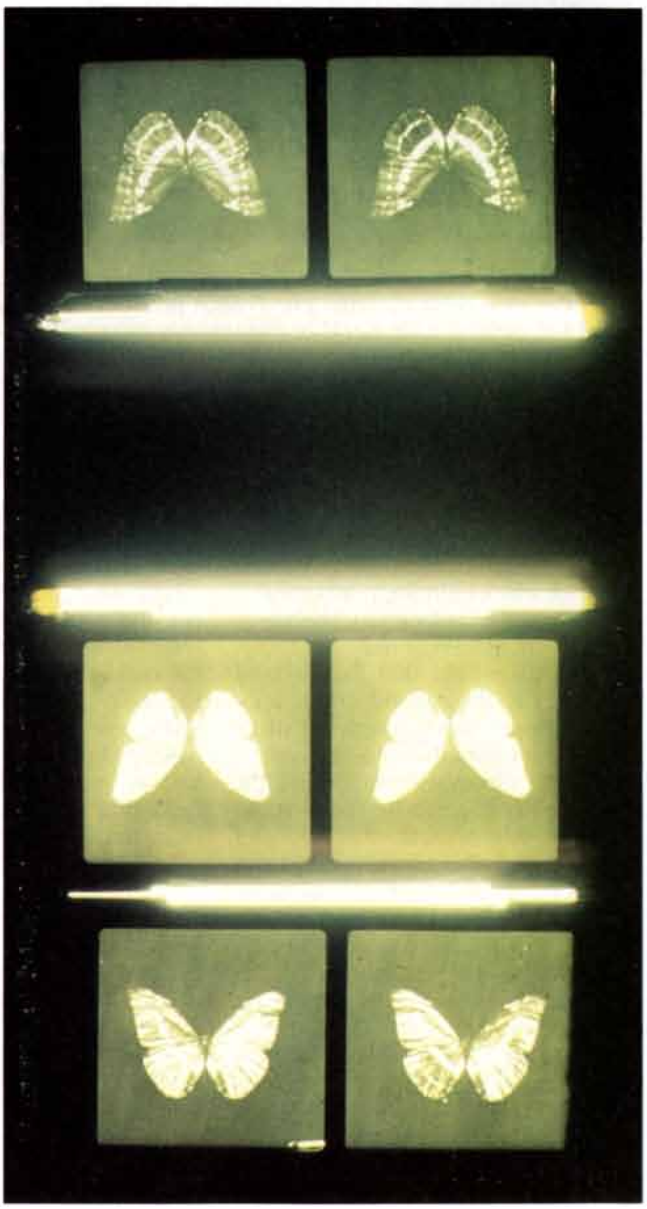
The first experiments were attempts to replicate the process of visual perception by recording the three primary components of color separately and then recombining them to present a full-color image. Most systems separated the primary colors by making three monochromatic negatives exposed through red, blue and green filters. The three negatives were made into positives and subsequently recombined by either "additive" or "subtractive" methods.

Additive systems reconstitute images by mixing together the light of the three primary colors. The mixing can be accomplished by projecting three colored images together or by juxtaposing small lines or dots of primary colors so that the eye blends the colors. Subtractive systems, on the other hand, utilize dyes of the complementary colors—cyan (blue-green), magenta (blue-red) and yellow (green-red)—each of which selectively absorbs one primary while allowing the other two to be perceived. Cyan absorbs red light, magenta absorbs green light and yellow absorbs blue light.

The British physicist James Clerk Maxwell first demonstrated the additive process in photography in 1861 at the Royal Institution in London [see "Maxwell's Color Photograph," by Ralph M. Evans; SCIENTIFIC AMERICAN, November, 1961]. Maxwell superposed in a lantern-slide projector three positive, uncolored slides of a hair ribbon. Each slide had been photographed







KROMSKOP CAMERA AND VIEWER **(top left and right)** ***operated according to the principles established by Ducos du Hauron; by the time the American inventor Frederic E. Ives began marketing the pair in 1895, more sensitive emulsions had made the designs workable. The camera used partially transmitting mirrors and prisms to split light entering through the lens and filters to separate the primaries*** **(above).** ***The circuitous routes the light traversed ensured that the three beams had gone equal distances before they reached the emulsions. A more elaborate model of the Kromskop had two lenses and made stereoscopic photographs*** **(right).**

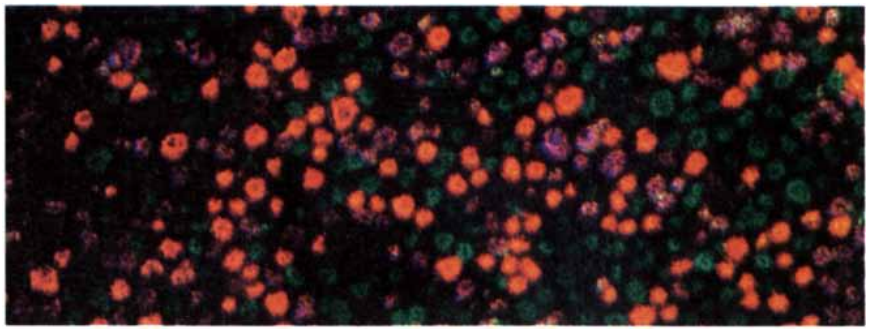
through a colored glass or liquid, and Maxwell projected each through a filter of the same color. The combined images re-created the varied colors of the ribbon.

Maxwell performed his experiment to verify his work in colorimetry (the measurement of color), and so he was satisfied. But the demonstration did not solve the problems of color photographers. The emulsions available at the time were much more sensitive to blue light than to any other, and even when the exposure times for red and green were adjusted to compensate, those images were not as fully realized as the blue ones.

In 1862, a year after Maxwell's demonstration, a 25-year-old Frenchman named Louis Ducos du Hauron reviewed the basis of almost every photographic color system extant at the time and proposed the one destined to become the foundation of the color systems used today. His proposal involved making color separations by means of filters and then superposing the primary-color positives on a single print. Later Ducos du Hauron did just that, and he showed the first successful three-color photographic prints—again, a product of an additive color process—at the Paris Photographic Society in 1869. It was an accomplishment qualified only by the fact that he wrongly identified the primary colors as red, yellow and blue.

In 1868 Ducos du Hauron had suggested that the three-filter, three-negative process could be circumvented by exposing an emulsion through a screen of very fine lines of red, yellow and blue drawn on glass. The red lines would allow only red light to reach the emulsion and expose it; likewise, the blue and yellow lines transmitted only blue and yellow light, respectively. If the positive were then overlaid with a similar screen in exact register, the exposed areas of the positive would reflect light through the same lines of colors that had created the exposure. The fine, primary-colored lines would be blended in the eye of the beholder to re-create the original colors.

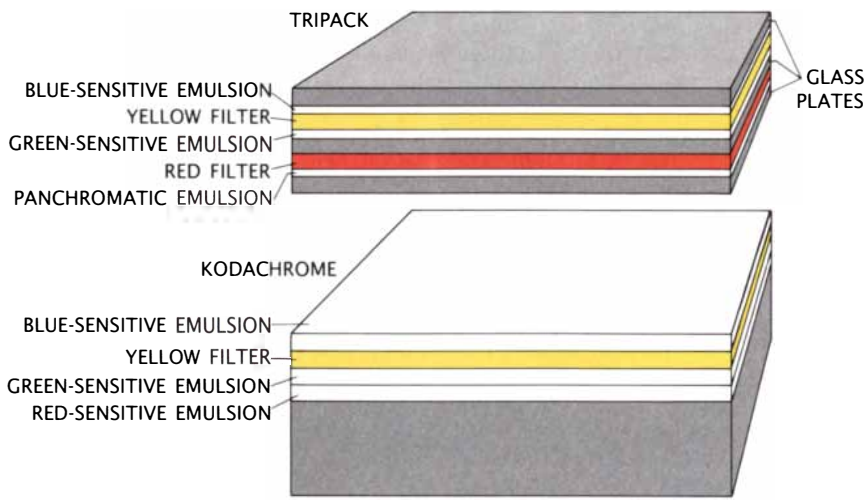
Ducos du Hauron lacked the financial means to act on his own theory. Later in the century, however, entrepreneurs in Ireland and the U.S. adopted it. Their systems were plagued by problems with registration, by the prohibitive expense of the ruled screens and by the persistent lack of sensitivity of emulsions to the red end of the spectrum. The French pioneer moviemakers Auguste and Louis Jean Lumière circumvented those problems in 1907 with their "Autochrome" process, the first truly practical color process and also an additive one.



POTATO-STARCH GRAINS, dyed in hues close to the three primary colors, served the same function as the filters in the cameras designed by Ducos du Hauron and Ives. The pioneer French filmmakers Auguste and Louis Jean Lumière used the starch grains in the Autochrome process, which the brothers introduced in 1907. A single layer of the grains was embedded in the photographic emulsion before exposure; after exposure and bleaching, the light transmitted through the grains re-created primaries that the eye blended to produce the colors of the subject.

The Lumière brothers did get a bit of help. By 1907 panchromatic emulsions had been introduced that were equally responsive to both ends of the spectrum, obviating the trouble with red sensitivity. The Lumières went on to eliminate the registration problems and the exorbitant expense of the screens by devising a low-cost alternative: they dyed potato-starch grains red-orange, green and violet and then combined the photosensitive emulsion and the starch grains on a transparent plate in a layer one grain thick. Light filtered through the starch grains exposed the emulsion, which, when bleached, would transmit light back through the grains, thereby reproducing the colors to which the emulsion had been exposed. The Autochrome process and its variations remained commercially viable until the 1930's, when they were made obsolete by Kodachrome and other forerunners of the subtractive processes that hold sway today.

Ducos du Hauron had initiated the work on subtractive color reproduction in 1874 by boosting the color sensitivity of red and green photographic plates with sensitizing dyes. (That improvement was made possible by the German chemist Hermann W. Vogel's discovery of optical sensitizing dyes in 1873.) Ducos du Hauron brought the exposure times of the red and green plates into line with those of the blue plates, clearing the way for



TRIPACK AND ITS SUCCESSOR, Kodachrome* (bottom), *combined the three color negatives on a single plate. The tripack, invented by Ducos du Hauron in 1897, consisted of a glass plate coated with silver bromide (which at brief exposures is blue-sensitive), followed by a yellow filter (which allows only red and green light to pass), a layer of green-sensitive emulsion, a red filter and a final emulsion. The Kodachrome plate is almost identical; no red filter is required because red-sensitive emulsions were available by the time Kodachrome was introduced in the 1930's.

HINDENBURG BLAZES in a 1937 photoessay. Emulsions that could simultaneously register three colors on a single negative—the legacy of the tripack—made possible color records of rapid and unexpected events such as the dirigible's crash.

simultaneous rather than successive exposures.

To take advantage of that advance, Ducos du Hauron invented a camera with three lenses that could take three colored exposures at the same time. Each lens, however, had a slightly different line of sight, and so the three exposures could not be brought into register when the image was reconstituted. He therefore designed a camera with one lens, in which mirrors split a beam of light into three beams that passed through filters to their respective plates [*see illustration on page 93*].

Ducos du Hauron's camera required emulsions still more sensitive than the ones available in the 1870's. By 1895 better emulsions had been devised, enabling an American inventor named Frederic E. Ives to begin to market a device, called the Kromskop, that operated according to the principles Ducos du Hauron had laid out [*see illustration on page 94*]. The camera could even be adapted to make separation negatives that were stereoscopic. The separations were joined by ribbons to keep them in the correct arrangement; they could be viewed with a device that was similar in its essentials to a viewer proposed by Ducos du Hauron in 1869.

All that remained to bring color photography into the 20th century was a scheme to combine the three separation negatives on a single plate. In 1897 Ducos du Hauron devised such a scheme with his "tripack." It consisted of a glass plate coated with a transparent layer of silver bromide (which at brief exposures is blue-sensitive), next to a yellow filter (which allowed red and green light to pass), a thin green-sensitive emulsion, a red filter and then a panchromatic emulsion [*see bottom illustration on preceding page*]. Ducos du Hauron made negatives from the positives and then made a yellow print from the blue negative, a magenta print from the green negative and cyan print from the red negative. By combining the prints of those complementary colors, he produced a full-color reproduction. Today's color films are variously refined versions of Ducos du Hauron's original tripack.

I have touched on only some of the highlights of color photography's history in the 1800's; there are still other innovations more elaborate and extensive. Of the panoply of approaches, few are still practiced. Yet if anniversaries are for remembering, then the history of color photography deserves to be commemorated in this year's celebrations. There is much worthy of remembering in the photographic techniques of the past that may still contribute to the ongoing evolution of photography.

FURTHER READING

HISTORY OF PHOTOGRAPHY. Josef Maria Eder. Translated by Edward Epstean. Columbia University Press, 1945.

HISTORY OF COLOR PHOTOGRAPHY. Joseph S. Friedman. Focal Press, 1968.

HISTORY OF THREE-COLOR PHOTOGRAPHY. E. J. Wall. Focal Press, 1970.

COLOUR PHOTOGRAPHY: THE FIRST HUNDRED YEARS 1840–1940. Brian Coe. Ash & Grant, 1978.

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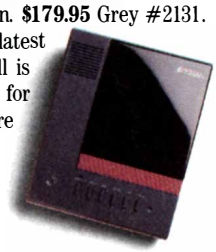

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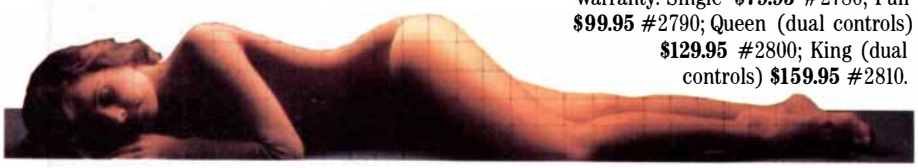

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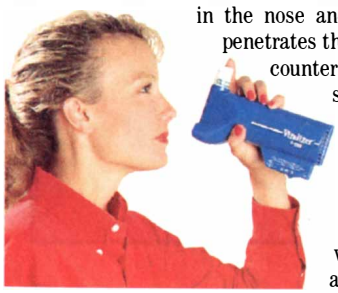

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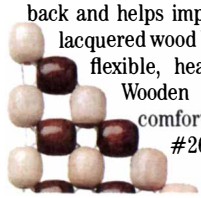

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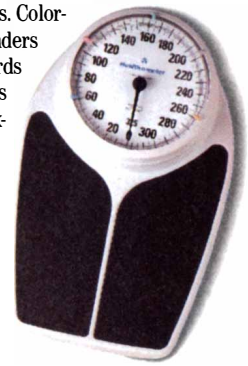

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Manufacturing Intelligence

If it's so smart, why ain't it rich?

Smart factories, tractable plastics, cutthroat economists, a deficit of dismay

In the early 1980's expert systems followed on the heels of numerically controlled machine tools, robotics and "manufacturing resource planning" as the latest key to more efficient factories. Ultrasophisticated, artificially intelligent computer programs based on rules and logical inference would guide cooperating robots, analyze machine breakdowns in a flash and respond to anomalies such as missing parts. Companies would be able to fine-tune assembly lines to meet demand and even reconfigure them to make new products.

It hasn't happened. The growth of artificial intelligence (AI) in factories has been only "moderate," says Mark S. Fox, head of Carnegie-Mellon University's robotics laboratory. Although the number of commercial projects being developed has grown from perhaps 500 worldwide in 1985 to several thousand today, that remains a tiny fraction of the potential applications.

About half of the money spent on AI so far has produced nothing but "very expensive conference papers," Karl Kempf of Intel said at the Eleventh International Joint Conference on Artificial Intelligence in August. A few AI programs have made headlines, but almost all of the intelligence on the factory floor still resides in the heads of workers and engineers. Why?

Fox suggests that corporate managers are the bottleneck: until they understand what AI is all about, intelligent manufacturing will languish. E. J. van de Kraats of Shell Research argues instead that AI has simply had to compete for investment dollars with other technologies, such as high-speed computing, mathematical analysis and materials science. AI's slow adoption represents not its own failure but a vote of confidence in something else, van de Kraats contends. Kempf agrees: managers are "busy but not stupid." There is an inherent conservatism in manufacturing, he says; people "have been snake-oiled before." AI must prove its worth before it finds wide acceptance.

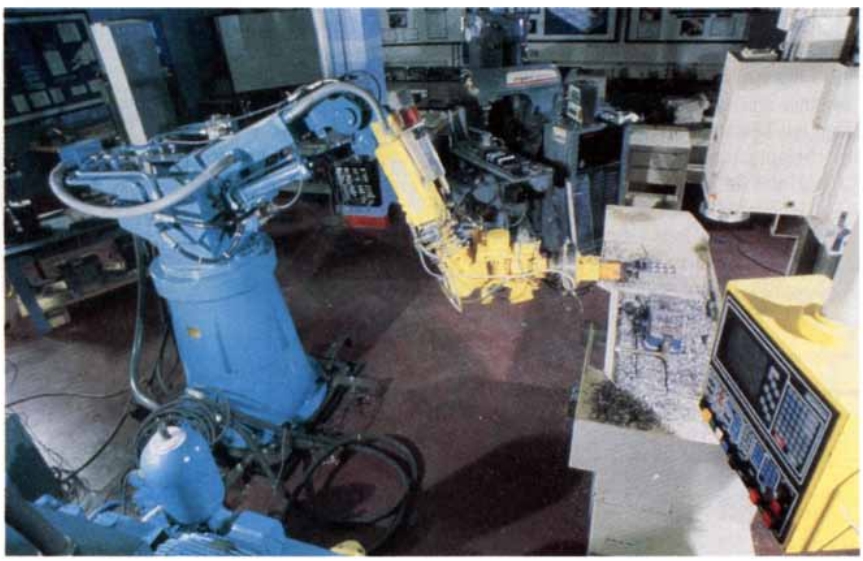
Paradoxically, much of the success artificial intelligence has had in manufacturing has been away from the factory floor. Frank S. Lynch of the Digital Equipment Corporation observes that workers at Digital developing knowledge-based systems for in-house use make a point of not trying to apply AI to the actual manufacturing and assembly of computers. Instead they exploit the technology to streamline paperwork and reduce the indirect labor required to sell, produce and deliver each machine.

Digital scored its first success in AI about 10 years ago with XCON, a program that used rules and logical inference to configure its VAX computers for installation—to ensure that each order included the right cables, power supplies and other parts and that the computer cabinets could hold the components. Since then XCON has been expanded to deal with a wider range of Digital's computer products, and other programs have been added to advise salespeople and customers and to link marketing and production. The company estimates it spends less than $30 million on AI every year but saves about $140 million as a result.

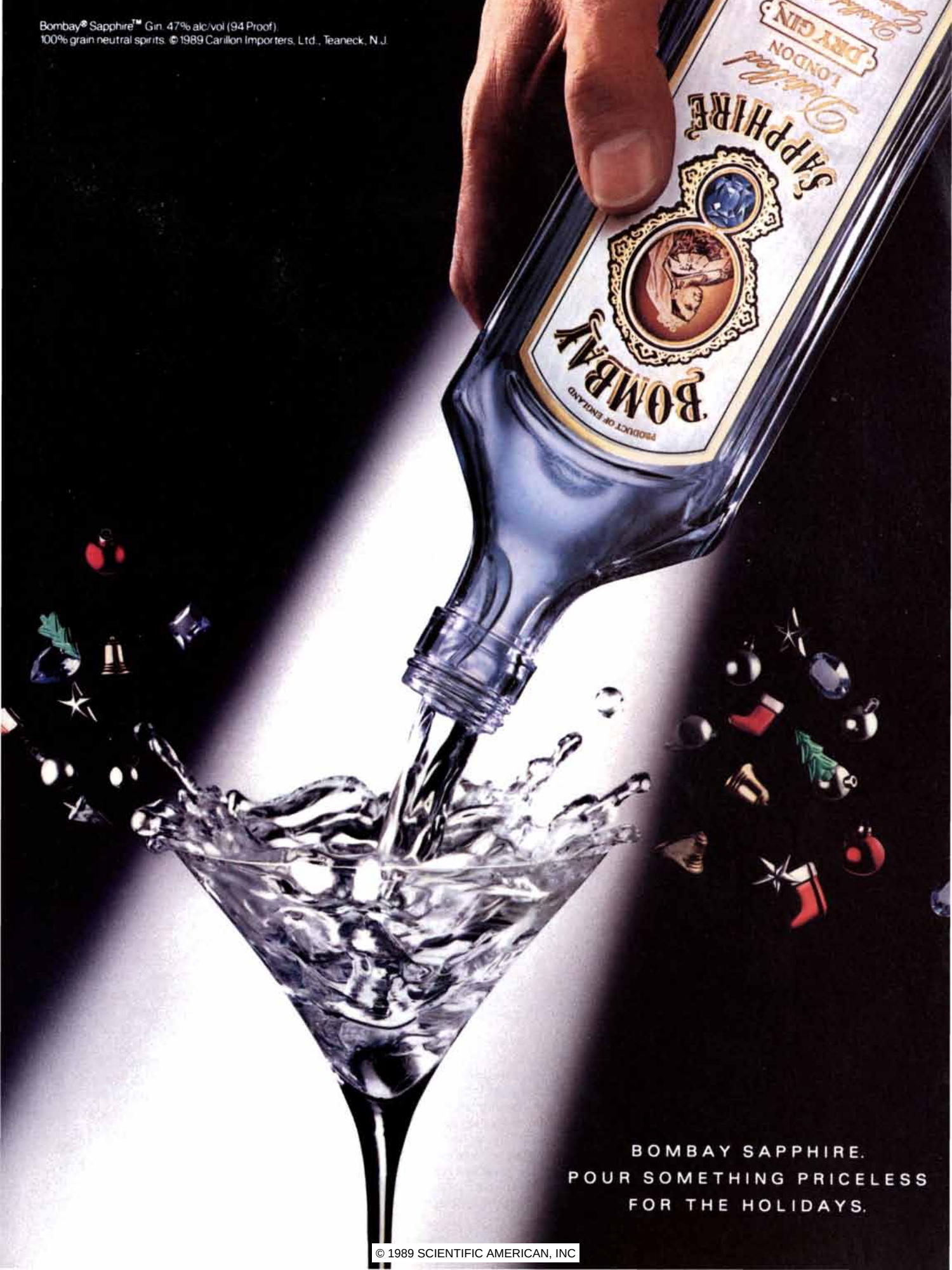
Indeed, current AI programs—expert systems, knowledge-based systems and so on—appear to do best when they are left out of the business of actually stamping, cutting or forging metal or otherwise directly handling parts. Encoding real-world information (the sound of a lathe cutting metal or the millisecond-by-millisecond position of a robot arm) in a compact, machine-readable form is difficult. Knowledge-based programs deal more easily with symbolic information (production schedules or the symptoms of a machine breakdown).

One suitable task is job-shop scheduling: timing the flow of work to machines in a factory so as to minimize both the time required to manufacture items and the time during which machines stand idle. Scheduling has been an important and visible success for AI in manufacturing, Fox says, ever since one of the first scheduling programs doubled the efficiency of a manufacturing facility for printed-wiring boards the day it was installed.

Yet such advances are not without



***ROBOTS THAT WORK ON ASSEMBLY LINES** were once at the center of artificial-intelligence research; now simple robot control is done by conventional software while complex tasks are still beyond the capabilities of most artificial-intelligence systems. AI workers focus on managerial tasks, such as scheduling the flow of parts through a factory. Photograph courtesy of Carnegie-Mellon University.*



cost. When General Electric installed a pioneering scheduling system in one of its jet-engine plants, it first had to revamp the factory. GE began by installing a custom-built communications network so the scheduling program could determine the status of the machines it was to regulate.

Kempf identifies three classes of potential AI applications. Relatively simple programs can codify the knowledge required for reasoning tasks that people already do well, such as troubleshooting relatively simple equipment. These programs can help novice workers perform at near-expert levels and help save experts from drudgery. AI programs can also be invaluable in jobs that people understand well but solve poorly (such as scheduling) because of the volume of information involved or the rate at which it comes in. Intelligent programs for a third class of problems—those that people do not know how to solve—are bound to fail, Kempf says. AI developers should avoid problems in this category (computer-integrated manufacturing is one) at all costs, he adds.

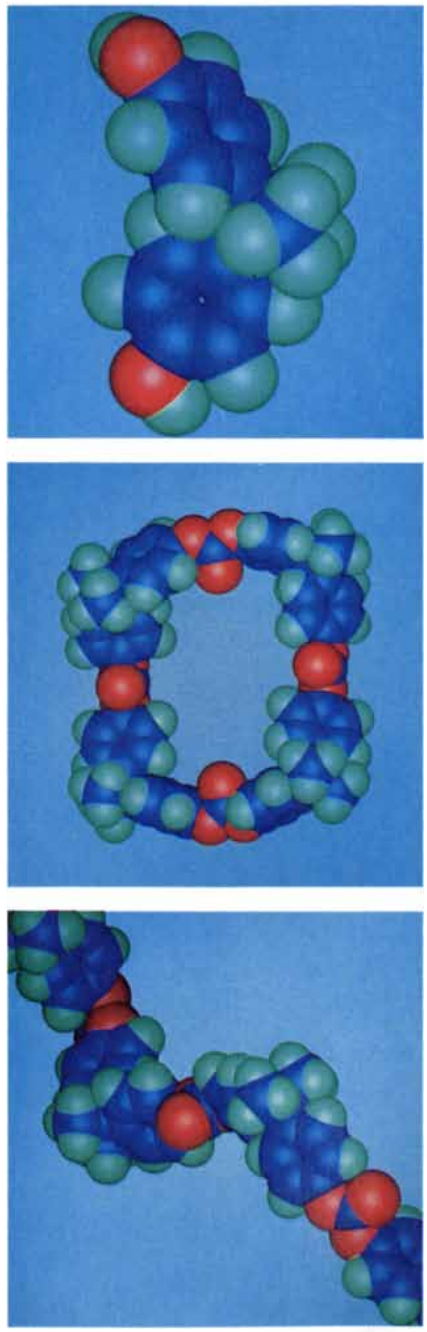
Developing an artificial-intelligence algorithm accounts for only about one fourth of the effort required to build a working system, however. The non-AI parts take more work than anyone imagines, Kempf says: analyzing the task at hand thoroughly and then building a system that ordinary people can use and extend.

Van de Kraats recalls a knowledge-based system for oil-reservoir engineering that Shell introduced with great fanfare and then junked within a year. The problem: the program addressed the oil-drilling and recovery issues that the company's reservoir specialists considered most interesting but could not solve the simpler problems that occurred in the field.

Developers of artificially intelligent systems should spend far more effort on choosing and analyzing their tasks, Kempf says. "AI people want to do the fun part and then walk away," he comments. "That's not going to work."

Lynch concurs, adding that artificial intelligence is only one tool for automating manufacturing operations. Today AI systems are regularly designed to dip into corporate data bases for information they need and to deliver their conclusions to conventional software. (This process can be difficult; Kempf points to one AI project for flexible manufacturing that was scrapped because it would have taken workers two years to write programs for extracting data from conventional computers.)

The evolution of AI from hot new panacea for manufacturing to everyday tool has been mirrored in the fortunes of firms selling artificial intelligence, Fox notes. Once the market was crowded with firms selling tools for building expert systems, but only a few of those companies survive. Consulting and engineering firms are now profiting by tailoring programs to specific jobs. "The real issue," Fox says, "is solving problems." —*Paul Wallich*



MOLECULAR RING* (middle) *is the basic component of a new, more tractable form of polycarbonate. The rings, formed from the polycarbonate monomer* (top), *reduce the plastic's viscosity so that the resin can permeate the reinforcing fibers of a composite. The rings are then opened and latched together, forming the polymer chains* (bottom) *that give the plastic its toughness. Illustrations courtesy of General Electric.

Pourable Plastics

They may open the way to new composite materials

Composites, consisting of strong fibers that are embedded in a cohesive matrix, are lightweight and tough—but have been frustratingly hard to shape. Now researchers at General Electric have developed a technique for turning some plastic resins that are viscous at high temperatures into liquids that flow as easily as motor oil. The result is a plastic that flows readily into the interstices of a fibrous mesh to form a composite material that can be reshaped easily with heat.

Composites can be attractive alternatives to heavier materials such as metal in industrial applications, says John W. Verbicky, a manager at the GE Research and Development Center. Prior to GE's work, composite makers working with plastic faced sharp constraints in their choice of a binder material. They could use a "thermoset" plastic, such as epoxy, to wet the fibers; once the resin had hardened, however, the composite could not be reshaped or remelted.

Ordinary thermoplastics, which become malleable when they are heated, are too viscous to combine well with fibers. The only way to skirt this problem has been to dilute a thermoplastic extensively and then evaporate the solvent. Yet it is a costly alternative that works for only about half of all thermoplastics.

The technique for making thermoplastics more tractable should help GE find wider markets for its plastic resins and products. Every year, for example, the company reportedly churns out more than 400 million pounds of polycarbonate, a tough thermoplastic found in windows, electronic devices and sporting equipment. So when Daniel J. Brunelle, an organic chemist from the R&D center at GE, visited his colleagues in the company's Mt. Vernon, Ind., facility, he was handed a request: make a polycarbonate that flows easily when melted so that it can be incorporated into composites.

The viscosity of a material reflects its molecular structure. Polycarbonates consist of molecular units (monomers) linked together in long chains

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(polymers). The heavy polymers give the material its desirable characteristics—durability and strength—but they also can tangle easily, turning the resin viscous. To make the material flow readily, Brunelle knew he only had to transform the monomers into rings that could slip past one another. Within about four months he had identified a reaction that transformed about 70 percent of a small sample of a polycarbonate into molecular rings.

In the past scientists had found ways of making rings of this type with 20 or 30 members, or atoms, Verbicky says. But such small rings are feasible only for plastics having flexible monomers that can be bent easily. Polycarbonates, in contrast, have stiff, rigid monomers. Consequently, Verbicky says they "wanted 24 to 240 members [per ring] in high concentration."

Making rings was only a starting point, Brunelle recalls. To be useful, the final plastic had to have the same properties as conventional polycarbonates. But "the rings don't spontaneously become polymers," observes Thomas L. Evans, a polymer chemist who worked on the project. The researchers needed a second reaction to induce the long chains of polymers to form. The material could then become viscous and eventually harden.

Over the past few years the GE researchers developed many catalysts for regulating the speed and timing of polymerization. Evans says catalysts have been found that change about 99 percent of the molecular rings into polymers from anywhere between 30 seconds and half an hour. Yet working with large batches of material is still hard, GE researchers concede.

This "cyclization chemistry" works for a variety of plastics, Verbicky says. Researchers have successfully applied the technique to almost a dozen materials other than polycarbonates. All are "condensation polymers," which lose light molecules such as water when they are formed.

Although GE officially introduced its pourable-plastic technology at a meeting of the American Chemical Society in early September, Verbicky emphasizes that it is not ready to roll into production. GE has yet to develop a business strategy for commercializing the technology, he says. "Considering this is research and development, this [lack of business strategy] is typical," he says. "Everybody's got ideas on where we should go," he says, "but there's still a lot of work to do" to bring the manufacturing process up to speed. —*Elizabeth Corcoran*

Economic Intrigue

Murder mysteries served up by an invisible hand

Pausing briefly to kiss his mistress good-bye, the president's chief of staff, Admiral Harry Green, leaves her Georgetown retreat and sets off for the centers of power. She picks up the phone and calls a prominent economist. Yes, she says, the admiral did decide the nation's economic fate over breakfast. Along with coffee, the lady had served up a convincing argument that increasing taxes would lead to inflation.

A Washington scandal? Not this time. Instead it is a scene from *In the Long Run We Are All Dead,* an economics murder mystery by Murray Wolfson, an economist at California State University at Fullerton, and Vincent Buranelli, a writer. A handful of such books have surfaced since "Marshall Jevons" penned the earliest economics mystery, *Murder at the Margin,* in 1976. (Marshall Jevons is the pseudonym of economists Kenneth G. Elzinga of the University of Virginia and William Breit of Trinity University in San Antonio.) Some are classic whodunit's starring an economist; others are disguised texts meant to coax college freshmen through the tedium of economic theory 101. They also offer intriguing glimpses of how economists view themselves and their world—and a helping of self-parody as well.

The economists of *In the Long Run* are brilliant, articulate and almost totally baffling. Called in to advise the president during an economic crisis, they leave him flummoxed. "I can't tell what they're fighting about," he complains to his chief of staff. Green is charged with devising a program.

As Admiral Green shuttles from one economist to another, enduring a Berlitz course in macroeconomic theory, dogmas clash. The Keynesians worry about the short-term hardships of unemployment. The monetarists argue that the forces of the market will reach equilibrium, given a little time. And hard-line supply-siders and rational-expectations economists pop up from time to time, serving to illustrate that there are far more than two ways to run an economy.

Just before Green is supposed to announce his economic policy, he is fatally shot. Here the book's didactic program emerges: to identify who would gain the most from the admiral's death, the reader has to deduce the slain official's policy choice.

In *The Fatal Equilibrium,* the second Marshall Jevons novel, Harvard economist Henry Spearman (who sounds suspiciously like Milton Friedman) obsessively points out the economic rationale for every twitch of life. When an ambitious young economics professor who was refused tenure at Harvard University is found dead, Spearman's uncompromising economic theory comes to the rescue.

"Conceptually [Spearman] realized that an individual took his life when the discounted lifetime utility remaining to him was negative. But for a young person who had so much potential satisfaction to be enjoyed by living, such an act would be irrational," the narrator explains. Spearman (and the astute reader) solves the murder by studying a table of data in a book while seated in a comfortable chair on the *Queen Elizabeth 2.* —*E.C.*

THE ANALYTICAL ECONOMIST

The imbalance of payments

"The country, indeed, which has not capital sufficient for all those three purposes [trade, farming and manufacturing] has not arrived at that degree of opulence for which it seems naturally destined."

—ADAM SMITH,
The Wealth of Nations

One look at the U.S. balance of payments, the difference between imports and exports, might leave Adam Smith shaking his head. Last year, continuing a trend that began in the early 1980's, the U.S. imported nearly $112 billion more in goods than it exported. More recently the traditionally robust services sector of the trade account also ran up a deficit. Yet few Americans doubt that the U.S. is among the most opulent countries.

National economies have become distressingly complex since Smith first published *An Inquiry into the Nature and Causes of the Wealth of Nations* in 1776. Although Smith might have been quick to condemn deficit accounts, economists today disagree about whether the U.S. trade imbalance is cause for concern. "I don't look at these [trade-deficit numbers] with great fear," says Robert Eisner, an economist at Northwestern University. But others worry that the deficits, fi-

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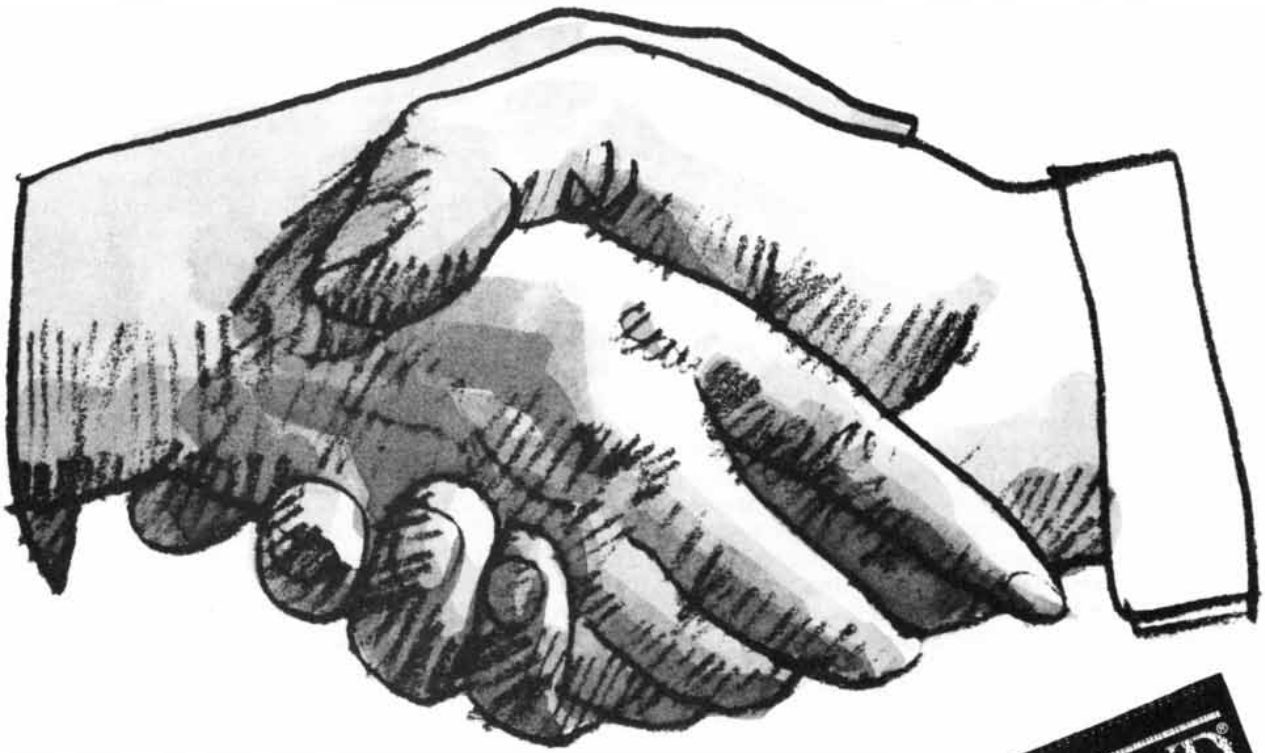

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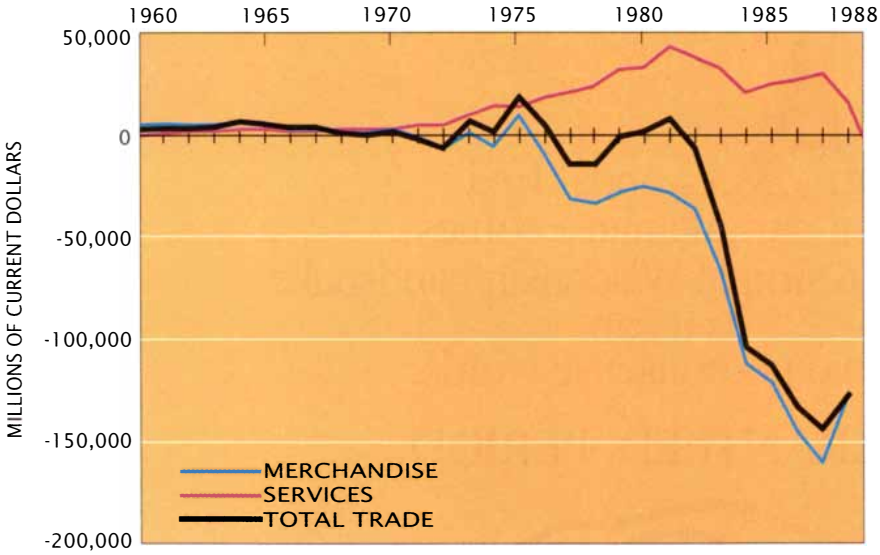

BALANCE OF CURRENT ACCOUNT shows that the U.S. has run an overall deficit* (black) *since 1982 even though trade in merchandise* (blue) *has shown a deficit since 1976. (The current-account balance is the sum of U.S. imports plus exports, along with "unilateral transfers.") The services sector of the account* (red) *ran a deficit in the second quarter of 1989. Source:* Survey of Current Business, *U.S. Bureau of Economic Analysis.

nanced by an influx of capital from abroad, may be draining funds that could otherwise support investments in manufacturing or research.

Perhaps the best measure of the value of the goods and services flowing across U.S. borders is the "current account," which the U.S. Bureau of Economic Analysis tallies every quarter. The account divides transactions into two categories: merchandise and services. The merchandise sector consists of agricultural products, automobiles, consumer goods and so on. The services sector tracks the value of interest payments and other financial transactions, fees for legal and technical services, royalty payments and travel expenditures. (A few items are trapped between categories and so are not fully included in the accounts, BEA officials concede. Computer software, for example, is classified as merchandise, and so exporters need report only the value of the physical product—say, 50 cents for the floppy disk itself. The BEA is trying to revise reporting rules to remedy this glitch.)

When the merchandise sector of the U.S. current account plunged into deficit in 1976, the cause was clear: skyrocketing prices for imported oil. Yet soon U.S. manufacturers were also losing business. By 1982 the entire current account had been dragged into the red. The deficit exceeded $140 billion in 1987 but decreased somewhat in 1988.

The causes of the deficit in the services sector, recorded in the second quarter of this year, are subtler. The shortfall, the first the account has suffered since 1958, is puny—a mere $176 million. It says little about the health of the U.S. banking industry; instead the deficit means that the nation is paying more interest and dividends to foreigners holding U.S. investments—from corporate stocks to treasury bonds—than its own investors are earning abroad. In the second quarter of 1989, this difference was about $5 billion. (Surpluses in other activities, notably tourism, kept the net services-sector deficit small.)

Experts are divided about the significance of these various trade deficits. As the January, 1989, *Economic Report of the President* observed: "In some cases a current account deficit signals an inherent problem in economic policies or in underlying economic conditions. In other cases a current account deficit reflects a healthy, growing economy where citizens are borrowing in order to invest and consume in anticipation of a robust future."

Which is it? Among the most sanguine are economists who helped to draw up economic policies during the Reagan Administration, including Paul Craig Roberts, now at the Center for Strategic and International Studies. "In a world of international capital markets, if you're a net debtor, you're a favored place of investment," Roberts says. Debt, consequently, can be "just a sign of your success," he adds.

Roberts's argument hinges on his belief that direct investment in the U.S.—that is, money spent on manufacturing plants, research and so on—has increased as the U.S. trade imbalance has grown. Growth in real, gross investment over the past few years has been "unprecedented," Roberts says. Other economists quarrel with his conclusion, pointing out that net investment (gross investment minus the value of old equipment or plants that are being retired) has declined.

Eisner says that even if the U.S. ran a trade deficit of $150 billion for five consecutive years and paid 4 percent real interest on the resulting debt, annual interest payments would barely be half a percent of the U.S. gross national product. He argues that this is a "trivial" burden for future generations. Policies that aim to slow U.S. purchases as an antidote for the trade imbalance pose a greater threat by risking recession, he says. Eisner instead looks for ways to improve the export side of the accounts by lowering interest rates and by allowing the value of the dollar to fall.

Making the dollar cheaper with respect to other currencies should encourage foreign countries to buy more U.S. products and dampen U.S. enthusiasm for imports, Eisner says. Moreover, lower interest rates should spur U.S. companies to invest at home (although foreign investment may fall). Eisner thinks that the increase in domestic savings and investment as well as the gains in exports should cover any losses in foreign investment.

The Congressional Budget Office, however, takes a grimmer view of the current-account deficit. A recent CBO report on the account argues that foreign loans are primarily feeding consumption, not financing investments. In effect, says Frederick Ribe, who co-directed the CBO study, the account deficit reflects a U.S. spending spree—and the resulting decline in domestic savings and investment. "If we could increase the savings of households, that would be great," he says. But because changing individual habits is difficult, the government should aim to curb its own spending, he adds.

The debates continue. Increasingly there are calls for boosting national savings. Of this, Adam Smith would have most heartily approved: "If the prodigality of some was not compensated by the frugality of others, the conduct of every prodigal, by feeding the idle with the bread of the industrious, tends not only to beggar himself, but to impoverish his country."

—Elizabeth Corcoran and Paul Wallich

Napoleon Bonaparte

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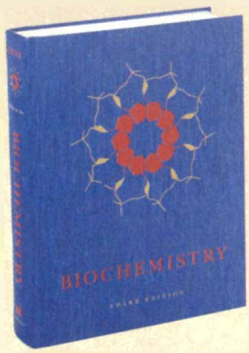

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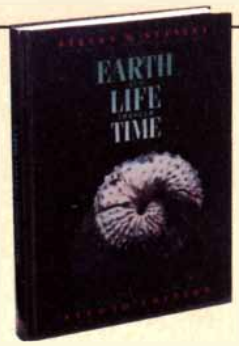

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Microclusters

Small aggregates of atoms constitute a distinct phase of matter. Their chemistry, at once highly reactive and selective, has possible applications in catalysis, optics and electronics

by Michael A. Duncan and Dennis H. Rouvray

Divide and subdivide a solid and the traits of its solidity fade away one by one, like the features of the Cheshire cat, to be replaced by characteristics that are not those of liquids or gases. They belong instead to a new phase of matter, the microcluster.

Microclusters consist of tiny aggregates comprising from two to several hundred atoms. They pose questions that lie at the heart of solid-state physics and chemistry and the related field of materials science: How small must an aggregate of particles become before the character of the substance they once formed is lost? How might the atoms reconfigure themselves if freed from the influence of the matter that surrounds them? If the substance is a metal, how small must its cluster of atoms be to avoid the characteristic sharing of free electrons that underlies conductivity? Do growing clusters proceed gradually from one stable structure to another, largely through the simple addition of atoms, or do they undergo radical transformations as they grow?

MICHAEL A. DUNCAN and DENNIS H. ROUVRAY are both in the department of chemistry at the University of Georgia. Duncan, an associate professor, participated in the initial experiments at Rice University to produce metal clusters by laser vaporization. He received his doctorate at Rice in 1981, then studied atmospheric chemistry at the Joint Institute for Laboratory Astrophysics in Boulder, Colo., on a fellowship sponsored by the National Bureau of Standards. He joined the Georgia faculty in 1983. Rouvray, an associate research scientist, is a graduate of the Imperial College of Science, Technology and Medicine, University of London. He became interested in developing mathematical models to predict chemical behavior 16 years ago at the University of Oxford and is now the editor of the *Journal of Mathematical Chemistry*. This is his second article for SCIENTIFIC AMERICAN.

Many cluster properties are determined by the fact that a cluster is mostly surface. A closely packed cluster of 20 atoms has only one atom in its interior; a cluster made up of 100 atoms may have only 20. Other properties stem from clusters' unfilled electronic bonding capability, which leaves them "naked" and hence extremely reactive. This reactivity makes them effective tools for the study of the solid state and, potentially, for such industrial processes as the growing of crystals, selective chemical catalysis and the creation of entirely new materials with made-to-order electronic, magnetic and optical properties. Such materials, in turn, could enhance the performance of products as diverse as lasers, photographic films, electrosensitive phosphors, magnetic disks and supercomputers.

The potential importance of clusters was recognized long before they could be prepared in the laboratory. Perhaps the earliest reference to clusters was made in 1661 by the English chemist Robert Boyle, in his *Sceptical Chymist,* which speaks of "minute masses or clusters [that] were not easily dissipable into such particles as compos'd them." Because of their microscopic size and extreme chemical reactivity, clusters could not be investigated with the techniques of traditional surface chemistry or even synthesized in the laboratory, until the 1950's.

In these early efforts, an oven was used to vaporize a metal, which was then precipitated as clusters on a substrate. Alkali metals such as sodium and potassium were tried first, at about 1,000 degrees Celsius; metals with higher melting and vaporizing points were studied later. But the metals with the higher transition temperatures could usually be made in clusters of only three to five atoms. This made it impossible to determine how many atoms were required for the emergence of properties more like a solid and less like a cluster.

A more generally effective procedure, in which a solid metal is vaporized with a laser, was devised in 1981 by two groups, one led by Richard E. Smalley of Rice University, the other by Vladimir E. Bondybey of AT&T Bell Laboratories. One of us (Duncan) was a doctoral student under Smalley at the time and was therefore one of the first to observe laser-generated clusters. The technique has been refined considerably and can now produce clusters of up to 100 or more atoms composed of virtually any substance that can exist as a solid. Clusters have also been made of mixed materials.

The process begins when pulsed laser light is tightly focused on a metal bar or disk that sits in a channel, evaporating its atoms into an extremely hot plasma. A gust of helium, released previously into the channel, cools the vapor so that it condenses and forms clusters of varying sizes. It sweeps the clusters along into an evacuated chamber, where the pressure differential causes the spray to expand supersonically. Collisions that take place during this expansion cool the clusters to a temperature near absolute zero, stabilizing them for further study.

The center of the spray passes through an aperture on the opposite side of the chamber. The resulting beam is then irradiated by an ultraviolet laser energetic enough to strip electrons from the clusters. Removal of the electrons imparts a positive charge to the clusters, so that they can be accelerated in an electric field of given strength over a path of known length. This instrument, a time-of-flight mass spectrometer, sorts the clusters into different packets, with the heaviest species (those with the most atoms) at one extreme and the lightest ones at the other.

Subtle clues to cluster geometry can be gleaned from the distribution

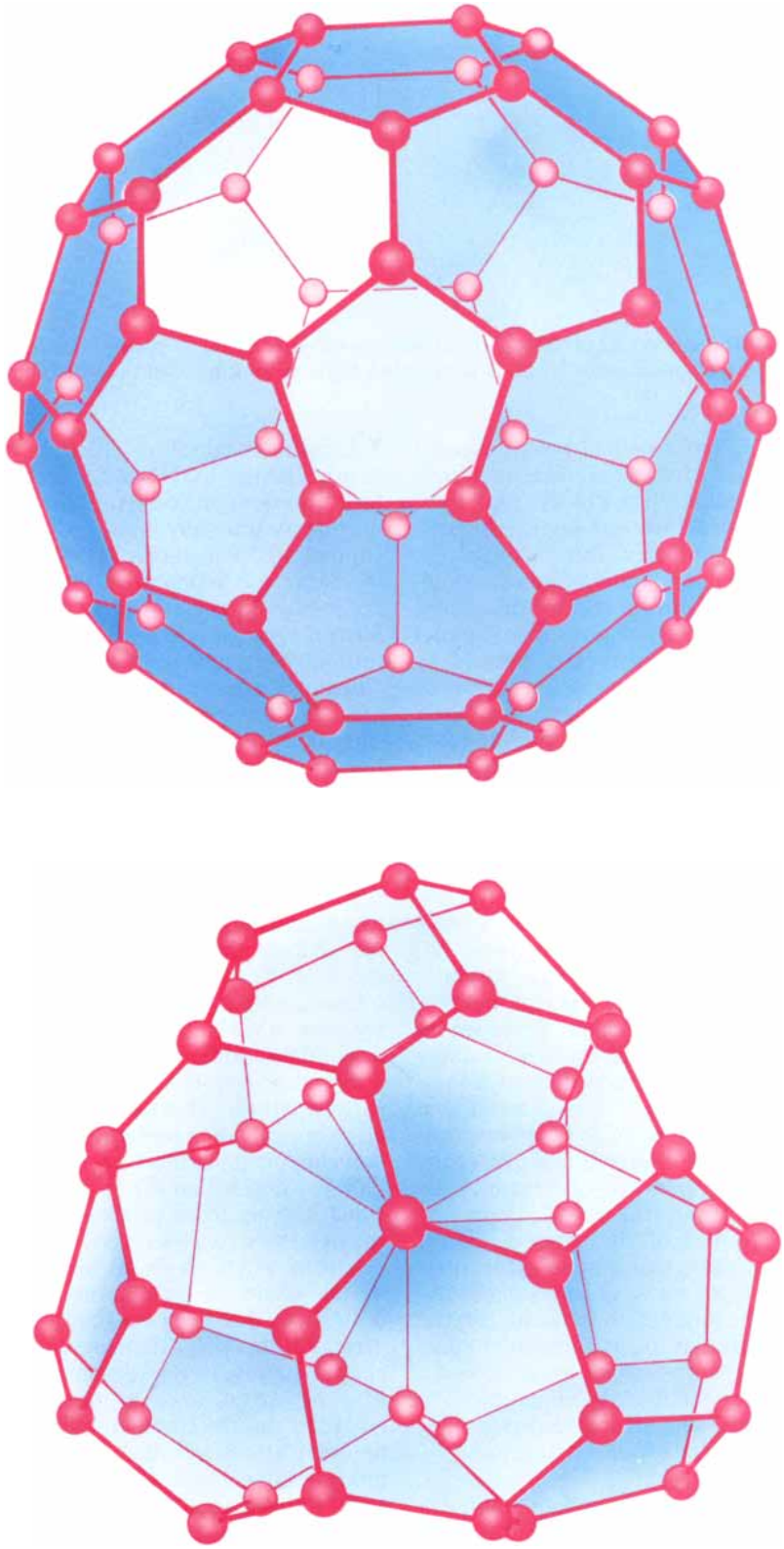
of cluster sizes. The sizes that appear particularly often are thought to be associated with particularly stable configurations. Such cluster species, which appear as spikes when the number of atoms is graphed, are called magic numbers (by analogy with the quantum model of atomic nuclei, in which certain combinations of protons and neutrons are allowed and others are not).

Magic numbers may sometimes be useful predictors of geometry. Consider, for a moment, the mass spectrum of lead, in which seven- and 10-atom clusters are found at twice the frequency of neighboring species, or cluster sizes. Each of these two forms is believed to have a structure that is a precursor to packing patterns seen in solid lead. The 10-atom formation is a key element in the diamond lattice structure, in which chemical bonds act in fourfold symmetry to keep atoms fixed in relatively open networks. Seven-atom clusters may form pentagonal bipyramids, with five atoms in a plane and the sixth and seventh above and below it, respectively. These configurations are the first building blocks of cubic close-packing, a familiar pattern that is seen in solid lead.

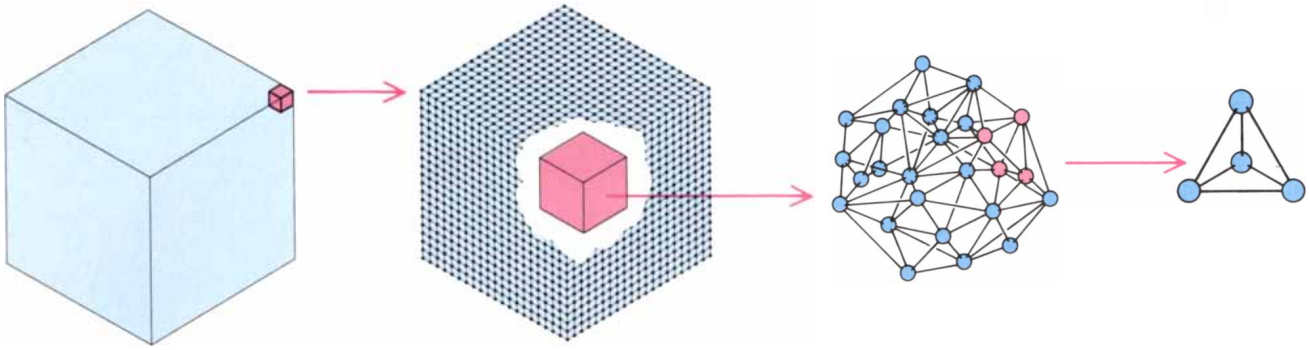
Pentagonal bipyramids can easily accept six more atoms to form icosahedrons—nearly spherical figures that are the most stable way to close-pack a cluster. Their pattern differs only slightly from that found in a close-packed solid.

Another example of how structures are inferred from mass spectral data is seen in the case of 14-atom lead clusters, which occur at only one third the frequency of cluster sizes. That phenomenon can be explained by the relative stability ascribed by theory to the 13-atom icosahedral cluster, a stability that makes it difficult for 14 atoms to cohere. They tend, instead, to form a 13-atom cluster, leaving one atom free.

We became interested in applying magic numbers to the study of clusters made of mixed metals that form alloys in the solid state. In our research at the University of Georgia we discovered that clusters of lead mixed with antimony—both members of the main-group metals—had elemental ratios that diverged unexpectedly from those found in the alloy. Two mass peaks indicated the disproportionate presence of one ion with two lead and three antimony atoms and another ion with four atoms of lead and five of antimony. It struck us that such



PROPOSED STRUCTURES for clusters of 60 carbon atoms (*top*) and of 45 silicon atoms (*bottom*) should in theory have great stability, but their existence has not yet been proved. The soccer-ball shape suggested for carbon 60, a species found in sooty hydrocarbon flames and perhaps in interstellar dust, is called buckminsterfullerene, after the inventor of the geodesic dome. The knobbier symmetry recently proposed for silicon 45 could be derived from the same kinds of polygonal elements.



SOLID SHRINKS TO A CLUSTER without passing through a well-defined transition point. Various properties, such as melting point, ionization potential and geometry, change from those of the solid state to those of a microcluster at different stages.

bonding patterns had been observed in a class of stable molecules known to inorganic chemists as Zintl ions, whose structure was known from X-ray crystallography. Our microclusters (and a related family of gas-phase alloy clusters, in which the constituent particles are themselves mixed molecules of different metals) seemed to have stability patterns like those of Zintl ions, which suggests that their structures are the same: five atoms in a trigonal bipyramid (with six triangular faces) or nine atoms in a capped, square antiprism (with 12 triangular faces and one square face).

Perhaps most appealing of all for their mathematical beauty are the two structures that have been proposed for cluster species of carbon and silicon, respectively. Although the putative structures have the great theoretical stability that would be expected for the species, which are remarkably inert, no conclusive evidence for their existence has yet been adduced. The carbon structure holds 60 atoms in an open cage of hexagons and pentagons resembling a soccer ball. Smalley calls it "buckminsterfullerene," in honor of the inventor of the geodesic dome, and suggests that it may be the interstellar dust whose absorption of radiation is thought to account for the observed gap in the ultraviolet spectrum. Recently Smalley has proposed a still more complex shape, also faced in hexagonal and pentagonal rings, for the cluster of 45 silicon atoms.

It may seem natural to impute a kind of protosolidity to tiny clusters of a material that would be a solid if only there were enough of it. Indeed, this imputation appears to be valid for those metals whose cluster-packing structure closely resembles that found in bulk. But in other cases such an approach presumes more than the evidence will bear.

A counterexample is seen in the case of clusters that form isomers, different molecular configurations that may be assumed by a given chemical compound. Each isomer is locally stable because it economizes on energy, but it may shift to a different isomeric form if enough energy is introduced through heating. One example of such "fluxional" clusters is the sodium trimer: the three atoms form an isosceles triangle whose unique angle continually bounces from one vertex to the other even at temperatures just above absolute zero. Because their shape is not fixed on a microscopic level, fluxional clusters should perhaps be regarded more as liquid droplets than as solid particles, to the extent that such words have meaning on this level.

One can learn about cluster geometry from other kinds of data. Electronic configurations, for example, have a direct bearing on the frequency of various cluster sizes because specific electronic bonding patterns make certain clusters particularly stable. These patterns depend on the orbitals from which the electrons originate and on the degree of freedom enjoyed by the electrons. When electrons are shared by the whole cluster in a delocalized pattern, so that negative charge is no greater at one point than another, the cluster may take on certain aspects of solid metal, such as conductivity. When the electrons are all tightly bound to atoms, the clusters resemble discrete molecules.

Delocalized electrons are found in clusters of such alkaline metals as sodium and potassium and in such coinage metals as copper and silver. Both classes of metal atoms have a single electron in the *s* orbital that is then dispersed, or shared, among all the atoms in a given cluster. As the number of atoms in the cluster rises, the atomic orbitals combine to form molecular orbitals containing all the cluster's electrons; molecular orbitals then give way gradually to "bands," or energy states, akin to those of a solid. These metals show cluster frequency peaks at the sizes that are predicted by a quantum model for a spherically symmetrical body with shared electrons. The predictions closely resemble magic numbers derived from the quantum model of atomic nuclei and are similar in some respects to the electron shells calculated for the hydrogen atom.

As Walter D. Knight, Marvin L. Cohen and their co-workers at the University of California at Berkeley have discovered, abundance peaks coincide with sodium clusters of 8, 20, 40, 58 and 92 atoms. The pattern constitutes compelling evidence that the electrons in these particular cluster systems are delocalized in the same general way as electrons in the corresponding solids. It should be noted, however, that the quantum model that predicts these abundance peaks cannot be translated to the solid state, which, unlike the cluster, is not a spherically symmetrical system.

Bonds seem to be more localized in clusters of main-group metals such as lead and antimony. Here the outermost electrons occupy the *p* orbitals, which are spatially more constricted. Only *p* electrons participate in bonding, which gives the bonds more of a local character than is the case for the alkali and coinage metals. These main-group metals tend to be less reactive, which explains why they sometimes form naked clusters when dissolved in liquids, as exemplified by Zintl ions. Zintl ions are particularly stable because their electron shells are closed; thus, it is shown that *p* bonding dominates these electronic systems both in the gas phase and in the condensed phase. It is also believed that *d* bonding is involved in transition metals

such as iron, chromium and nickel, but these metals are harder to model.

Further information about the electronic configuration of clusters can be gleaned from the amount of energy it takes to eject an electron from one of them. In the case of molecules, this energy requirement is called the ionization potential; for solids it is known as the work function. Lone atoms grip their electrons more tightly than clusters of atoms grip shared electrons, which is why most metals have ionization potentials about twice as high as their work functions. If clusters behave like bits of a solid, theory would predict a smooth, inverse relation between cluster size and electron-binding energy that would converge, at the limit, with the work function.

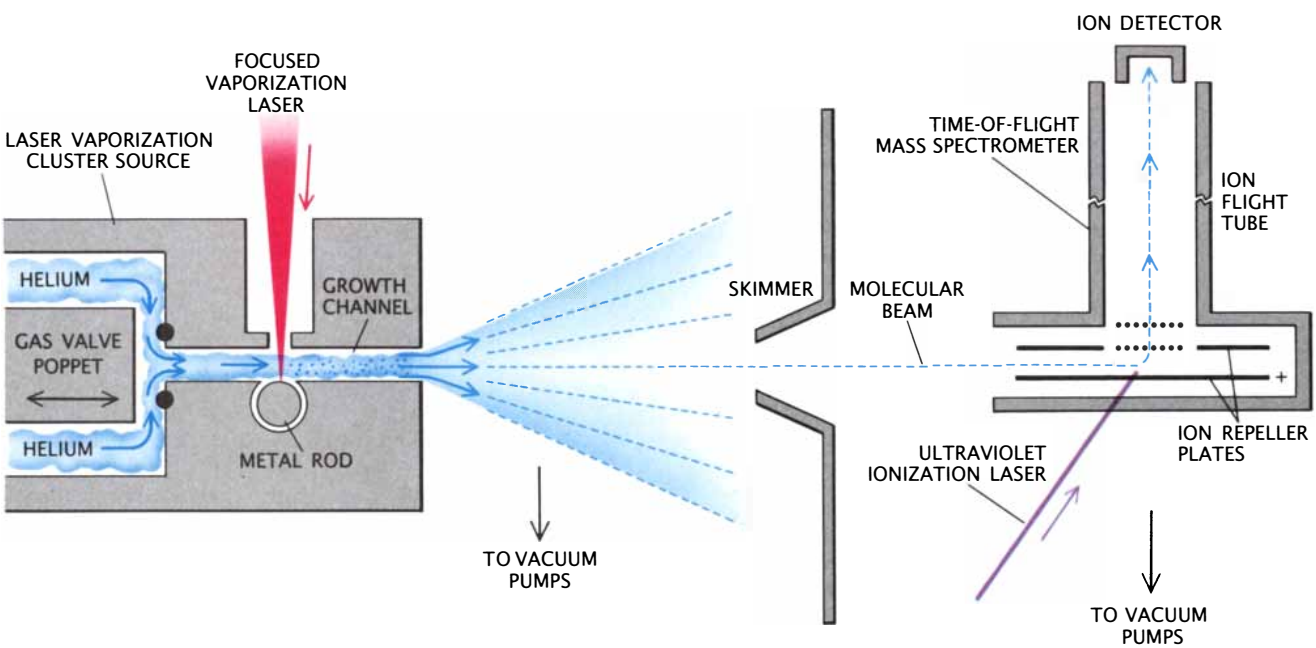
Andrew Kaldor and his colleagues at the Exxon Research and Engineering Company were among the first to determine the ionization potentials of iron and niobium clusters. They irradiated clusters with a tunable ultraviolet laser, beginning with a low-energy frequency and slowly increasing the frequency until they detected the first charged clusters in their spectrometer. They continued to increase the laser's frequency while plotting the distribution of cluster mass, and indeed, they found that as cluster size increased, ionization potential decreased. But the curve was not smooth; certain clusters behaved more like molecules than like bits of a solid. These results, as well as those of other researchers working with different metals, show that in clusters of up to 100 atoms the ionization potential does not converge to the work function. The transition from the cluster phase to the solid phase clearly takes place in larger aggregates.

Other properties of the solid are also thought to emerge in clusters as they grow, although the transition points have rarely been found. Gold clusters supported on a substrate will reach the melting point of solid gold only if they contain 1,000 or more atoms, although it is unclear to what extent the melting point is influenced by the substrate.

Average atomic spacing has been found, through X-ray analysis, to be significantly smaller in two-atom copper clusters than in the solid metal, with the value converging to that of the solid only in clusters containing more than 50 atoms. Yet despite this substantial difference, clusters as small as 14 copper atoms already exhibit the cubic close-packed pattern characteristic of the solid. Orbital energies of copper, aluminum and silicon clusters (calculated from the energy at which electrons are ejected after being knocked loose by radiation of known frequencies) do not converge to the solid pattern even in clusters as large as 40 atoms. Larger clusters have not been examined in this way, in part because it is harder to generate beams containing large numbers of them.

The conclusion to be drawn from these studies is that different physical characteristics of clusters converge with those of solids at different scales. The solid does not emerge all at once, but like the Cheshire cat it fades into view slowly, with the smile appearing first.

How might the surface chemistry of clusters be exploited? One promising application is in industrial catalysis, which is central in petroleum refining (to recover gasoline fractions from heavier distillates), in pollution control (to oxidize or reduce noxious emissions) and in the synthesis of pharmaceuticals. Catalysis begins when the surface of a catalyst adsorbs, say, molecules of carbon monoxide and nitrogen oxide. These molecules then drift to "active sites" where bonds are broken and reformed, say to nitrogen and carbon dioxide. The molecules thus produced are desorbed, and the catalyst is freed to repeat the process. The efficacy of a catalyst depends on its ability to attract reactants strongly enough for adsorption yet hold their end products weakly enough for desorption [see "Bimetallic Catalysts," by John H.



CLUSTER GENERATOR uses a pulsed laser to vaporize metal in a channel swept by helium gas, which cools the vapor so that it condenses to form clusters of varying sizes. The clusters pass into a vacuum where they expand rapidly, cooling to almost absolute zero. They are then ionized by an ultraviolet laser and accelerated in an electric field over a known distance, which sorts the clusters by mass into packets, or abundance peaks. The larger peaks may indicate particularly stable structures.

Sinfelt; SCIENTIFIC AMERICAN, September, 1985]. Critical to the entire process is the active site, the geometry of which remains a tantalizing mystery for most catalytic reactions.

Clusters are ideal laboratories for studying active sites because their unfilled bonding capacity makes them adsorb readily and their small size limits the number of possible adsorption geometries. This constraint also makes them likely sources of highly specific catalysts, which do what they are intended to do and no more. That specificity is highly prized in industry, because many catalysts speed undesired reactions just as effectively as they speed desired ones.

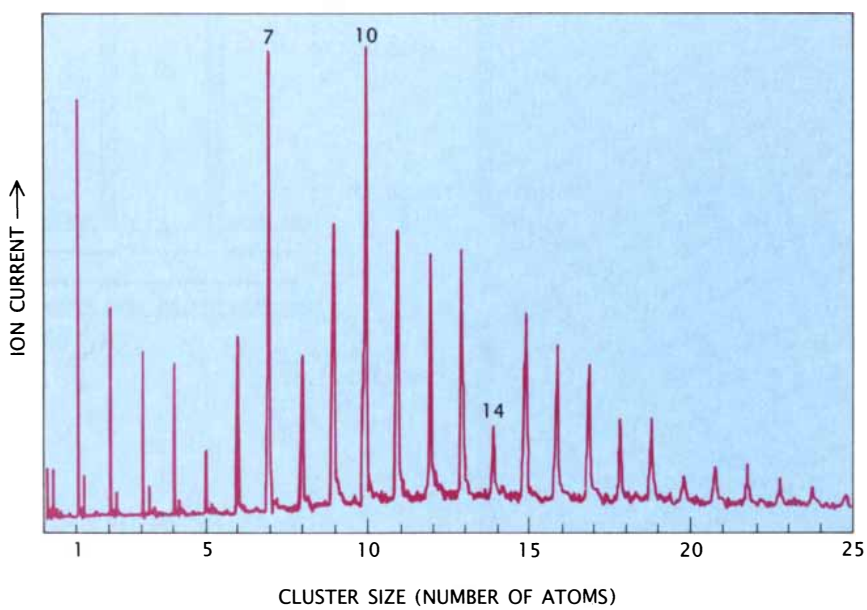
Pioneering studies of cluster catalysis were carried out in the early 1980's by the Smalley and Kaldor groups and by a group under the direction of Stephen J. Riley of Argonne National Laboratory. Cluster catalysis has since been pursued at the University of California at Los Angeles, the University of Utah and several other institutions.

The quest for the made-to-order catalyst began with simple systems in which clusters of iron, cobalt, niobium or aluminum were tested for their efficacy as adsorbents of hydrogen gas. In many cases, certain cluster sizes were immensely more effective than others. Iron, for example, adsorbs hydrogen 1,000 times as fast in 10-atom clusters as it does in 17-atom clusters. Kaldor's group showed that adsorption rates correlate with low ionization potentials, which led to the hypothesis that loosely bound electrons are involved in the adsorption. But later work found that clusters of niobium, for example, adsorbed hydrogen as efficiently when they were ionized as when they were neutral. That is, they worked with or without their outermost electrons, which suggests that cluster catalysis depends on shape as well as on bonds.

The discovery that small changes in cluster size can produce large differences in adsorptive behavior strengthens the notion that clusters represent a distinct phase of matter. It also suggests that specifically adsorptive clusters might be chosen by size and deposited on a substrate for industrial catalysis, whereas unreactive clusters might be selectively deposited to form protective coatings.

Such a capability would represent a great advance, because most industrial catalysts are still the products of a black art. Now, for the first time, the secrets of catalysis are beginning to yield to the tools of cluster science. Scanning tunneling microscopy, a new technique that enables investigators to take a snapshot of individual atoms in a reaction, may play an important role in elucidating the interaction between clusters and their substrate. Migration, the process by which clusters attach to supports and then rearrange themselves, is one phenomenon that may be clarified by scanning tunneling microscopy.

Ernst Schumacher of the University of Bern has approached cluster-substrate interactions differently. He has imprisoned alkali-metal clusters in larger, hollow molecules called zeolite cages, which prevent the clusters from participating in undesired reactions without interfering with their ability to catalyze the polymerization of ethylene to polyethylene [see "Synthetic Zeolites," by George T. Kerr; SCIENTIFIC AMERICAN, July]. The extension of this work to clusters of transition metals promises to provide zeolite catalysts with very specific characteristics.



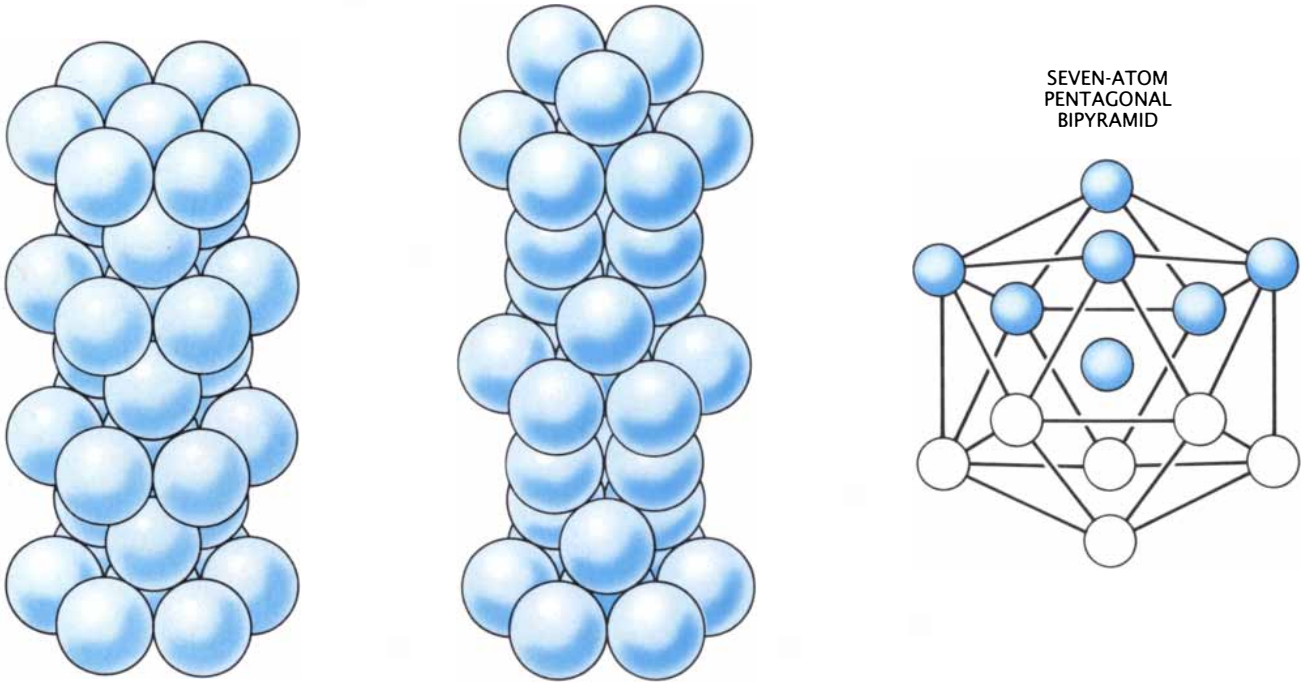
MASS SPECTRUM of lead clusters shows peaks at seven and 10 atoms and a deficit at 14 atoms. These are called magic numbers, as in the quantum model of atomic nuclei.

Further progress in cluster catalysis will depend on the establishment of systematic knowledge. Studies must first correlate particular metals and the sizes of individual particles with specific chemical activities. The next step will be to select the proper clusters and deposit them on suitable substrates, perhaps by stacking them in precise, three-dimensional lattices that may support growing molecules, as enzymes do. If successful, a breakthrough of this type might greatly advance synthetic chemistry.

Thin films of clusters possessing desirable electronic qualities would be of great interest in microelectronics. Here, too, the field is in a preliminary stage of development, but it is possible to envision applications in optical memories, image processing and superconductivity. Given the potential for constructing parts from networks of clusters, it may eventually be possible to make electronic devices on a molecular scale. Ultimately a machine might be designed that could serve as a link between solid-state electronics and biological systems, such as systems of neurons. Such a link might convey data from a television camera to the brain of a blind person.

The first step is to form semiconducting cluster films about 100 angstroms thick. Atoms have already been used to make precise crystalline lattices, in a technique known as molecular-beam epitaxy; if a way can be found to use clusters, instead, as building blocks, then films with more complex structures might be created. The trick is to smash clusters against a substrate with enough force to anneal them but not to destroy them. Isao Yamada's group at the Ion Beam Laboratory at Kyoto University has done this with clusters of various materials, such as aluminum, on substrates such as silicon. The resulting films have shown uniform thickness, optical reflectance and resistance to oxidation.

Recent work in our laboratory indicates that mixtures of metals such as iron and bismuth, which cannot be alloyed in bulk, may be formed into clusters in the gas phase. If such clus-



CLOSE-PACKED lattices in solids, which can be hexagonal (*left*) or cubic (*center*), may guide cluster growth. If they do, one might expect clusters such as the seven-atom pentagonal bipyramid (*shaded at right*) and the 13-atom icosahedron based on it.

ters could be deposited in films, it would be possible to create a new class of alloys exhibiting valuable hybrid qualities.

Efforts are now being made to deposit clusters in thin films that could function as superconductors. We have recently prepared clusters of yttrium-barium copper oxide, which may be able to form such films. The research, however, is still in a nascent stage, and even the most valuable properties of such films cannot yet be exploited commercially because size-selected clusters cannot be produced in quantity.

Clusters of certain metals have a great ability to absorb light. This is caused by the extreme density of their valence electrons, their high surface-to-volume ratio (which puts many electrons near the surface) and the ease with which their electron clouds can be distorted, or polarized. It is possible to predict, on the basis of a given cluster's chemistry and size, which wavelengths of light it will absorb. Such characteristic wavelengths have been established recently for alkali metals by Knight and his group. Because clusters are so photoreceptive, they can often absorb more than one photon, a useful quality in light-initiated chemical processes. If suspended in a transparent medium, they may also make efficient radiation detectors, wavelength-specific light filters or elements in an optical-memory system.

Eventually it may be possible to exploit the chemical and optical properties of clusters to create photographic films possessing new properties. Film is exposed when a photon hitting a tiny silver halide crystal converts a bit of it into a silver metal cluster. The cluster serves as a catalyst during the developing process, turning the rest of the crystal into silver metal. If more sensitive clusters—perhaps of different metals—could be created, it might allow the production of faster films. Smaller formations made of suitable clusters could lead to films that can resolve sharper images.

The great reactivity and precise photon-emission patterns of clusters are also of value as a chemical fuel for lasers. James L. Gole of the Georgia Institute of Technology has demonstrated that triatomic sodium clusters react with chlorine to produce excited diatomic sodium in sufficient abundance to create a population inversion, from which the process of stimulated emission yields a coherent beam in the blue-green end of the visible spectrum. This color is readily transmitted in water, and therefore, a laser using this fuel could be a new medium for submarine communications.

In the past decade, cluster researchers have created an interdisciplinary science and have raised fundamental questions about the nature of molecular surfaces. The chemistry of this new phase of matter is still in its infancy, but sufficient knowledge now exists to suggest that it has great relevance to fields as diverse as materials science, electronics and astrophysics.

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The Birds of Paradise

Diet has a major influence on the social and sexual behavior of these tropical birds. It explains why some species are monogamous and why others are highly promiscuous

by Bruce M. Beehler

The birds of paradise, denizens of a tropical realm far removed from the museums and laboratories of the Western world, have been the focus of scientific curiosity for many years. In 1871 Charles Darwin referred to them in his book *The Descent of Man and Selection in Relation to Sex*, noting that "when we behold a male bird elaborately displaying his graceful plumes or splendid colors before the female . . . it is impossible to doubt that she admires the beauty of her male partner."

Although nearly 120 years have passed since Darwin first remarked on the plumage of the male birds of paradise, the evolution of specialized plumes and other aspects of the birds' reproductive behavior continues to interest evolutionary biologists. Within the past 10 years a new generation of investigators—armed with fresh insights from sociobiology and behavioral ecology—have learned much about social organization in the birds of paradise.

Thane K. Pratt of the U.S. Fish and Wildlife Service in Hawaii, Clifford B. and Dawn W. Frith of Wildlife Conservation International, Stephen G. and Melinda Pruett-Jones of the University of Chicago and I have collectively invested more than a decade in the field studying the lives of these birds. Thousands of hours of field observation have shown that the diversity of social and sexual behaviors in this remarkable avian family has an ecological basis. In addition, it is now known that the birds, which feed mostly on fruit, play a key role in maintaining and regenerating the Papuan rain forest.

MALE RAGGIANA bird of paradise displays for a nearby female (not shown) by bending over, head down, and spreading his wings and orange flank plumes. The male raggiana sits on his perch every day for at least six months a year.

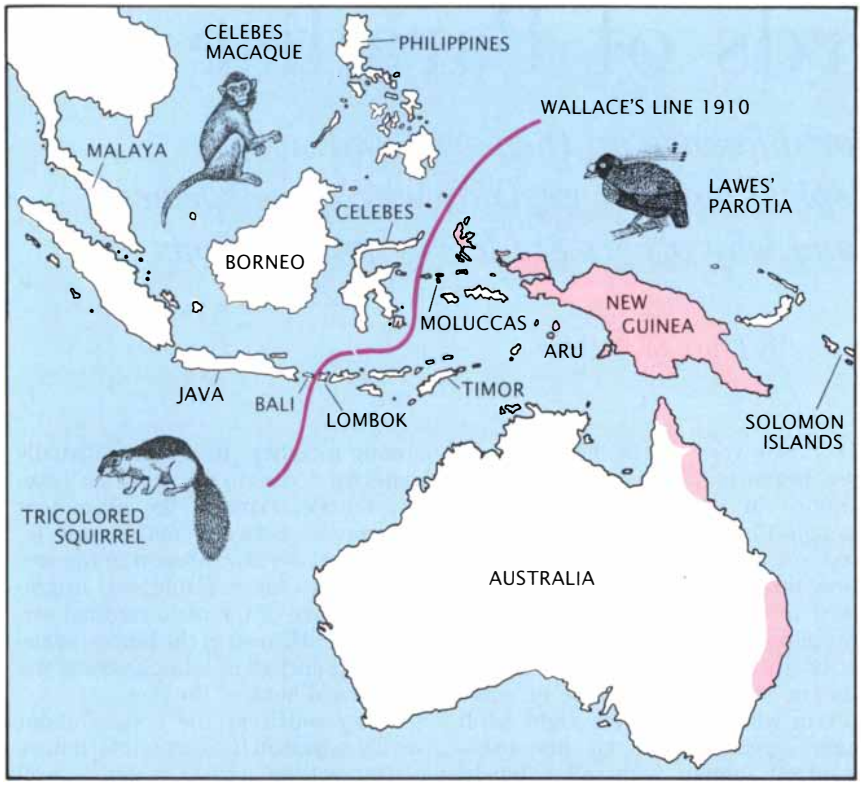
My own work on the birds of paradise began in 1975 with a 15-month sojourn in Papua New Guinea. Although 14 years have passed since I first set foot on the island, an early foray into the forest remains sharply fixed in my mind. Pushing my way through a lush tangle of tropical vegetation in the Upper Watut Valley of eastern New Guinea, I came on a tall tree in which there were eight adult male raggiana birds of paradise—beautiful animals with yellow heads, iridescent green throats and velvety brown breasts. They flashed their long orange plumes as they bowed and displayed to a visiting female, who was perched less than six inches from a male at the center of the group. To me the color, movement and sound of the mating display was—and continues to be—one of nature's most thrilling sights.

There are 42 species in the family Paradisaeidae. Of these, 36 are endemic to New Guinea and its satellite islands, four occupy eastern Australia and two occur as far west as the northern Moluccan Islands of Indonesia. Included in the family are a number of superficially diverse birds: sicklebills, parotias, long-tailed astrapias, heavily plumed paradisaeas and blue-black manucodes. All are robust in build, with powerful legs and feet, yet from species to species there is great variation in color and plumage. In most species the birds are sexually dimorphic, that is, the males and females differ markedly in appearance: the males are often gaudily colored and have long, ornate feathers called nuptial plumes, whereas the females lack the specialized plumes and are always predominantly brown or black.

The bright colors and courtship displays of the male birds of paradise are testimony to the power of sexual selection, the process by which some individuals win (and others lose) the right to reproduce. Competition among members of one sex (usually male) for access to the other sex (usually female) explains the prominent differences between males and females that are so common in the animal world—for example, the bright-red plumage of the male cardinal versus the dull brown of the female or the enlarged antlers of a buck versus the unadorned head of the doe.

Today much of the debate about sexual selection focuses on the nature of interactions among males as well as those between males and females. Why, for example, is sexual dimorphism so pronounced in some bird-of-paradise species and yet virtually nonexistent in others? Do the remarkable plumes of the males represent badges of dominance within a mating hierarchy, or are they advertisements to a female of a male's physical health and vigor? If the latter is the case, is there evidence that females discriminate between males on the basis of physical characteristics? Although complete answers to these questions are still forthcoming, much has been learned recently about the ecological basis of behavior in the birds of paradise. Before these findings can be presented, however, a review of so-

BRUCE M. BEEHLER is a zoologist at the Smithsonian Institution's National Museum of Natural History. He has been avidly interested in birds since his boyhood. During his senior year at Williams College he was awarded a Thomas J. Watson Fellowship, which enabled him to make his first ornithological expedition to New Guinea. He then went to Princeton University, where he earned a Ph.D. for research on the behavioral ecology of the birds of paradise. Altogether, Beehler has spent some 60 months in the rain forests of New Guinea studying the ecology of the bird fauna there. He is now studying the ecology and biogeography of the Indian avifauna in collaboration with S. Dillon Ripley, secretary emeritus of the Smithsonian.



BIRDS OF PARADISE are endemic to rain forests in Australia, New Guinea and the Moluccan Islands of Indonesia. In certain respects, the birds occupy the ecological niche held elsewhere by arboreal, fruit-eating mammals. The absence of mammals can be attributed to the presence of a deep-water barrier that separates the islands of Southeast Asia from Australia and New Guinea. The barrier, first recognized by Alfred Russel Wallace in 1863 and redefined by him in 1910, is known as Wallace's Line. To the east of the line are birds of paradise; to the west are placental mammals, including tricolored squirrels and macaques, both of which feed on fruit.

cial organization in the Paradisaeidae is needed.

Not all birds of paradise are sexually dimorphic. Nine of the 42 species in the family are monomorphic: the males and females are virtually identical in appearance. Monomorphic species, such as the trumpet manucode, *Manucodia keraudrenii,* are also monogamous: they form tight pair-bonds and perhaps mate for life. Moreover, both sexes cooperate in raising their young. In contrast, dimorphic species, such as the raggiana bird of paradise, *Paradisaea raggiana,* are polygynous: the males are promiscuous, mating with as many females in one season as they can. After mating, the females receive no additional help from the males and rear their offspring alone.

Why have such different mating strategies evolved within one family? Why, specifically, are some species polygynous and others monogamous? The answer has two parts. The first has to do with the influence of anisogamy, the inequality of male and female sex cells, on polygyny; the second part—as I shall explain later—has to do with the foraging behavior of a species and the nutritional and economic impact of diet on reproductive strategies.

Unlike eggs, sperm are tiny and energetically cheap to produce, and so in many species males can maximize their reproductive output (that is, the number of genes they pass on to the next generation) by mating with as many females as possible. Females, in contrast, produce only a few eggs and so are generally restricted in their reproductive output. The result is a behavioral and morphological dichotomy between the sexes: males tend to be promiscuous and to compete—fiercely at times—for access to females, whereas females tend to be selective, favoring males that possess certain characteristics over others.

Thus, in a monogamous population, where there is little competition because individuals pair-bond, there is little sexual dimorphism. In a polygynous population, where competition is stiff, dimorphism evolves because males with the brightest plumage and most elaborate displays mate with more females and thus pass along more of their genes and traits to the next generation. For a male who is competing with his neighbors, a slight edge—a louder call, more aggressive behavior or more conspicuous plumes—can spell the difference between no matings and multiple matings.

In both monogamous and polygynous populations, females tend to be drably colored. Because they are always in demand by males, they need not look flashy in order to reproduce. In the absence of any reproductive value for bright coloration, natural selection is thought to favor drab females over colorful ones: a cryptic or camouflaged female tending her nest is less likely to attract predators searching for eggs or young nestlings.

The male raggianas, such as those I saw displaying together in 1975, are typical in many ways of species that are sexually dimorphic and polygynous. Their courtship ritual is elaborate, and because it is performed at the same time by several males clustered together, it is also competitive. A group of courting males, called a lek, assembles at dawn each morning in a display tree. They advertise their presence to females within earshot by calling loudly: *wau, wau, wau, Wau, Wau, Wau, WAU, WAU, WAU, WAU,* with increasing volume and speed. If a female responds by joining them in the display tree, the males will initiate a courtship dance: they raise their orange display plumes, shake their wings and hop from side to side, while continuing to call.

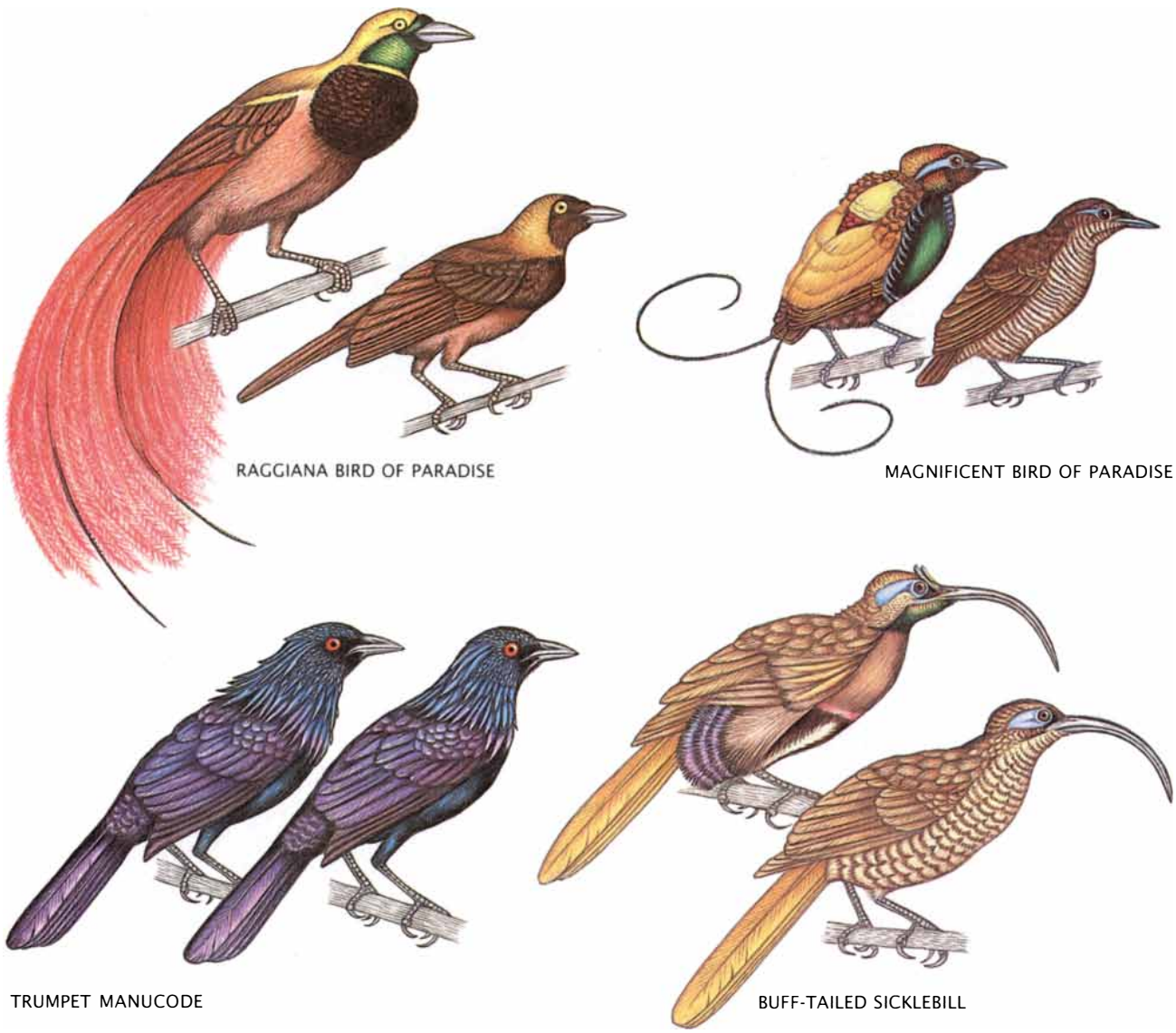
After a brief bout of noisy display behavior, the males become silent and lean upside down from their perches, with their wings thrown forward and their erect orange plumes forming a resplendent fountain of color. The group holds this pose until the female, who moves silently among them, selects a mate and crouches beside him. The other males watch passively as the chosen male performs a precopulatory dance and then mounts and mates with the female. The female separates from her mate soon thereafter and flies off to her nest, where in a day or two she will lay an egg.

The males of other polygynous species behave similarly, but each species has a unique courtship ritual, which is enhanced by the males' distinctive color and plumage. The male buff-tailed sicklebill, *Epimachus albertisi,*

for example, displays by hanging upside down and erecting his plumes to form a circular cape; the magnificent bird of paradise, *Cicinnurus magnificus,* forms a shield of feathers that looks like a high-necked collar and dances like a mechanical toy, tail feathers erect, while clinging to a vertical stem. The Lawes' parotia, *Parotia lawesii,* displays on the forest floor in a most remarkable fashion: while the female observes from above, the male throws his six stiffened head feathers forward like antennae, spreads his plumes into a skirt and hops delicately about.

In some polygynous species, such as the raggiana, the males form mating clusters, or leks, in which they congregate and display for visiting females. The type of lek varies from species to species. Raggianas, for instance, tend to congregate in one tree, whereas the males of Lawes' parotia form what is known as an exploded lek: instead of clustering tightly together so that each one is only a few feet from his neighbor, they space themselves from a dozen to 100 meters or more apart yet still behave as members of a single mating group. In some species, such as the magnificent, the males are solitary and do not form leks at all.

The presence or absence of leks raises additional questions about the evolution of mating strategies in the Paradisaeidae. In most leks one or two dominant males, usually the ones perched near the middle of the group, mate most often. Only rarely do peripheral males have an opportunity to mate. In a lek of the lesser bird of paradise, *Paradisaea minor,* for example, I recorded that a single male carried out 25 of the 26 observed copulations during one month of the mating season. Why, if competition among males is so fierce, do males cluster together? Might a male's chances of mating not be greater outside a lek than in it? And why do some species



PHYSICAL DIFFERENTIATION between males and females (known as sexual dimorphism) is represented here by four bird-of-paradise species. Sexual dimorphism is most pronounced in the raggiana (*upper left*): males are larger than females and festooned with orange flank plumes, which are highly visible when the male displays. The female raggiana, like all female birds of paradise, is drably colored. Male and female magnificents (*upper right*) are similar in size, but the male is brightly colored and has two unusual feathers, called tail wires, which he flashes when courting. Males and females of the buff-tailed sicklebill (*lower right*) have long, curved bills, with which they extract insects from wood and fruits from inside capsules. Males and females of the trumpet manucode (*lower left*) are monomorphic, almost identical in appearance.

form leks, whereas others do not? Answers to all three questions show that lek formation, like polygyny, is related to the foraging ecology of a species.

An initial clue that polygyny might be related to diet came from research conducted in the 1970's by David and Barbara Snow of the British Museum of Natural History. Their studies focused on the relation between mating organization and dietary specialization in two families of birds: the cotingas (Cotingidae) and the manakins (Pipridae), both of which are endemic to the rain forests of Central and South America. Although the cotingas and manakins are only distantly related to the birds of paradise, they exhibit remarkably similar patterns of sexual dimorphism and mating behavior.

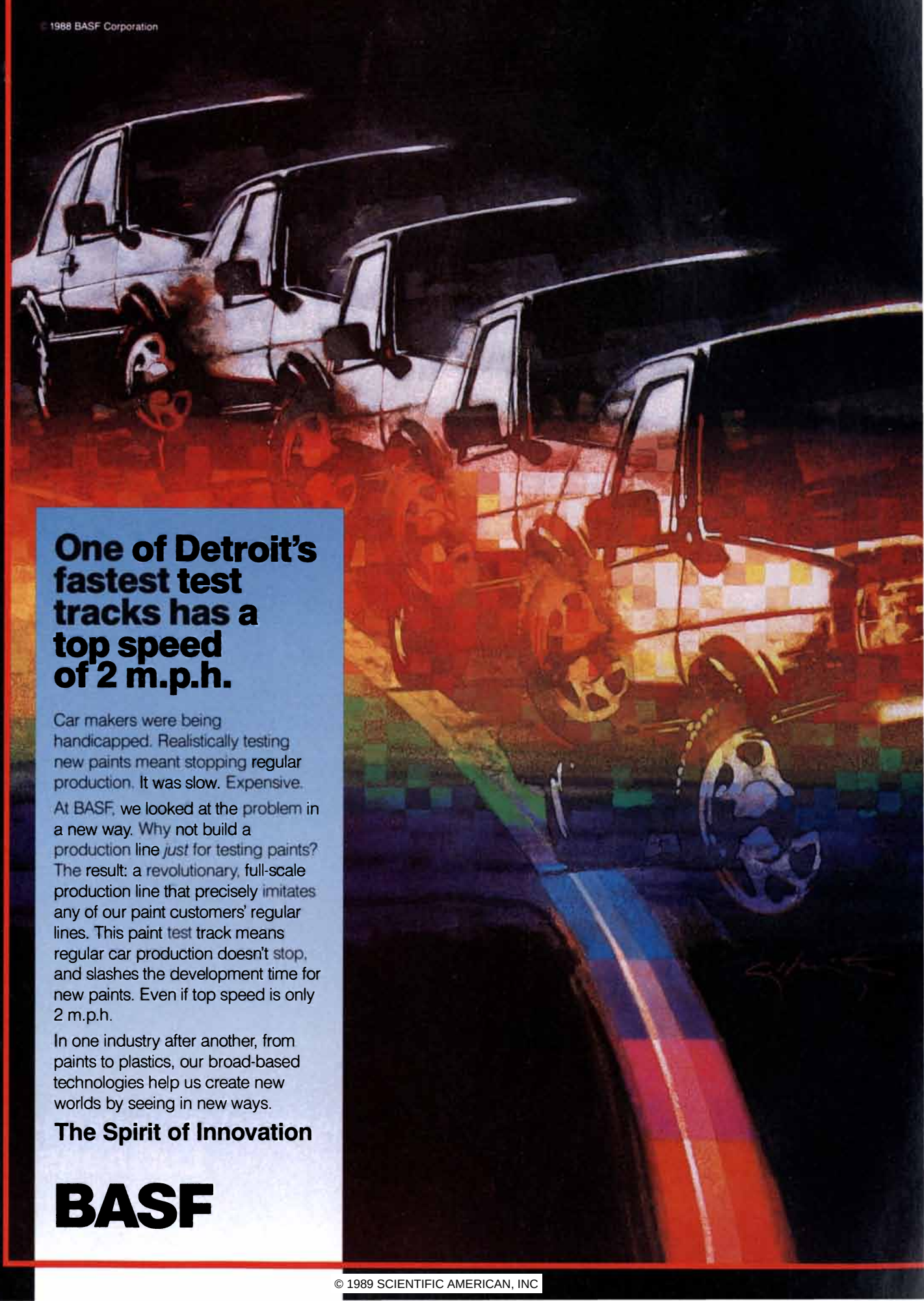
The Snows found that most polygynous species are frugivorous (fruit-eating), whereas most monogamous species are predominantly or entirely insectivorous (insect-eating). They also demonstrated that more time and energy is needed to forage for insects than is needed to forage for fruit and reasoned that only by eating fruit would polygynous males have sufficient time in which to pursue their promiscuous mating strategies. Would a similar pattern emerge, I wondered, for the birds of paradise?

As it turns out, the correlation between diet and mating behavior is considerably more complex in the Paradisaeidae than it is in the cotingas and manakins, and if anything, the pattern seen by the Snows is reversed. Research my colleagues and I have done shows that dietary specialization has had a significant influence on the evolution of the Paradisaeidae—promoting species diversity in the family at the same time that it has promoted a shift to polygynous mating behavior.

I have found that the fruits on which the birds of paradise feed fall into two distinct categories: simple, raspberry-like fruits, such as figs, which are plentiful in the forest and provide a ready source of water and carbohydrates, and complex fruits, such as nutmegs, which are large, usually protected by a tough outer capsule and produced in relatively small quantities. Such capsular fruits are often rich in fats or proteins, which makes them valuable commodities for foraging birds.

Pratt and I found that all the birds of paradise and just about every other bird in the rain forest will eat large quantities of figs when they ripen. Because most fig plants produce thousands of small, rapidly ripening fruits in cycles that are both nonannual and

MATING RITUALS among birds of paradise vary from species to species and are highly elaborate affairs. The male blue bird of paradise (*left*) hangs upside down, waving his feathers at a female who watches intently from above. The male raggiana (*right*), having completed the upside-down phase of his display, is preparing to mate with the receptive female above him.



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asynchronous, figs are available at unpredictable times throughout the year. When a plant does bear fruit, the avian response is spectacular: manucodes, fruit doves, fig parrots, pitohuis, honey eaters and birds of paradise all flock to the plant, gorging themselves on its ripe fruit.

Yet only one bird of paradise, the monogamous trumpet manucode, feeds almost exclusively on figs. Although most other birds of paradise will eat figs opportunistically, polygynous species spend the bulk of their foraging time searching for complex fruits, generally the capsular type. The fruits ripen in small numbers throughout a long fruiting season and are eaten by birds that visit ripening trees on a daily basis. Capsular fruits are more difficult to harvest than figs because they are encased in a tough woody capsule and consist of a single seed (with an edible portion attached), which must be swallowed whole.

It turns out that the ability of certain species to gain access to capsular fruit, which is difficult to reach and difficult to open, is related to their ability to feed on insects. The birds forage on limbs and trunks of trees, hammering and prying away at bark and dead wood to extract bark beetles and other wood borers, much as woodpeckers do. They also feed on insects that hide inside curled leaves by holding the leaves with their feet and pulling the insects out with their bill. The anatomical adaptations, such as a long beak and well-developed claws, that permit such specialized insectivory also make it possible for the birds to feed on capsular fruit.

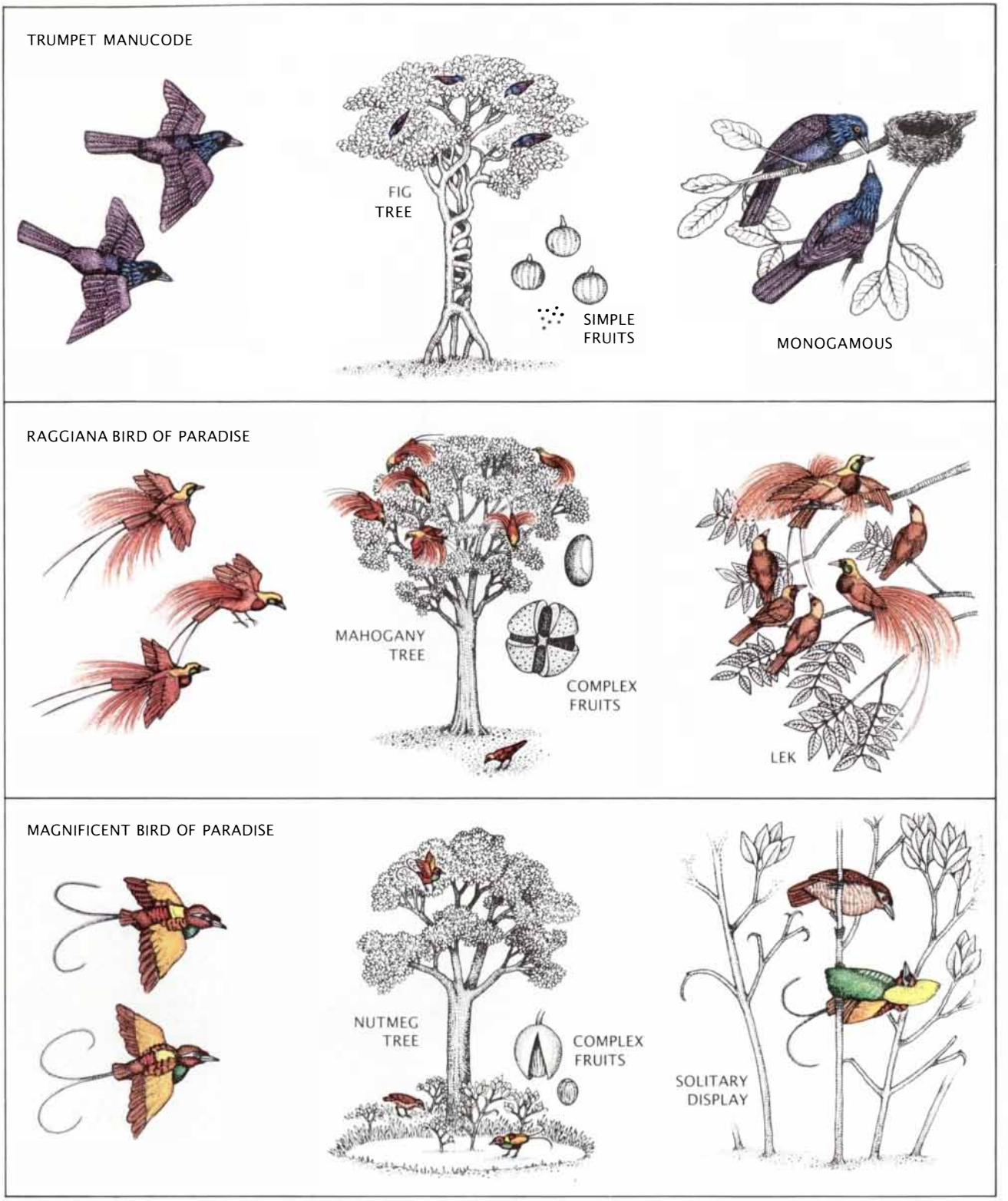
Fig feeders are rarely seen foraging in the trees that produce capsular fruit, and many of the plants that bear those fruits are visited predominantly or exclusively by the polygynous birds of paradise. How did such an exclusive association come about? The answer has to do in part with a biogeographic twist of fate.

Monkeys and squirrels (and indeed most placental mammals) have been unable to disperse across a deep-water barrier called Wallace's Line, which separates Australia and New Guinea from the shelf islands of Southeast Asia. In tropical habitats west of the line, monkeys and squirrels harvest and consume virtually all fruits, even well-protected capsular varieties. In many instances the plants derive no benefit from the arrangement: unlike the birds of paradise, the mammals often destroy or consume seeds rather than dispersing them. In New Guinea few mammalian seed predators exist, and so the birds of paradise have little competition for the highly nutritious capsular fruits.

But there is more to the story. Pratt and I have shown that the polygynous Paradisaeidae are among the best avian seed dispersers in the rain forest. The birds eat small numbers of fruits at one time and digest only the seed's nutritive covering, not the seed itself. Moreover, during their daily foraging period the birds actively fly from one tree to another; as they move about, the birds scatter the seeds throughout the forest and do not deposit them in clumps as other fruit feeders often do. Having well-protected complex fruits that are inaccessible to most foragers ensures that the seeds of these plants are handled by effective dispersers that are attracted to the fruit rewards the plants offer.

Compare the foraging strategies of the monogamous trumpet manucode with those of the polygynous magnificent bird of paradise. The trumpet manucode is a specialist: it is not particularly adept at foraging for insects, and so it feeds mostly on figs. Although there are advantages to such a diet—figs are superabundant, easy to harvest and easy to digest—there are also disadvantages: the figs

FEMALE LAWES' PAROTIA is perched on a branch watching a male display on the ground. The male has fluffed out his flank plumes, forming what looks like a skirt. After dancing he will join the female and attempt to mate with her. Parotia males form exploded leks: they display together but space themselves some distance apart.



SOCIAL ORGANIZATION in the birds of paradise is influenced by a species' foraging ecology. The trumpet manucode (*top*) is both monomorphic and monogamous: males and females pair-bond and cooperate in raising their young. They feed mostly on figs, and both parents rear their nestlings on a diet of fig pulp. The raggiana (*middle*) is dimorphic and polygynous. The males court females actively and then mate with any that are receptive; individuals do not pair-bond, and the females raise their offspring alone. Raggianas feed primarily on complex fruits, such as those of the mahogany tree. The males form mating clusters called leks, hoping thereby to attract females foraging through the forest. The magnificent (*bottom*) is also dimorphic and polygynous, and like the raggiana, it feeds on complex fruits, such as the nutmeg. But magnificent males are solitary; each one establishes a display ground in the midst of a thicket, which includes a circular area that is cleared of leaves. The male sings from his thicket, and if a female visits, he displays to her from the stem of a small sapling or vine.

are available at unpredictable times (and so the birds must continually search for them), and they are also poor in nutrients essential to growth and development. As a consequence, the male must help the female to forage for food to feed their nestlings.

The magnificent bird is also a specialist in that it feeds mostly on complex fruits, but the key determinant of its social behavior is the extent to which it supplements its diet with insects. The advantage to feeding on a mixed diet of complex fruits and insects is that both are temporally and spatially predictable and so provide the magnificent with a reliable source of food year round. More important, such a diet is sufficiently high in nutrients that a female can feed her nestlings without the help of a partner. Magnificent males are thus free to spend their time maintaining display sites, which they leave only periodically to obtain a daily ration of food.

From our studies we were able to conclude that the shift from monogamy to polygyny has occurred in those species whose diets include complex fruits in addition to some insects and simple fruits. In species that feed almost exclusively on figs, such as the trumpet manucode, the shift to polygyny has not occurred—probably because both males and females are needed at the nest.

What do such findings reveal about lek formation in the birds of paradise? Why does the raggiana, for example, display in tightly clustered leks, whereas the magnificent and the sicklebill display as solitary males? Jack W. Bradbury of the University of California at San Diego postulates that the evolution of lek behavior is linked to the availability of females, which in turn is determined by foraging behavior and ultimately by diet. He believes that leks form when the females forage far and wide for food and establish overlapping ranges; under these circumstances lekking males have the potential to attract many of the wide-ranging and nonterritorial females.

Bradbury's theory accords well with our data. Females of such well-studied species as the raggiana and Lawes' parotia have large overlapping ranges. A single lek site is likely to be visited by many females, and so the potential for polygyny in these species is high. In other species, such as the magnificent or the sicklebill, the females are not so wide-ranging but forage instead in relatively small, nonoverlapping patches of forest. As a result, not many of them are likely to encounter a display site, and so the potential for polygyny in these species is low.

MALE LAWES' PAROTIA looks strikingly different from the female. His vibrant chest colors and the "head wires" (highly modified feathers) at the back of his head are secondary sexual characteristics, which in parotias and other dimorphic species may have evolved in response to competition among males for access to females.

One can conclude that polygyny and lek formation are promoted by three factors. First, the clumped distribution of fruits creates conditions under which males stationed at a single site are likely to make contact with many females. Second, the predictability and nutrient content of complex fruits make it possible for females to provision their nestlings without the help of a mate and for males to shift to a promiscuous mating strategy. Third, a greater dietary reliance on fruits promotes the expanded ranges of females and the shift of males to lek groups. The raggiana and parotia, for example, feed almost exclusively on complex fruits (rarely on insects) and form leks, whereas the magnificent and the sicklebill frequently feed on insects and are solitary.

Studying the evolution of mating behavior in the Paradisaeidae from an ecological perspective has led to a new understanding of diet as a determinant of social organization. It is now clear that the birds and the plants on which they feed are interdependent. In addition, my colleagues and I are now aware that only through an understanding of the birds' relation to their rain-forest habitat do the diverse reproductive strategies in this remarkable avian family make sense.

Still, many questions have yet to be answered. For example, will the generalizations we have made about diet and behavior hold true for the birds of paradise that have yet to be studied? On what basis do females discriminate among lekking males, and why do some species have exploded leks, whereas others have tightly clustered ones? And finally, why do males maintain leks when the competition in them is so great? These and other sociobiological riddles will continue to attract biologists for years to come.

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Teleoperators

In the absence of fully autonomous robots, machines operated by a person at a distance can carry out tasks in remote or hostile environments

by William R. Uttal

How can physical tasks be carried out safely in a hostile environment—a nuclear hot cell, for example, the front lines of a battlefield or the depths of the ocean? One strategy, for the moment a speculative one, is to rely on an autonomous robot. Another, already embodied in working devices, is to call on a teleoperator: a machine operated by a person at a distance. Such a device can bring a human worker's perception, judgment and dexterity to bear on a task while allowing the worker to control the teleoperator from a position of safety and convenience.

Whether the remote work site is in the next room or on a distant planet, the basic idea behind a teleoperator is simply to provide a longer "reach" for a worker than a conventional tool can provide. In a strict sense a teleoperator is not a robot, because the machine is controlled by a human's intelligence, perception and motor skills rather than by the central processing unit of a computer. Hence, teleoperation, or the process of transmitting work-related information to and from a distant location, is essentially an exercise in two-way communication. The human operator must constantly monitor the remote site while he or she sends control signals to the tools at work there.

The fact that teleoperators are controlled by humans is actually a major advantage. The past three decades have seen several periods of optimism that fully autonomous, computer-controlled robots would become available to work at sites where a human would be at peril or where considerations of time, cost or distance rule out a human presence. Time after time these hopes have run up against technical difficulties as the needed artificial-intelligence technology turned out to be more difficult to master than expected. Some obstacles only await new developments in technology for their solution. Other barriers to full automation seem to be more fundamental.

Fortunately it is not necessary to depend entirely on a fully competent and autonomous computer to do useful work in dangerous or remote locations. In many instances, teleoperators are already doing the job, as one did in the recent exploration of the *Titanic* wreck. Several laboratories around the world, including the Hawaii laboratory of the Naval Ocean Systems Center (NOSC), where I worked for three years, are trying to expand the role of these remotely controlled machines. The fundamental challenge is to design powerful, flexible links between the human operator and the distant machine. The task is shaped as much by human perceptual, cognitive and motor abilities as it is by engineering considerations.

All teleoperator systems share several basic features: sensors to acquire information about the remote location; a display that enables the operator to monitor the situation; controls by which the operator implements his or her decisions; a remote effector, or tool; and—perhaps most important—communications links to carry information from sensors to display and from controls to effector. In addition, every teleoperator has basic housekeeping requirements. The remote workstation must be transported to its location, must be able to navigate as it does its work and must have sufficient power to operate the tools and any supporting vehicle.

The first teleoperators to be worthy of the name were remote manipulators for radioactive materials, developed during the 1940's. The display was simply a window through which the operator peered, and the controls were linked directly to the effectors—typically claws and grasping devices—by mechanical connections: either rigid rods or cables and wires. In modern teleoperators the linkages are often indirect, consisting of signals transmitted by electrical cables, optical fibers or even radio or television waves. Hydraulic actuators have proved to be effective in some modern systems operating over short distances. Whatever the technology or the distance spanned, the task of the communications components remains the same. They must provide the operator with adequate information about the tool's status and environment, and they must transmit control signals that enable the effectors to reproduce the motions of the human operator.

Insofar as the display reproduces the scene at the remote location, the human operator experiences a sense of "remote presence." It is still controversial whether this illusion of "being there" improves performance in any significant way. Nor is it known how best to create a feeling of remote presence. Clearly, one does not want to reproduce the exact properties of the remote location, including the heat, pressure, radiation or other dangerous circumstances that led to the use of a teleoperator in the first place!

At the same time, mismatches between the display and the actual work environment certainly can impede performance. As a result, much effort has gone into determining, among other things, the optimum field of view for a display, which affects the apparent velocity of objects moving across the field. Deciding just which visual stimuli should be supplied to the human

WILLIAM R. UTTAL is professor of psychology at Arizona State University and chair of the department. He received a B.S. in physics from the University of Cincinnati in 1951 and a Ph.D. in psychology and biophysics from Ohio State University in 1957. Uttal has written 13 books on topics in computer science, physiology and experimental psychology. This article grew out of a three-year stay as a research scientist at the Naval Ocean Systems Center's Hawaii laboratory.

controller, and in what form, is a major challenge in teleoperator research and development.

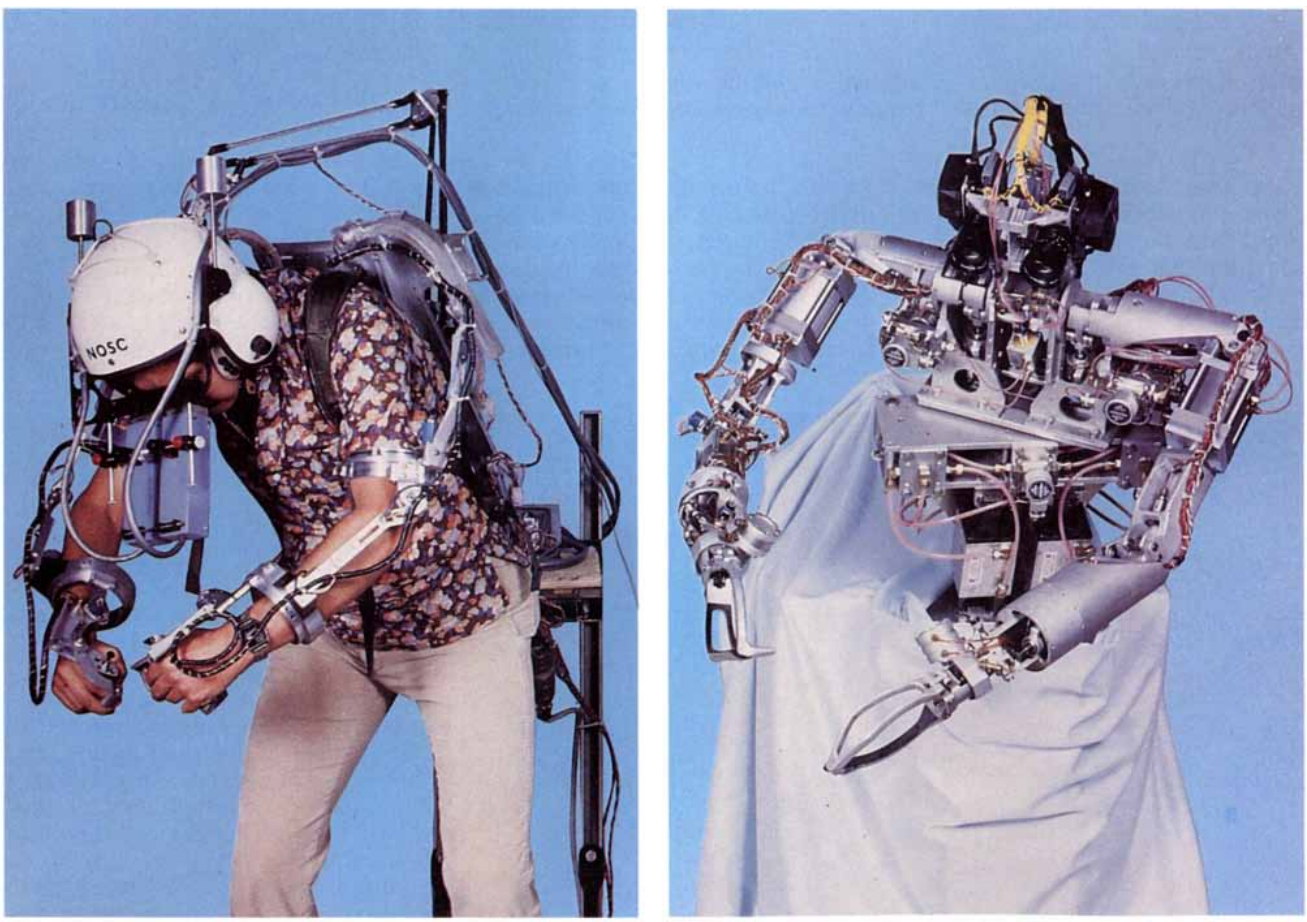
In several of the teleoperators being developed at NOSC, the operator views a stereoscopic display. The display is driven by twin cameras on the remote machine and provides a powerful illusion of being on the spot. The separation of the twin cameras need not be limited to the usual separation of the human eyes. Moving the two cameras farther apart can considerably improve the operator's ability to resolve objects in depth. Edward H. Spain of NOSC has discovered, however, that there is an optimum separation for the cameras beyond which the operator's ability to discriminate depth declines rather than improves.

Television sensors able to detect forms of electromagnetic radiation other than visible light can also extend the operator's perceptual powers, making it possible to "see" objects that would ordinarily be invisible to a human observer at the work site. In the near future it is likely that computer image-processing techniques will enhance the visual data sent from the sensors to the display. Objects will be isolated from complicated backgrounds; poorly imaged surfaces will be reconstructed automatically. Poor-quality visual information may not always need computer enhancement, however: my research indicates that an observer can readily perceive a pattern or object as being nearly complete even when presented with an incomplete or "noisy" display.

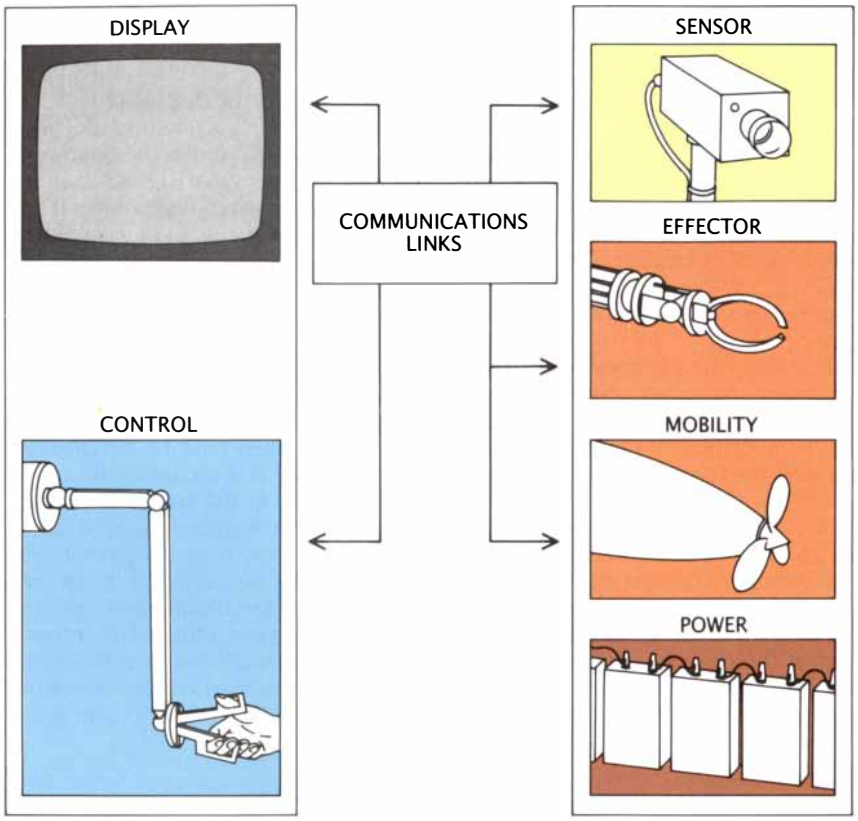
In some systems, sound augments the visual display; for example, sound can alert the controller of a teleoperated underwater vehicle to collisions in murky waters. Designers are also trying to incorporate "tactile" displays into teleoperator systems. Such displays could provide feedback from remote tools, enabling the operator to control the force he or she exerts on an object and so avoid damaging it. Systems are now being developed in which the information from a remote tactile sensor is reproduced in a glove-like "feel" display, enabling the operator to "palpate" the distant object.

A tactile-display system could provide information about the shape of an object when visual signals are obscured by, for example, turbid water or where the work is out of a camera's line of sight. The ability to "grasp" an object may be of great value in a teleoperator, just as it is for a person groping about in the dark or working on something hidden from view.

Whereas considerable attention has been paid to developing visual and tactile displays for teleoperators, in the past little effort was spent on engineering new controls. Until now, controls have been simple joysticks, switches or levers. Such devices are designed simply to cause the remote effector to reproduce the operator's motor responses: to close its claw when the operator closes a scissors grip, for example.



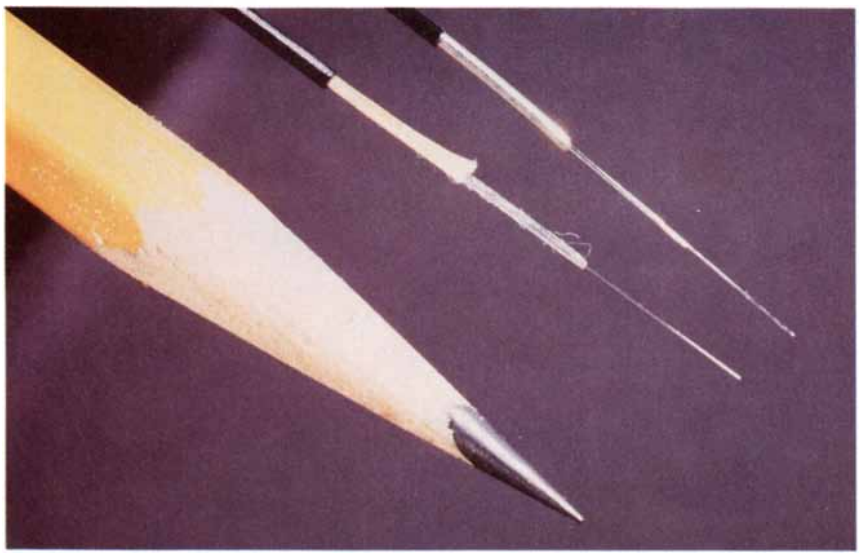
"GREEN MAN" teleoperator enables a human being (*left*) to operate a humanlike workstation (*right*) from a distance. Two television cameras on the station send information to two miniature helmet-mounted television screens positioned directly in front of the operator's eyes; sound is transmitted as well. The motions of the workstation mirror those of the operator. Control signals are transmitted hydraulically from the operator's harness to the workstation. The experimental system serves for human-factors studies of teleoperation at the Hawaii laboratory of the Naval Ocean Systems Center (NOSC).



COMPONENTS of any teleoperator are a display, a control, a sensor, an effector (or tool) and communications links. Other components may provide power and mobility.

Computer technology has recently begun to supplement teleoperator-control systems in exciting ways. Just as a computer can be inserted into the path between the sensor and the display in order to enhance the image, so too a computer could be inserted into the communications pathway between the controls and the effector. The computer could, for example, eliminate the need for the control to move with precisely the same degrees of freedom as the effector, by automatically translating input in one coordinate system into output in another system. A computer might also be programmed to amplify the tool's response nonlinearly—without requiring the operator to apply a corresponding increase in force at the control end. Other computer-aided transformations, both complex and simple, would allow the interface between the operator and the control to be as natural as possible.

Several novel controls are currently under development. James D. Foley of George Washington University has developed a glovelike device that can sense the complex motions of the human hand and transmit the information to a distant handlike tool [see "Interfaces for Advanced Computing," by James D. Foley; SCIENTIFIC AMERICAN, October, 1987]. Other investigators have been developing systems that employ electrical outputs from the muscles of the body to control the movements of prosthetic limbs. (Even though the distances over which the limbs must work are much smaller than those of typical teleoperators, such systems present problems similar to those faced by teleoperator designers.)



OPTICAL FIBERS are valuable for communications links in teleoperators. Single-strand cables may be less than a quarter of a millimeter thick and yet possess sufficient mechanical strength to be paid out from an airplane in flight without breaking.

In some teleoperators copper wires and mechanical or hydraulic links suffice for transmitting sensory and control information, respectively. In most systems, however, the operator and effector must exchange much larger amounts of information. The transmission requirements for control signals are relatively modest, but a stereo display typically employs two broadband color television channels.

The burden of communication from the sensors to the display can sometimes be eased by taking advantage of human perceptual capacities. Ross L. Pepper, now at Science Applications International Corporation, has shown that the potential for overloading the communications system can be reduced by transmitting a low-resolution color image along one television channel and a high-resolution monochrome image along another. Combining the images at the operator's station yields a moderate-quality but functional color stereo image. The image quality is good enough for the observer to be unaware of the economical means of transmission.

Teleoperators designed to operate over extremely long distances in outer space or on the earth must communicate by means of radio or television transmissions or, in the ocean, acoustic signals. But for teleoperators that can maintain a physical link between

the operator and the tool, optical fibers have been a boon. A single optical fiber can carry up to 400 million bits of information per second. The small diameter of the fibers makes it possible to pay them out over long distances—up to about 300 kilometers—from a single reel. Carefully spooled fibers can even be paid out at high speeds from aircraft for controlling teleoperated military systems, as Jack E. Holzschuh has demonstrated with fibers developed by Arthur T. Nakagawa and his colleagues at NOSC.

Optical fibers are also being deployed from on board ships, for undersea teleoperator systems. In such teleoperators, which include the Advanced Tethered Vehicle, developed at NOSC by Robert T. Hoffman, the remote workstation is generally suspended from a cable that, in addition to carrying information, must also supply power and support substantial weight. The weight includes not only the weight of the workstation but also that of the cable, which can be surprisingly heavy. Substituting optical fibers for copper in the communications links can greatly reduce the weight of the cable—from 23 to nine tons in the case of a cable supporting a deep submersible station. (For functions other than communication, the cable still needs a large amount of copper, steel and other materials.)

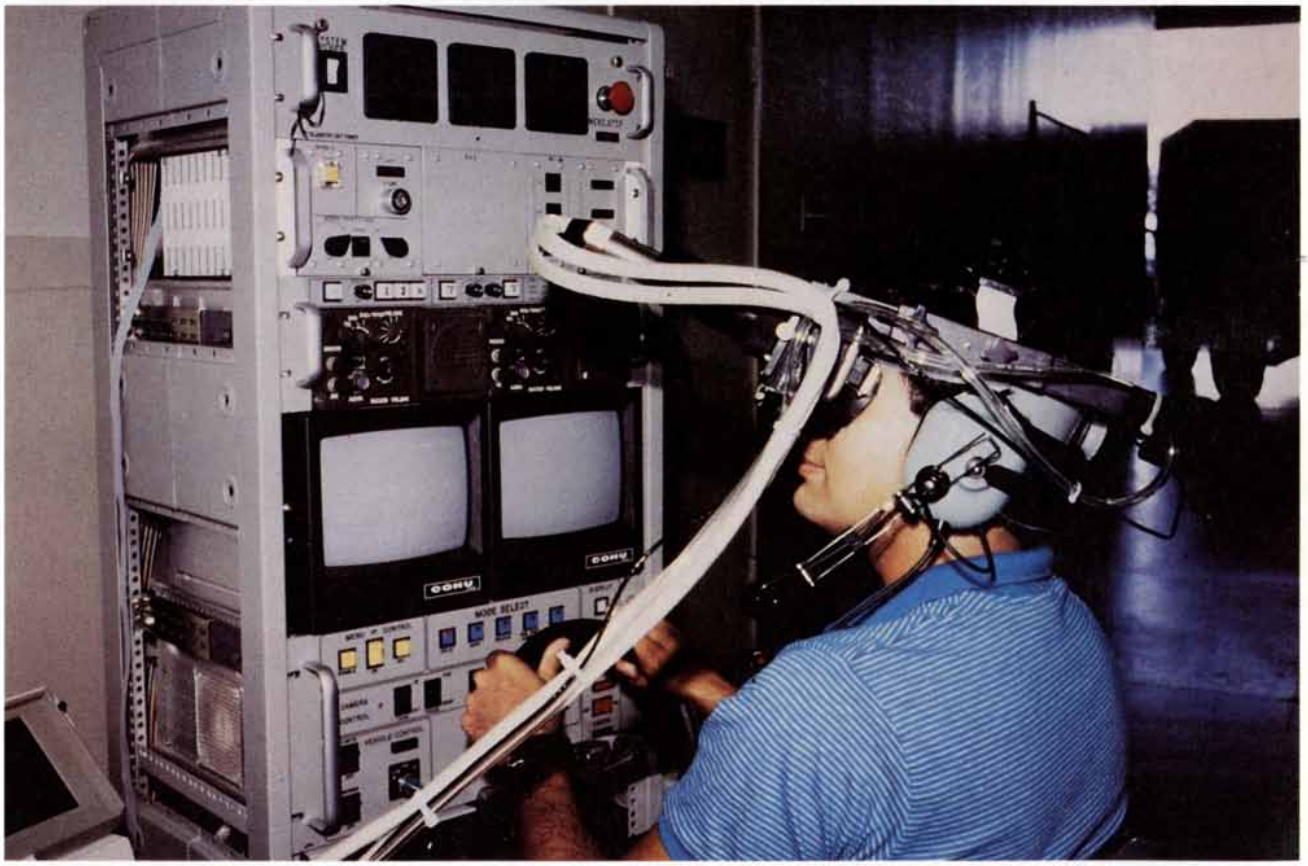
In addition to being light and compact, fiber-optic cables are remarkably tough and resistant to breakage when they are properly sheathed. Vehicles can run over the cables repeatedly without causing them to lose their optical or mechanical integrity. Fiber-optic cables are also secure from eavesdropping, unlike electric cables.

Now that I have described the basic teleoperator components and some of the challenges in their design, I can discuss a few of NOSC's advanced teleoperator systems as a whole. Perhaps one of the most conceptually stimulating is the so-called green man: a prototype of an anthropomorphic (human-shaped) teleoperator. David C. Smith and Frank P. Armogida conceived the device, and Herbert L. Mummery built it. The operator wears an exoskeletonlike harness and gazes at two miniature helmet-mounted television screens, which are directly in front of the operator's eyes. The controls of the teleoperator consist of the hinged exoskeleton framework, which follows the operator's motions. Besides duplicating head and arm motions, the green man is also capable of following the motion of the neck and torso.

The workstation, which is currently separated from the operator by only a few feet, is a humanlike "tool." The station has two television cameras to send visual information to the screens and two microphones to send sound into the operator's headphones, providing an extraordinary binaural experience. Meanwhile signals from the operator, sent through a hydraulic communications system, move the torso and neck and manipulate the arms and clawlike hands. The motions of the station mirror the movements of the operator.

Anthropomorphic teleoperator systems have special advantages and are particularly well suited for some kinds

DISPLAYS AND CONTROLS of a teleoperated system may be quite complex. The picture shows the surface operator station for a remote underwater workstation developed at NOSC. The armlike device at right controls an underwater manipulator.



TELEOPERATED TRUCK has proved to be a highly practical reconnaissance platform that can scout a dangerous location without jeopardizing a human operator. The truck (*top*) has twin cameras in the driver's seat and is guided by signals sent over a fiber-optic tether from a remote operator's station. The controls (*bottom*) duplicate those of a conventional truck.

of work, such as underwater repair jobs in which the precise nature of the task cannot be anticipated. The sense of remote presence one experiences in the green man's operator station is quite strong, and there is virtually no need for the operator to think about how to translate his or her motions into motions at the remote work location. Yet much work remains before such teleoperators will become practical devices, able in particular to duplicate human dexterity.

Thomas W. Hughes and his colleagues, meanwhile, are developing a teleoperated version of the U.S. Army's HMMWV (High-Mobility Multipurpose Wheeled Vehicle), which replaces the classic jeep. The operator views the terrain through a helmet-mounted stereoscopic display, which receives signals through a fiber-optic tether from twin television cameras on a "head" in the driver's seat. The optical properties of the cameras and display have complex effects on the operator's ability to control the vehicle—effects that are still being studied intensely.

A rather unpleasant human factor this teleoperator's designers must contend with is simulator sickness—a euphemism for frequently incapacitating nausea, produced largely by the conflict between the operator's perception of motion (which is strengthened by the stereoscopic display) and the absence of inner-ear stimulation. Individual susceptibility to simulator sickness varies widely, and investigators are aggressively trying to determine the exact stimulus conditions that precipitate it.

Another teleoperator Hughes and his colleagues are building is the Airborne Remotely Operated Device (AROD), a small, highly mobile observation platform. The AROD can hover or move about under the control of a remote operator and provide reconnaissance data that might be unavailable to an observer on the ground. Here, too, the human role in the system raises challenging issues. Although the human operator can provide an enormous amount of "computing power," slight changes in the configuration of the system can dramatically affect the operator's ability to control it. No one knows, for example, whether the sensors should be mounted on the platform to give the operator the illusion of flying on board or whether the sensors should observe the platform from a distance. The optimal display mode might differ for a novice operator and an expert, and it might vary from one phase of a mission to the next.

FLYING PLATFORM can be controlled from a distant operator's station. The experimental platform, which is about two feet high and is lofted by a fan, can hover as well as reconnoiter large areas. The cameras can send signals to a display giving an operator the impression that he or she is actually on board the device.

These prototype teleoperators show that most of the physical technology needed for these highly complex and useful teleoperators is already available. The major challenges now lie at the interface of human and machine. Until sufficient progress in computer technology makes it possible to substitute artificial intelligence for human intelligence, psychological insights into the best ways to link human operators to machines will pace the evolution of remote workstations.

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The Mithraic Mysteries

The icons of this ancient Mediterranean cult can be deciphered only in terms of a worldview that placed the powers controlling human destiny not on the earth but in the stars

by David Ulansey

In hundreds of underground temples scattered across the territory of the Roman Empire from England to Syria, modern archaeologists have uncovered paintings and carvings of a young man killing a bull. The significance of this picture, the central icon of a secretive cult known as Mithraism, has been one of the great unsolved archaeological mysteries of this century. What mythical event is depicted by these figures? What clues does the bull slaying yield about the teachings of the cult? I and several other researchers have come to a conclusion that may seem unlikely at first: the image does not represent a myth about events on the earth; instead it is an astronomical code with strong religious implications.

This surprising interpretation gains credibility when considered in light of the widespread religious and social upheavals of the time. Mediterranean civilization in the seven centuries between Alexander the Great and Constantine provided exceptionally fertile soil for the growth of new religions. Alexander's conquests, solidified by his Hellenistic and Roman successors, had rapidly created a unified Mediterranean culture out of what had formerly been a diverse collection of individual nations, city-states and tribes. Older forms of religious expression, which had generally been the product of smaller, close-knit societies, were losing their ability to furnish a sense of meaning for individuals adrift in a vastly expanded and increasingly impersonal empire.

As the Hellenistic and Roman empires swallowed up the older city-states and tribes, people came to feel that the powers determining their lives lay out of reach, in the distant parts of the empire. Any philosophy or religion that could offer people a sense of understanding or control exercised a strong attraction.

The emergence of Christianity was one response to these conditions. It offered membership in a symbolic community—the "New Israel"—to people whose actual communities, now submerged in the imperial order, could no longer supply a firm sense of identity. Another response was the rise of fatalism—the idea that life was completely controlled by an impersonal fate. Indeed, a personified form of Fate or Chance came to be worshipped as a god in many Hellenistic cults. The name of one Hellenistic philosophy that embraced this fatalistic worldview, Stoicism, survives today, signifying resigned endurance of whatever life may bring.

The general fatalism of the time prepared the way for the success of the more specific fatalism of astrology. Astrology, which first began to gain popular acceptance during the Hellenistic period (the time following the conquests of Alexander), claimed, with a persuasive aura of mathematical accuracy, that all events were predetermined by powers residing in the stars. The growth of fatalism and astrology in this period makes it plausible that a religion based on the stars should have arisen.

The cult known as the Mithraic mysteries, or Mithraism, was one of the most important—and certainly one of the most intriguing—of the religions that arose at about the same time as Christianity. It came into existence in the first century B.C.; Plutarch writes that the Cilician pirates were practicing Mithraic rites by 67 B.C. (The pirates, based in the province of Cilicia in Asia Minor, numbered about 20,000; at their height their operations extended over the entire Mediterranean Sea.) Mithraism reached its peak in the third century and finally succumbed to the expansion of Christianity in the late fourth century, about the time that the Western Roman Empire was falling.

The cult's membership for the most part comprised soldiers, state bureaucrats and merchants; women were excluded. Like a number of other ancient religions (the mysteries of Isis and the Eleusinian mysteries among them), Mithraism limited its membership to those who had passed through a secret initiation ritual. Initiates were forbidden to speak to outsiders about cult secrets, and hence, they were named *mysteria,* a word whose root means to keep silent. The English word mystery and related words such as mysticism are ultimately derived from the Greek name for the cults. Mithraism was organized around seven distinct grades of initiation, forming a hierarchical structure through which members gradually ascended.

The cult's secrecy meant that no written record of Mithraic doctrines survives. As a result, the only information available to scholars attempting to reconstruct the cult's teachings is the elaborate iconography that decorates the temples. Most of it depicts various activities involving the cult's god, Mithras; the crucial scene is the so-called tauroctony, or bull slaying, in which Mithras, accompanied by various figures, is shown in the act of killing a bull. A tauroctony is found in the most prominent location in virtually every Mithraic temple, and it is clear that this icon holds the key to the central secret of the Mithraic mysteries. In the absence of any written explanation, however, deciphering it has

DAVID ULANSEY is assistant professor in the department of religion at Boston University. His research interests include ancient Mediterranean religions and the origins of Christianity. He received both his B.A. and his Ph.D. from Princeton University and taught in the history department at the University of California, Berkeley, before moving to Boston. Ulansey's book *The Origins of the Mithraic Mysteries* was published this fall; he is currently at work on a new one about the role of cosmological symbolism in early Christianity.

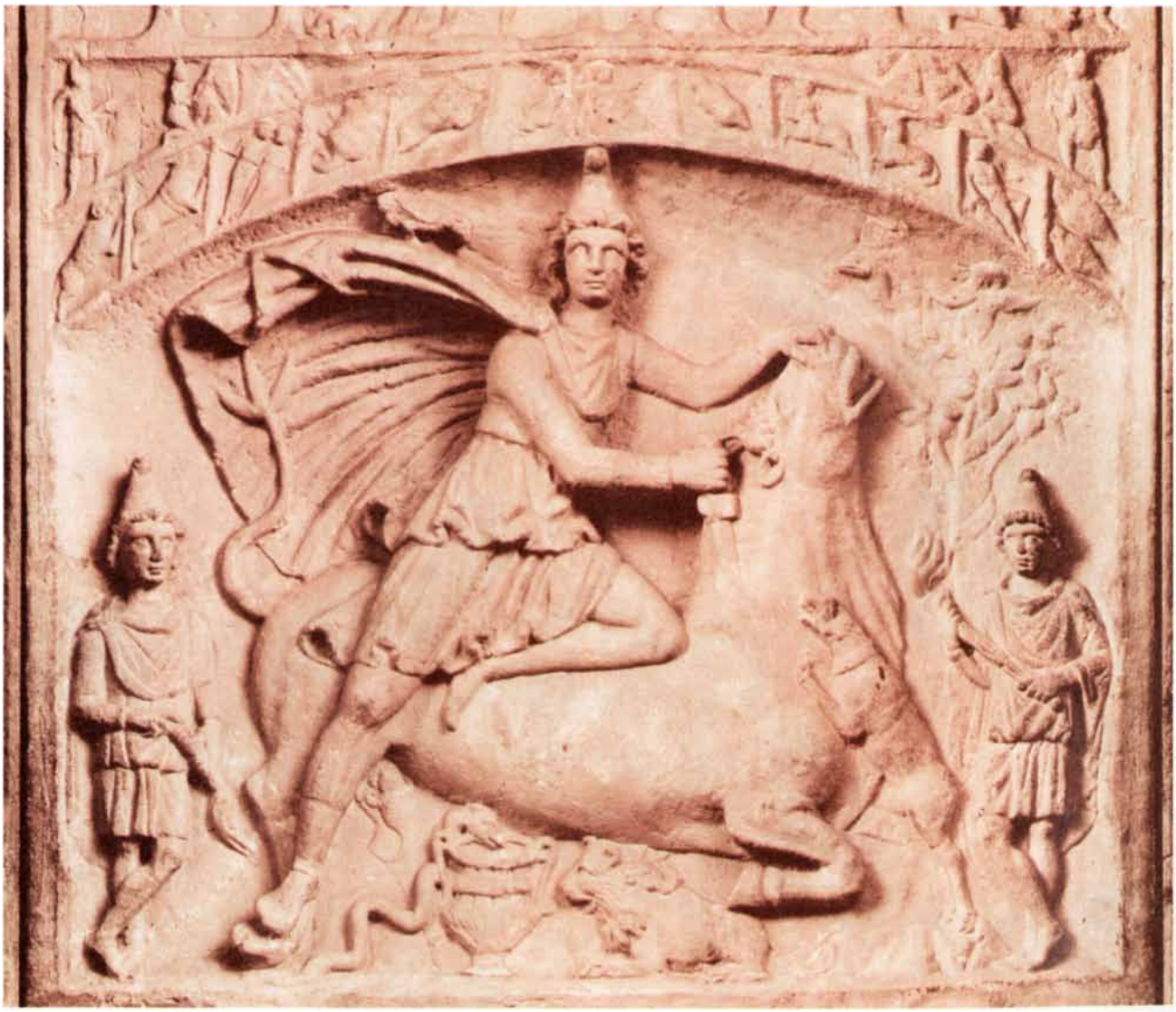
proved a notoriously difficult task.

For most of the 20th century scholarly attempts to explain the tauroctony were dominated by the work of Franz Cumont, the famous Belgian historian of religion. Cumont's interpretation, first presented in 1899, was based on the fact that *Mithras* is the Greek and Latin name of a much older Iranian god, Mithra. Cumont concluded that Mithraism was imported from the ancient Iranian cult of Mithra, who represented light and truth and was believed to be the special guardian of contracts and agreements. Cumont argued that deciphering the tauroctony was simply a matter of finding parallels to its symbolic elements in ancient Iranian mythology.

Cumont's approach had significant problems. Most important, there is no known Iranian myth in which Mithra has anything to do with killing a bull. Cumont seized instead on an Iranian creation myth in which Ahriman, the embodiment of evil, kills a bull from whose blood and body spring all the living creatures of the earth. He claimed that this myth must have existed in a variant form (for which there is, however, no evidence) in which the good god Mithra replaced the evil Ahriman as the bull slayer. Cumont's eminence was such that his theories remained virtually unchallenged for more than 70 years.

The Iranian connection, and with it Cumont's interpretation of the tauroctony, came under concerted attack at the First International Congress of Mithraic Studies, held at the University of Manchester in 1971. Several scholars, chief among them John Hinnells of Manchester and R. L. Gordon of the University of East Anglia, suggested that Mithraism had in fact been created as a completely new religion somewhere in the Greco-Roman world and that it had merely adopted the name of the Iranian god to give itself an exotic flavor and an aura of antiquity.

If the tauroctony did not represent an Iranian myth, what did it represent? Starting in the mid-1970's, several scholars (including Roger Beck of the University of Toronto, Stanley Insler of Yale University, Michael Speidel of the



BULL SLAYING, depicted in this relief from Germany, is the central icon of the Mithraic religion. The figures in the main picture represent constellations and the signs of the zodiac decorate the arch above the image, demonstrating the pervasive influence of astrological symbols on Mithraic beliefs. The author argues that the image represents the astronomical precession of the equinoxes. In about 2000 B.C. the spring equinox, which had been in the constellation of Taurus (the bull), moved into Aries. Mithraists believed that their god controlled the precession; the bull slaying symbolizes this power.

University of Hawaii, Alessandro Bausani of the University of Rome and me) put forward new interpretations of the tauroctony (and of Mithraism) based on the hypothesis that the picture is actually a star map.

Astrological beliefs permeated Mediterranean religious and intellectual life at the time Mithraism originated. In part this was the result of the general fatalism of the age. In addition, for individuals cut off from their local traditions and free to move at will anywhere in the empire, astrology filled the need for new symbols that could help make sense of everyday life but were not tied to a particular locality or community, as were the older religious forms. The configurations of the stars appeared the same no matter where in the empire one traveled and so provided ideal raw material for such a universal symbolic system.

The acceptance of astrology led to a growing belief that the true dwelling place of the gods was in the realm of the stars. For example, it was during the Hellenistic period that it became the standard practice to call the planets by the names of various Greek gods, such as Zeus (Jupiter) and Ares (Mars). Astrology also encouraged a new conception of life after death, according to which the soul did not go to the underworld, as had earlier been believed, but rather rose through the planetary spheres to the sphere of the fixed stars and then to the paradise that lay beyond the outermost sphere. In time this journey came to be imagined as difficult and dangerous, with secret passwords required to cross each planetary threshold.

Astronomical concepts must have been important in Mithraism, given the frequent appearance of astronomical symbols in Mithraic iconography. The 12 signs of the zodiac and symbols of the sun, moon and planets often appear together with the tauroctony and elsewhere in Mithraic art. The classical author Eubulus, writing during the first or second century, said that the Mithraic temple was meant to be "an image of the cosmos." It now appears that the tauroctony itself was an astral symbol.

In addition to Mithras and the bull, the tauroctony contains a number of other figures: a dog, a snake, a raven, a scorpion and sometimes a lion and a cup. It cannot be coincidence that each has a parallel among the constellations: Canis Minor, Hydra, Corvus, Scorpio, Leo and Crater; the bull is paralleled by Taurus. My work has been directed toward explaining how these constellations could come to form the central icon of a powerful religious movement.

These seven constellations, I have

MITHRAIC TEMPLES were constructed underground throughout the Roman Empire. The majority of Mithraic artifacts have been found in Italy and along the Rhine and the Danube rivers in areas garrisoned by Roman legions. Many Mithraists

found, are linked in the sky as well as in the tauroctony. With the exception of Leo, they lie along a path defined by an ancient position of the celestial equator. The celestial equator is a projection of the earth's equator onto the celestial sphere. It is an imaginary circle tilted at an angle of 23 degrees to the plane of the earth's orbit (the ecliptic, or the plane that defines the circle of the zodiac). The celestial equator crosses the zodiac at the equinoxes—the points on the celestial sphere where the sun appears to be on the first day of spring and the first day of autumn.

In antiquity the celestial equator was far more than merely an imaginary circle. Ancient astronomers believed that the earth was located in the center of the universe and was absolutely immovable; the fixed stars were attached to a great sphere that rotated around the earth once a day on an axis running between the sphere's north and south poles. Features of this sphere, such as its poles and equator, played a crucial role in the ancient understanding of the structure of the cosmos. As a result, the celestial equator was much better known in antiquity than it is today; for example, Plato, in his dialogue *Timaeus,* writes that the creator of the universe began the formation of the cosmos by shaping its substance into the letter X to represent the crossing of the ecliptic and the celestial equator.

were soldiers and state officials, and so the religion was strong in the provinces.

For most of antiquity it was believed that the axis of the celestial sphere was, like the earth, immovable. In fact, the earth's rotational axis (the modern equivalent of the ancient cosmic axis) is not fixed; it has a wobbling movement. As it wobbles, the celestial equator wobbles with it, and the relative positions of the equator and the ecliptic change. This so-called precession of the equinoxes means that the position of the sun in the sky at the equinox moves backward along the ecliptic, and so the equinox occurs slightly earlier every year. The complete precession takes approximately 25,920 years; the sun moves through one constellation every 2,160 years. Today the spring equinox is in the constellation of Pisces; in about the year 2200 it will enter Aquarius. During Greco-Roman times the spring equinox was in Aries, which it had entered in about 2000 B.C. Before that it was in Taurus.

With the exception of Leo, all the constellations in the tauroctony lie on the celestial equator as it would have been seen when the spring equinox was in Taurus. (Leo marks the sun's location at the summer solstice—the position of which is also shifted by the precession—in that era.) The arrangement of constellations in the tauroctony, then, matches an astronomical situation that prevailed 2,000 years before the origins of Mithraism.

How could Mithraists have known of this ancient astronomical arrangement, and why would they have seen it as having religious significance? The precession of the equinoxes was unknown for most of ancient times. It was discovered in about 125 B.C. by the Greek astronomer Hipparchus, only a few decades before the initial rise of Mithraism. His careful observations showed the celestial equator was in fact gradually shifting backward through the zodiac. His calculations also made clear which constellations would have lain along the celestial equator when the equinox was in Taurus (its most recent position before the Greco-Roman period).

From the geocentric perspective, the precession (a movement of the earth) appears to be a movement of the entire cosmic sphere. For people who held both a geocentric worldview and the belief that the movements of the stars influenced human fates, the discovery of the precession would have been literally world-shaking: the stable sphere of the fixed stars was being unseated by some force apparently larger than the cosmos itself. Ancient intellectuals, accustomed as they were to seeing the work of the gods reflected in the works of nature, could easily have taken this great movement as evidence for the existence of a powerful, hitherto unsuspected deity.

The meaning of the tauroctony now becomes clear: the death of the bull aptly symbolized the end of the reign of Taurus as the constellation of the spring equinox and the beginning of the most recent era. The other figures in the tauroctony all represent constellations whose special position in the sky was also ended by the force of the precession.

By killing the bull—causing the precession of the equinoxes—Mithras was in effect moving the entire universe. A god capable of performing such a tremendous deed would be eminently deserving of worship. Furthermore, the ability to move the cosmos would be seen as endowing Mithras with other powers as well, such as the ability to overcome the forces of fate residing in the stars and to guarantee the soul a safe passage through the planetary spheres after death.

Other Mithraic images indicate that Mithras was in fact believed to embody such cosmic power; there are scenes that show Mithras bearing on his shoulder the sphere of the universe or in which a youthful Mithras holds the cosmic sphere in one hand while with his other he rotates the zodiac. In several tauroctonies, the starry sky is shown contained beneath Mithras's cloak.

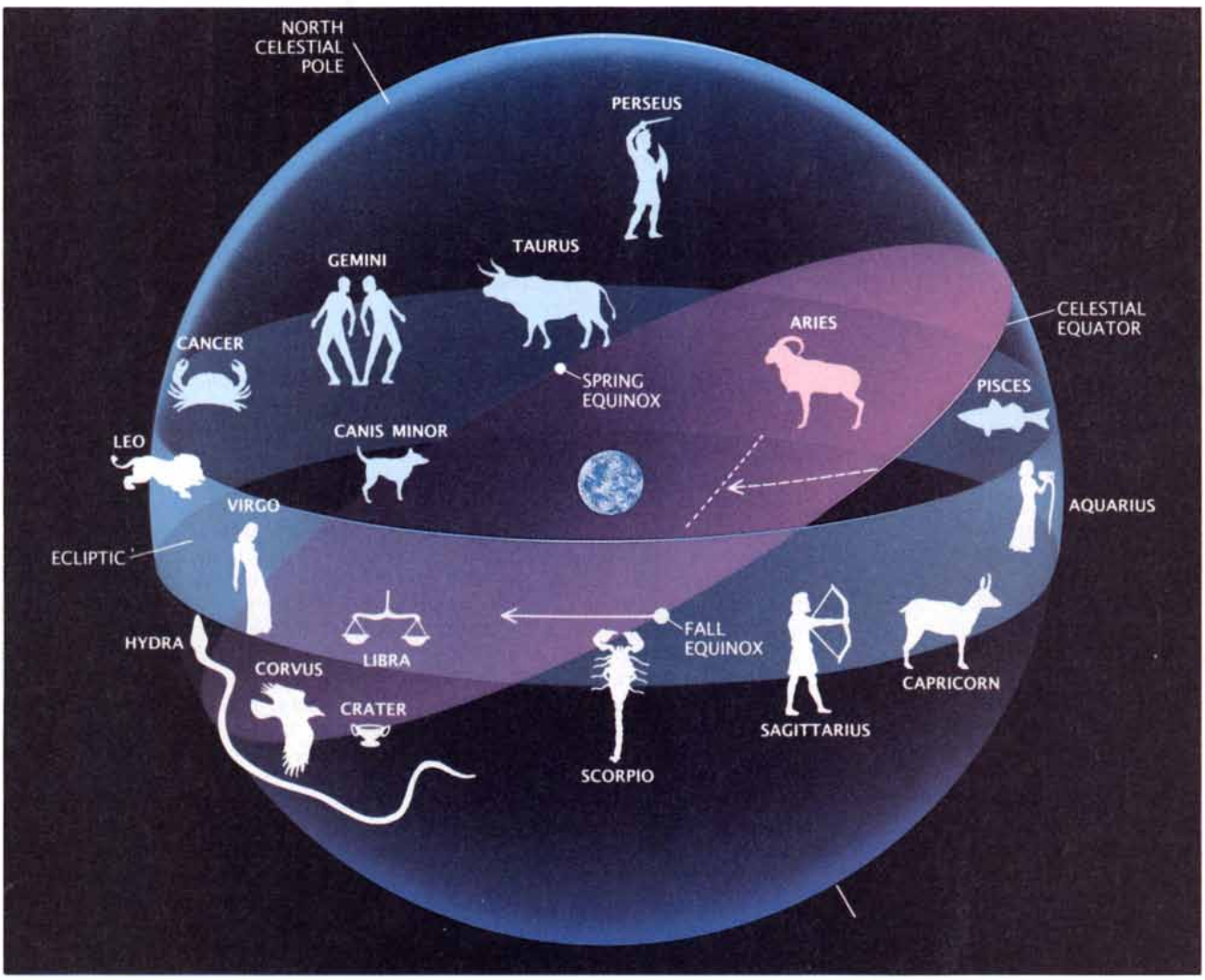
The status of Mithras as the motive force behind the precession of the equinox could also explain the secretive nature of the Mithraic mysteries. Adherents could well have believed that their knowledge constituted a powerful secret best kept to themselves and among selected initiates. For those chosen, an understanding of the complex astronomical structure underlying the nature of Mithras would have required a lengthy period of indoctrination. Only after acquiring

the requisite knowledge could initiates properly appreciate this new god.

An important question remains: If all the figures in the tauroctony represent constellations, then what constellation does Mithras represent? In the tauroctony, Mithras is located directly above the bull and is always depicted as a young man carrying a dagger and wearing a distinctive conical hat known as a Phrygian cap. The sky directly above Taurus, in fact, contains a constellation typically represented as a young man carrying a dagger and wearing a Phrygian cap: the Greek hero Perseus. Moreover, Perseus was worshipped as a god in Cilicia—precisely the region to which Plutarch traces the origins of Mithraism.

Tarsus, the capital city of Cilicia, was the home of one of the most important intellectual communities in the Mediterranean. This community was dominated by Stoic philosophers who were famous not only for their fatalism (which led them to be firm believers in astrology) but also for their tradition of personifying natural forces in the form of gods and heroes. Most likely, Mithraism arose as intellectuals in Tarsus, speculating about the force responsible for the newly discovered precession of the equinoxes, personified that power in the local Cilician god Perseus. Perseus, after all, was already identified as a constellation, and the message of his position in the sky was clear to read.

But if Mithras was originally in some sense Perseus, how did his name come to be Mithras? First, of course, it would make sense for a mystery religion to conceal the true name of its deity. Second, because of the sound of his name, Perseus was believed in antiquity to have been the founder of Persia (Iran) and thus could easily have become linked mythologically with the Iranian god of light and truth, Mithra. Third, around the time of the origins of Mithraism, most of Asia Minor came under the control of King Mithridates of Pontus, who formed a strong alliance with the Cilician pirates. Mithridates belonged to a dynasty named after Mithra; in addition, he and his ancestors believed that they were descended from Perseus. It was probably in the circles around King Mithridates—who fancied himself an intellectual and took a special interest in Greek religious beliefs—that the link



CELESTIAL EQUATOR (*purple disk*) moves through the sky as the earth's axis precesses. As a result, the equinoxes (points where the celestial equator crosses the plane of the ecliptic) gradually shift backward through the constellations of the zodiac. Those who believed the earth was at the center of the universe interpreted the precession as a motion of the celestial sphere—and hence as an unhinging of the entire cosmos. Figures depicted in the tauroctony, or bull slaying, represent constellations that lay on the celestial equator between about 4200 and 2000 B.C., when the spring equinox was in Taurus.

was formed between Perseus and Mithra that eventually led to the adoption of the name Mithras (the Greek form of the name Mithra).

Today Christianity is one of the world's dominant religions; Mithraism (along with any number of other cults) died out. Why?

One crucial difference between the two is that from its beginning Christianity sought to make as many converts as possible. The author of the gospel of Matthew, for example, ends by having Jesus say, "Go, therefore, make disciples of all the nations." Mithraism, in contrast, was based on a secret, and secrets lose their appeal in direct proportion to the numbers of people who know them.

In addition, Mithraism took hold mostly among groups of people—soldiers, bureaucrats, merchants—who were intimately bound up with the existing social order of the empire, and the cult's hierarchical structure fitted that order in a way that early Christianity, with its apocalyptic doctrine of the return of the messiah and disregard of earthly matters, did not. Early Christians (who were typically people whose social status was problematic in one way or another) possessed a revolutionary zeal that was completely absent in Mithraism.

While early Christians sought to enlighten the world, then, adherents of the Mithraic mysteries sought individual enlightenment and advancement within the existing culture. As a result, Mithraists had no hesitation in adopting practices that would necessarily limit the size of the cult's membership, such as excluding women from the cult, constructing temples as small underground cavities and establishing a complex series of initiation rites.

The heart of the matter, then, is not so much why Mithraism did not grow as Christianity did but rather how Christianity achieved the spectacular success that it sought: by the end of the fourth century it had led to the almost total elimination of competing religions in the Mediterranean world.

The precise reasons for Christianity's success are, of course, a matter of intense scholarly debate. There is a general consensus, however, that one of the most important factors was exclusivity. Becoming a Christian required that a convert give up all other forms of religious worship. Other religions of the times demanded no such single-mindedness: one could be an initiate of Mithras as well as of Isis, participate in sacrifices to Jupiter and at the same time venerate the spirit of a dead emperor. In a time when many people were experiencing the collapse of their traditional sources of meaning, the radical exclusivity of Christianity exercised a powerful appeal: it gave prospective converts the opportunity to make a truly decisive choice; those who did convert could believe that their lives had gained a real purpose and significance. In an age of confusion, Christianity offered its adherents a clear sense of identity.

TAUROCTONY painted during the second century A.D. in Italy shows the god Mithras in a position (relative to Taurus) matching that of the constellation that represents the Greek hero Perseus, with whom Mithras was linked. In this picture Mithras's cloak encompasses the stars and planets, symbolizing his power over the cosmos.

It is particularly interesting to note that Christianity appealed to some of the same astral-religious conceptions that lay behind Mithraism and other cults. Jesus was frequently described as having a power over the world of the stars. The author of the gospel of Mark (the earliest of the Christian gospels), for example, begins his story by describing how Jesus, at the moment of his baptism, "saw the heavens torn open." Through this image the author seems to have been attempting to convey the idea that the life of Jesus constituted a rupture of the cosmic order, the expression of a power greater than that of the heavens.

The same author also presents Jesus as saying, "In those days . . . the stars will fall from the sky. . . . Heaven and earth will pass away, but my words will not pass away." Paul's letter to the Galatians reads in part: "When we were children, we were enslaved to the elemental forces of the cosmos, but when the fullness of time came, God sent forth his son . . . to free [us]." Just as Mithras, by shifting the celestial sphere, upset the order of the universe, so the coming of Jesus was believed to have produced a rupture in the fabric of the cosmos.

Not only early Christianity and Mithraism but also many other religions and philosophical movements of that period expressed this same yearning for identification with a force that could break the boundaries of the cosmos and provide access to realms outside the limits of ordinary experience. Such a yearning was spurred by the upheavals of the time: as the local foundations of culture were undermined, individual horizons could expand. At the same time, scientists' imaginations suddenly stretched out to encompass a grand vision of the celestial spheres. Today's world, with its increasingly global culture and a science that in a single generation has leaped past the farthest galaxies, shows striking parallels with that ancient Mediterranean age.

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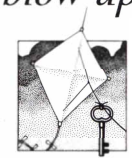
THE AMATEUR SCIENTIST

Why are the first few puffs the hardest when you blow up a balloon?



by Jearl Walker

Blowing up a common rubber balloon is child's play, but the inflation raises several challenging questions. Why is the inflation usually difficult at first and easier once the balloon is partially filled? (You might expect the inflation to get progressively more difficult as you stretch the rubber surface.) If you are inflating a cylindrical balloon, why does the inflation begin at one region and then travel down the length of the balloon? Suppose that you take two identical balloons, inflate them to different sizes and connect them with a tube. Will air flow from one balloon to the other so that they change in size, and if so, will they finally reach the same size?

To answer these questions, I must first explain a simpler object, a spherical soap bubble. The size of a bubble depends on a competition of two forces. One force derives from the internal air pressure, which attempts to expand the bubble. (Actually, the force is caused by the difference between the internal pressure and the smaller atmospheric pressure, but here I shall let "internal pressure" stand for the difference.) Countering the expansion is the surface tension of the soap film. The tension arises from the electrical attractions between molecules on and near the interior and exterior surfaces of the film. The tension attempts to contract the bubble.

When a bubble is blown, the competing forces automatically adjust the bubble's size and pressure until the forces are matched. In that state of equilibrium, the pressure is proportional to the curvature and inversely proportional to the radius of the bubble. Notice that the result means the air in a smaller bubble is under more pressure than the air in a larger one.

To understand why the pressure is less when the radius is larger, consider a cross section through a small patch on the bubble [*see illustration below*]. The edges of the patch are pulled outward along the surface by adjacent regions of the film. Each pull can be broken up into a component that is tangential to the center of the patch and a perpendicular component. The tangential components are matched in strength and pull on the patch in opposite directions, and so they cancel each other. The perpendicular components are also matched in strength, but since they both point radially inward, they add. When the bubble is in equilibrium, the air pressure on the patch balances the inward pull from the radial components.

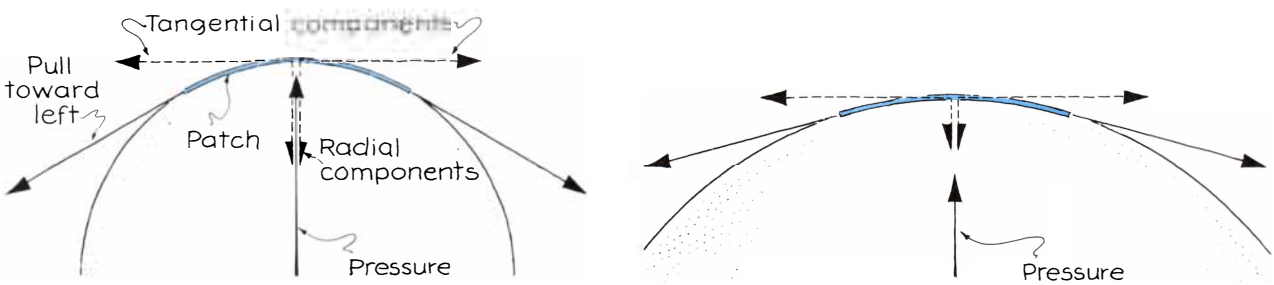
The pull on each side of the patch depends only on the surface tension, which does not vary as the bubble is inflated. How much of the pull is radial, however, depends on the curvature of the surface. Because the air pressure opposes the radial components, the pressure also depends on the curvature. When the bubble is small and tightly curved, the radial components are large, and so is the pressure. If the bubble is inflated to some larger size, the surface becomes less curved, and the radial components and the pressure become smaller.

In principle you can test the result by inflating a soap bubble. Dip a drinking straw into a bowl of water mixed with dish detergent and then blow into the other end of the straw to start a bubble. As the bubble grows, the air pressure you must produce decreases because the pressure in the bubble decreases. Of course, the expansion is so easy, even initially, that you may not notice any difference.

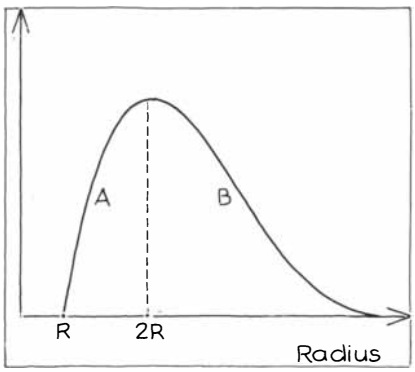
Because the surface tension in a soap bubble does not vary during inflation, the resistance to further stretching of the surface does not vary either, and the internal pressure is set only by the curvature. The rubber membrane of a balloon is different. It is elastic: the more it is stretched, the more it resists further stretching. The resistance can again be attributed to surface tension, but the tension does not come from a simple electrical attraction between molecules. Rather it comes from a cross-linked network of flexible, long-chain molecules. When the membrane is stretched, the interlinked molecules resist, trying to contract the membrane to its original size. The more the membrane is stretched, the harder the network resists.

The elastic property of a rubber balloon greatly complicates any study of how the internal pressure varies when the balloon is inflated. As with a soap bubble, the curvature still matters because it determines how much of the pull on the sides of a patch is radial. But with the balloon, the pull itself changes in size because of the elasticity. As the balloon is inflated, the decrease in the curvature tends to reduce the pressure while the increase in the stretching tends to raise it.

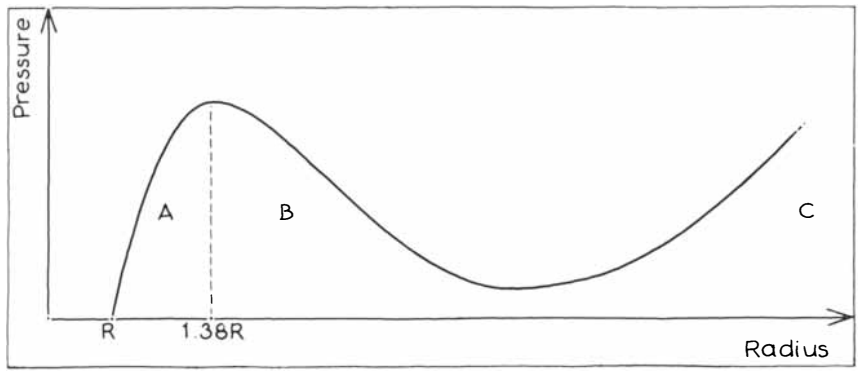
To see which tendency wins out during the inflation, one needs a model of



Forces on a patch of membrane in smaller and larger bubbles



Change in pressure as a balloon expands



Another analysis: the rubber resists extreme stretching

how the rubber in a balloon stretches. In 1986 Graham Read of the Open University in Milton Keynes, England, suggested that the stretching can be likened to the expansion of a spring. A spring resists stretching with a force that is proportional to the degree of elongation. For example, if you stretch a spring to twice its previous length, the force resisting you is twice as large as before, and so you must pull twice as hard to maintain the elongation or to increase it somewhat.

With his model Read computed how the pressure inside a spherical balloon varies with the radius of the balloon. The results are illustrated in the graph at the top left. (Recall that the pressure is actually the difference between the interior and exterior.) According to the computation, as the balloon expands, the pressure first increases in a region labeled *A*, peaks and then decreases in a region labeled *B*. In *A* the variation in the pressure is dominated by the rubber's resistance to stretching. In *B* the variation is determined by the decrease in the curvature. The peak is where the curvature takes control and the balloon begins to act like a soap bubble.

To follow the curve, imagine that you inflate a balloon. The balloon is initially flat, and your first puff serves to make it spherical without stretching the rubber. Let *R* be the radius of the balloon just then. The pressure and radius are represented by the lowest point of the curve in *A*.

When you blow in another puff of air, the point representing the balloon on the graph is driven up the curve: the balloon expands and the pressure increases until the balloon reaches an equilibrium state. Because the rubber's resistance to stretching dominates the balloon's behavior in *A*, the pressure of successive puffs must increase to expand the balloon further, to new equilibrium states. Read found that the peak pressure for an equilibrium state is reached when the radius is $2R$. When the radius is even larger (in *B*), each additional puff of air leaves the balloon in an equilibrium state with a lower pressure, and so the inflation becomes progressively easier. As you continue to blow into the balloon, you still must exceed the equilibrium pressure, but the equilibrium pressure gradually wanes.

According to Read's analysis, the pressure falls until the balloon is so large that it has no curvature. At that ideal limit, the tension would be quite large, but the pull on the sides of any patch on the balloon would have no radial, inward component. Of course, a real balloon would burst well before it reached such a limit.

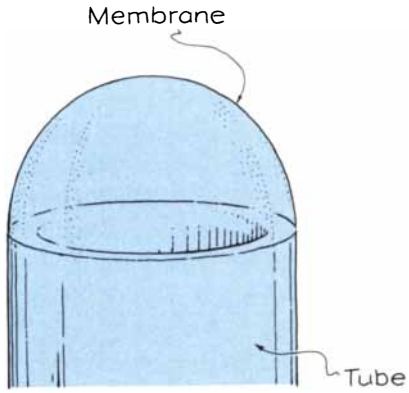
Another study of a balloon's inflation was published in 1978 by David R. Merritt and Frederick Weinhaus, both then at the University of Santa Clara. They employed a more complicated model of how the rubber of a balloon stretches, but their graph of the pressure versus radius is similar to Read's [*see illustration at top right*]. Again the pressure increases to a peak and then falls. They calculated that the peak pressure occurs at a radius of about $1.38R$. In addition, they noticed that if a balloon is inflated to a radius of several times *R*, the pressure begins to climb again, in a region I call *C*. The increase in pressure indicates that when the rubber is highly stretched, the resistance to further stretching increases faster than the curvature decreases.

A related study of inflation was published in 1973 by H. D. Crane of the Stanford Research Institute. Crane considered how a membrane would inflate if it were fastened over the opening of a tube in which the air pressure could be controlled. This arrangement differs considerably from the previous examples. When you blow into a bubble or balloon, you deliver a puff of air under a pressure that is higher than the existing pressure, but you do not maintain your pressure for more than a moment. In Crane's arrangement a regulator attached to a source of compressed air maintains the pressure continuously.

Suppose that a soap film spans the opening on the tube. Recall from the examples with soap bubbles that air pressure inside such a film is proportional to the curvature. Before the regulator is opened, the film is flat—it has no curvature. As the pressure is increased, the film bulges outward from the tube and the curvature increases in response. When the radius of the film matches the radius of the tube, the film is hemispherical. The curvature is then at a maximum, and so the pressure that the film can withstand reaches a peak. If the pressure is increased a little further, the film must expand outward, but the expansion reduces the curvature and hence the film's resistance to pressure. The film is no longer stable. Instead it expands uncontrollably until it bursts.

The soap film's behavior is charted in the lefthand illustration in the middle of the next page, where the pressure is plotted against the volume contained by the film. The graph resembles earlier graphs, although the horizontal axis shows volume instead of radius. The film's controlled expansion into a hemisphere takes place in *A*. The rapid expansion at the peak pressure is represented by the broken line that extends horizontally from the peak. The curve in *B* shows the pressure that could be balanced by the curvature when the film is larger than a hemisphere. The difference between the curve and the broken horizontal line is the pressure that drives the film outward during its uncontrolled expansion.

The analysis is similar when a rub-



Membrane billows from pressurized tube

ber membrane is substituted for the soap film on the end of the tube. Now, however, the graph of pressure versus volume has a region *C* in which the curve climbs a second time. *C* reflects the elasticity of the membrane; it is where the resistance to stretching begins to increase faster than the curvature decreases, thereby driving up the pressure.

Again imagine what happens when the pressure in the tube is gradually increased. A point representing the membrane first climbs through *A* until it reaches the peak. If the pressure is increased another notch, the membrane suddenly expands because the curvature cannot withstand the pressure. Like the soap film, the membrane expands dramatically. Just before the peak pressure is reached, the membrane swells only moderately from the tube. When the regulator is opened another notch, the membrane suddenly expands to several times its previous size. Yet the expansion does not continue uncontrollably, because the membrane can reach a new equilibrium state in *C*.

Next imagine what happens if the air pressure is slowly decreased. The point representing the membrane gradually slides down the curve until it reaches the lowest point—the bottom of the valley between *B* and *C*. If the pressure is then decreased slightly more, the curvature is too much for the pressure, and the membrane suddenly contracts to a new equilibrium state in *A*. The broken horizontal line extending to the left from the valley represents the contraction.

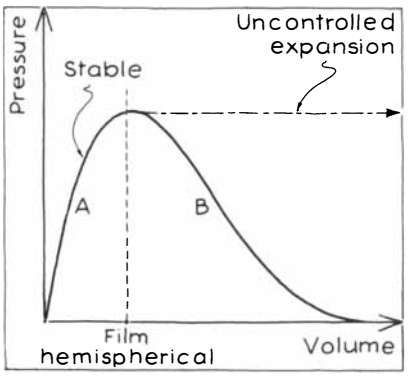
Crane suggested that a similar sudden contraction may be seen when an inflated balloon is released and allowed to rocket around the room. Suppose the balloon is initially inflated into region *C*. As air is discharged, the pressure drops, and the point representing the balloon on a graph falls to the valley between regions *B* and *C*. There the curvature of the balloon overwhelms the remaining pressure and suddenly ejects the rest of the air, which gives the balloon a final spurt.

How do these considerations of size and pressure apply to cylindrical balloons? In 1984 E. Chater and J. W. Hutchinson published a study of how a cylindrical balloon expands. As with a spherical balloon, blowing up a long balloon is hard at first, and then it becomes easier. In contrast to the inflation of a spherical balloon, however, the expansion is at first restricted to one spot, usually at the end nearest the opening.

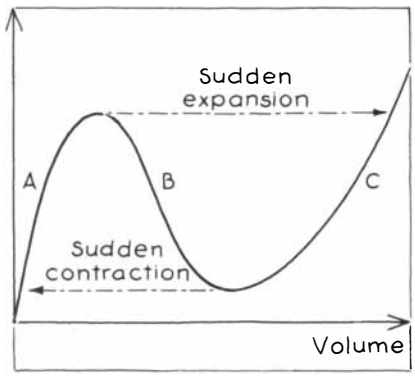
I will follow the graph of pressure versus volume that was developed by Chater and Hutchinson [*see bottom illustration on this page*], but I will interpret the mechanics of the inflation somewhat differently than they did. As the pressure is driven up through *A* on the graph, the balloon expands radially in a short bulge. The bulge initially behaves like a spherical balloon: once the pressure peaks, the decreasing curvature around the circumference of the bulge allows the pressure to decrease through region *B*. When stretching of the rubber in the bulge becomes extreme and the pressure is forced to rise a second time, however, something different happens. Just as the pressure begins to increase again, the bulge starts to extend.

Consider what happens when one more puff of air is blown into the balloon. The balloon needs to expand somewhere. The existing bulge resists further expansion because of the extreme stretching of the rubber there. Most of the uninflated part of the balloon also resists inflation because it lies in region *A*, dominated by the rubber's elasticity. Yet the uninflated part adjacent to the bulge is actually easy to inflate because of the membrane's curvature. Although the membrane is convex around the circumference of the bulge, it is concave for a short distance where the bulge meets the uninflated part. Components of the tension along the concave shape point radially outward, and so they actually help to expand the surface when more air is blown into the balloon. As a result, the front of the bulge travels along the balloon. Until the front reaches the end of the balloon, the pressure stays constant.

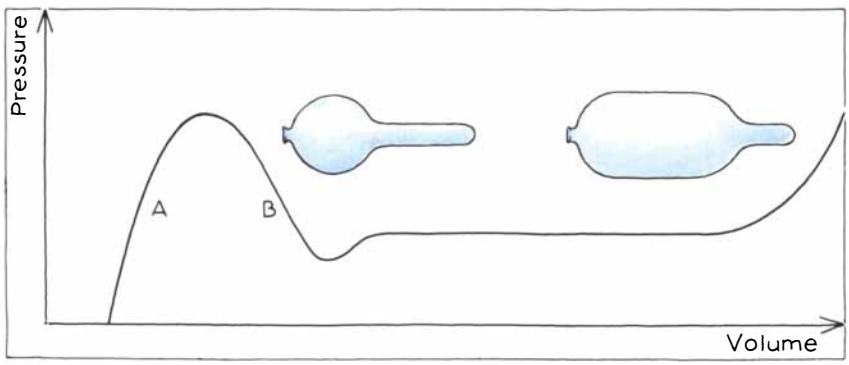
If you stop the inflation before it is complete, you can manually collapse



A soap film on the tube



A rubber membrane on the tube



Pressure during the growth of a cylindrical balloon

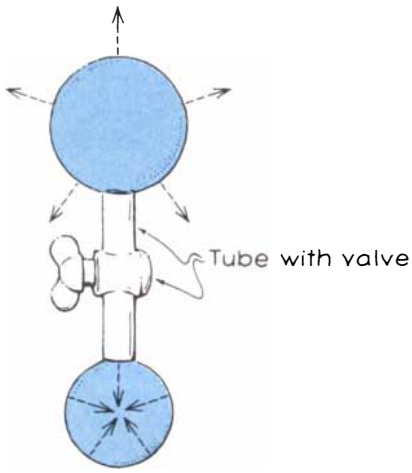
a spot in the inflated region. Squeeze the spot and shove the resulting smaller bulges off toward either end of the balloon. Twisting the balloon where you collapsed it also serves to drive the bulges apart. When you release the collapsed spot, it stays collapsed. Just like the uninflated part at the far end of the balloon, it cannot expand again unless you blow more air into the balloon. (Some party entertainers collapse several partially inflated balloons so that they can be wrapped around one another to form novel shapes.)

I now return to the question about balloons that are connected by a tube. Again soap bubbles can serve as a simple model. Suppose two bubbles of different sizes are connected by a tube with a valve that is closed at first so that air cannot flow between the bubbles. What happens when the valve is opened? Because the smaller bubble is under more pressure than the larger one, the smaller bubble collapses as its air flows into the larger bubble, which expands. The smaller the first bubble becomes, the harder it will push its air into the larger one because the pressure imbalance grows.

If the original bubbles are identical in size, they can remain so in principle, but their equilibrium states are unstable. If either bubble experiences the slightest chance disturbance, one will collapse and the other will expand.

The demonstration of interconnected bubbles was published in 1902 by Charles V. Boys, the British scientist who is remembered for his popularization of science. He did not comment on the final shape of the smaller bubble. I wondered about the final shape after reading about Crane's work with a soap film on a tube. The pressure in the smaller bubble does not increase steadily as it shrinks: instead it reaches a peak when the bubble contracts to a hemisphere and decreases thereafter, as the curvature decreases. In the meantime the pressure in the expanding larger bubble must also be decreasing since its curvature is also decreasing. Depending on the initial conditions, the bubbles must reach some final states of equilibrium in which their pressures match. The smaller bubble would then be smaller than a hemisphere, but not flat.

What happens when the bubbles are replaced with rubber balloons that are inflated to different sizes? The answer was given in 1978 by Weinhaus and William A. Barker, then his colleague, and independently in 1986 by Read. The answer depends on the initial states of the balloons when the valve between them is opened. If both balloons are in region *A* of their pressure-versus-radius graphs, the larger balloon will transfer air to the smaller balloon until the balloons are the same size and under the same pressure.



Interconnected bubbles

If the amount of air is greater than a certain critical value, however, the balloons will come to a common pressure but will have different sizes. One will be in *A*, the other in *B*. The critical amount of air is the amount needed to inflate both balloons to the pressure peak between *A* and *B*. One balloon could begin in *A* with a small amount of air, provided that the other balloon begins in *B* with enough air to put the total amount of air over the critical value, or both balloons could begin in *B*. On the other hand, if one balloon begins in *A* and the other in *B* but the total volume of air is below the critical value, then both balloons will end up in *A* with the same size and pressure.

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COMPUTER RECREATIONS

A Pandora's box of minds, machines and metaphysics

by A. K. Dewdney

"Are minds subject to the laws of physics? What, indeed, *are* the laws of physics?"

—ROGER PENROSE,
The Emperor's New Mind

Human intelligence outstrips artificial intelligence because it exploits physics at the quantum-mechanical level. That is a provocative position, but one that Roger Penrose, the noted mathematical physicist, leans toward in his new book. Although (as Penrose readily admits) the proposition cannot be rigorously proved at present, the intriguing arguments in *The Emperor's New Mind* have produced some healthy doubts about the philosophical foundations of artificial intelligence.

I shall present Penrose's arguments below—but because this column follows its own compass in charting unknown waters, I shall challenge some of his conclusions and tinker with some of his ideas. In particular, I shall expand the question How do people think? to ask whether human beings will ever know enough to answer such a question. If the universe has an infinite structure, humans may never answer the question fully. An infinite regress of structure, on the other hand, offers some unique computational opportunities.

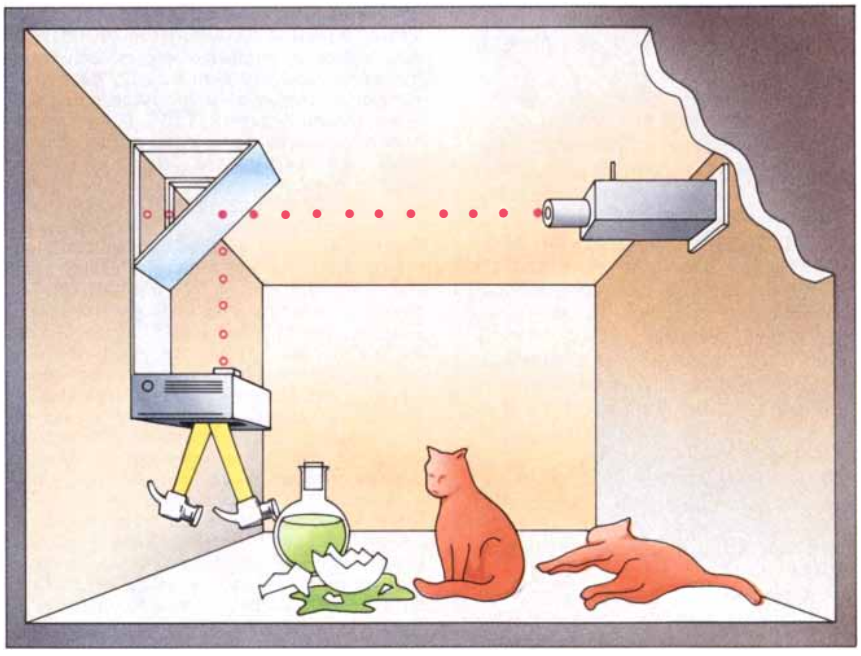
Before jumping into such matters, I invite readers to explore the recesses of *The Emperor's New Mind* with me. First, we shall visit the famed Chinese room to inquire whether "intelligent" programs understand what they are doing. Next, a brief tour of the Platonic pool hall will bring us face to face with a billiards table that exploits the classical physics of elastic collisions to compute practically anything. Moving along to Erwin Schrödinger's laboratory, we shall inquire after the health of his cat in order to investigate the relation between classical physics and quantum mechanics. Finally, we shall reach our destination: an infinite intelligence able to solve a problem that no ordinary, finite computer could ever hope to conquer.

Watching television one evening several years ago, Penrose felt drawn to a BBC program in which proponents of artificial intelligence made what seemed to be a brash claim. They maintained that computers, more or less in their present form, could some day be just as intelligent as humans—perhaps even more so. The claim irritated Penrose. How could the complexities of human intelligence, especially creativity, arise from an algorithm churning away within a computer brain? The extremity of the claims "goaded" him into the project that led to *The Emperor's New Mind.*

A methodical exploration of computing theory brought Penrose to criticize one of its philosophical cornerstones, the Turing test. Many computer scientists accept the test as a valid way of distinguishing an intelligent program from a nonintelligent one. In the test, a human interrogator types messages to two hidden subjects, one a person and the other a computer programmed to respond to questions in an intelligent manner. If, after a reasonable amount of time, the interrogator cannot tell the difference between the typed responses of the human and those of the computer, then the program has passed the Turing test.

Penrose argues that the test provides only indirect evidence for intelligence. After all, what may appear to be an intelligent entity may turn out to be a mockery, just as an object and its mirror image look identical but in other details are different. Penrose maintains that a direct method for measuring intelligence may require more than a simple Turing test.

To strengthen his argument, Penrose wanders into the Chinese room, a peculiar variation of the Turing test invented by philosopher John R. Searle. A human interrogator stands outside a room that only allows the entrance and exit of paper messages. The interrogator types out a story and related questions and sends them into the room. The twist: all messages that go into and out of the room are typed in Chinese characters.



Schrödinger's cat—is it dead, alive or both?

To make matters even more bizarre, a person inside the room executes a program that responds to the story by answering questions about it. This person exactly replaces the computer hardware. The task would be tedious and boring but, once the rules of execution were learned, rather straightforward. To guarantee the ignorance of the human hardware, he or she has no knowledge whatsoever of Chinese. Yet the Chinese room seems to understand the story and responds to the questions intelligently.

The upshot of the exercise, as far as Penrose is concerned, is that "the mere carrying out of a successful algorithm does *not* in itself imply that any understanding has taken place." His conclusion certainly holds if it is directed at the executing apparatus, whether flesh or hardware. After all, whether the program happens to be executed by a human or by a computer makes no difference, in principle, to the outcome of the program's interaction with the outside world.

But for this very reason the human in the Chinese room is something of a straw man: no one would fault a program because the hardware fails to understand what the program is all about. To put the point even more strongly, no one would be critical of a neuron for not understanding the significance of the pulse patterns that come and go. This would be true whether or not the neuron happened to be executing part of an algorithm or doing something far more sophisticated. Any strength in claims for artificial intelligence must surely lie in the algorithm itself. And that is where Penrose attacks next.

The world of algorithms is essentially the world of the computable. In Penrose's words, algorithms constitute "a very narrow and limited part of mathematics." Penrose believes (as I and many other mathematicians do) in a kind of Platonic reality inhabited by mathematical objects. Our clue to the independent existence of such objects lies in our complete inability to change them. They are just "there," like mountains or oceans.

Penrose cites the Mandelbrot set as an example. The Mandelbrot set was not "invented" by Benoit B. Mandelbrot, the renowned IBM research fellow, but was discovered by him. Like the planet Neptune, the set existed long before any human set eyes on it and recognized its significance. The Mandelbrot set carries an important message for those who imagine it to be a creature of the computer. It is not. The Mandelbrot set cannot even be computed! Do I hear howls of outrage? Strictly speaking, Penrose is right.

The Mandelbrot set, while it is but one landmark in the Platonic world, lies somewhat distant from algorithmic explorers. Readers may recall that points in the interior of the set can be found by an iterative process: a complex number c is squared and then the result, z_1, is squared and added to c, then the second result, z_2, is squared and added to c and so on. If the succession of z values thus produced never patters off into infinity, then c belongs to the set's interior. But here a grave question emerges. How long does one have to wait to decide whether the sequence of values remains bounded? The answer is, essentially, forever!

In practice one interposes a cutoff to the computation. In doing so one inevitably includes a few points that do not belong in the set because it takes longer for the sequence based on such points to diverge. Difficulties in computing the Mandelbrot set pale in comparison with other limitations on the algorithmic adventure. For example, mathematics itself is formally considered to be built of axiom systems. Set forth a modest collection of axioms, a rule of inference or two—and one is in business. A conceptual algorithm called the British Museum Algorithm generates all the theorems that are provable within the formal systems of axioms and inference rules. Unfortunately, the theorems thus produced do not necessarily include all truths of the system.

This discovery, by the mathematician Kurt Gödel, dashed hopes of mechanizing all of mathematics. Penrose takes Gödel's famous theorem as evidence that human intelligence can transcend the algorithmic method: "... a clear consequence of the Gödel argument [is] that the concept of mathematical truth cannot be encapsulated in any formal scheme." How then could Gödel's theorem itself be the result of an algorithm?

I do not know the answer to this question, but I have seen the point raised before. It does seem, however, that Gödel's theorem might be derived from other axioms and rules of inference and therefore could be produced by an algorithm. The theorem might be just part of a never-ending stream of metatheorems. I should be grateful to hear from knowledgeable readers who can set me straight on this point.

Whatever one's opinion on such questions, *The Emperor's New Mind* attacks the claims of artificial intelligence on another front: the physics of

computing. Penrose hints that the real home of computing lies more in the tangible world of classical mechanics than in the imponderable realm of quantum mechanics. The modern computer is a deterministic system that for the most part simply executes algorithms. In a somewhat jolly fashion, Penrose takes a billiard table, the scene of so many classical encounters, as the appropriate framework for a computer in the classical mold.

By reconfiguring the boundaries of a billiard table, one might make a computer in which the billiard balls act as message carriers and their interactions act as logical decisions. The billiard-ball computer was first designed some years ago by the computer scientists Edward Fredkin and Tommaso Toffoli of the Massachusetts Institute of Technology. The reader can appreciate the simplicity and power of a billiard-ball computer by examining the diagram on page 140D.

The diagram depicts a billiard-ball logic device. Two in-channels admit moving balls into a special chamber, which has three out-channels. If just one ball enters the chamber from either in-channel, it will leave by either the bottom out-channel or the one at the upper right. If two balls enter the chamber at the same time, however, one of them will leave by the out-channel at the lower right. The presence or absence of a ball in this particular out-channel signals the logical function known as an AND gate. The output is a ball if, and only if, a ball enters one in-channel *and* the other one.

A computer can be built out of this particular gate type and just one other, a chamber in which a ball leaves by a particular channel if, and only if, a ball does not enter by another channel. Readers may enjoy trying to design such a chamber, bearing in mind that additional balls might be helpful in the enterprise.

Everyone appreciates the smooth, classical motions of a billiard ball. It has other desirable properties that are hardly given a second thought. For example, no one ever has to worry whether a billiard ball is in two places at the same time. Quantum mechanics, however, produces such anxieties. Quantum systems such as the famous two-slit experiment leave open the possibility that a photon can be in two places at once [see "The Reality of the Quantum World," by Abner Shimony; SCIENTIFIC AMERICAN, January, 1988].

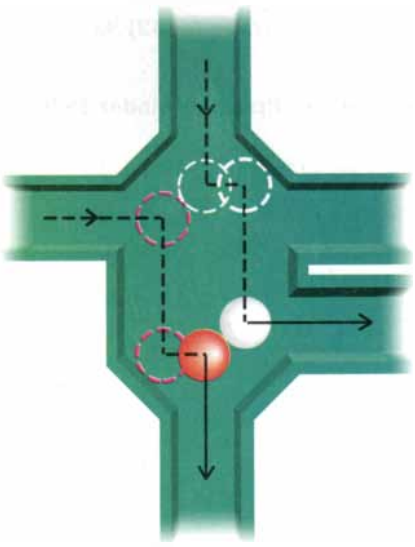
Briefly, when photons pass through a double slit, they can be regarded as waves that interfere with themselves. An interference pattern emerges on

a screen behind the slits unless one places a detector at either slit. The act of observation forces the photon to decide, in effect, which hole it will pass through! The phenomenon is called a state vector collapse. The experiment can be extended to an observation that takes place at either of two sites that are a kilometer (even a light-year) apart. The photon can decide which slit it will pass through, many physicists claim, only if it is effectively in both places at once.

At what point in the continuum of scales, from the atomic to the galactic, does a quantum-mechanical system become a classical one? The dilemma is illustrated by Schrödinger's famous cat. In this *gedanken* (thought) experiment, a scientist who has no fear of animal-rights activists places a cat and a vial of toxic gas in a room that contains a laser, a half-silvered mirror, a light detector and a hammer.

When the room is sealed, the laser emits a photon toward the mirror. If the photon passes through the mirror, no harm comes to the cat. But if the photon is reflected in the mirror, it hits the detector, which activates the hammer, which smashes the vial, which contains the gas, which kills the cat. From outside the room one cannot know whether the cat lives or dies.

In the quantum-mechanical world, the two possible events coexist as superposed realities. But in the classical world, only one event or the other may occur. The state vector (and possibly the cat) must collapse. Penrose suggests that current theory lacks a way of treating the middle ground between classical physics and quantum mechanics. The theory is split in two but should be seamless on a grand scale. Perhaps the synthesis will come from an area known as quantum gravity.



A billiard-ball AND gate

Now back, finally, to the human mind. For Penrose, consciousness has a nonalgorithmic ingredient. At the quantum level, different alternatives can coexist. A single quantum state could in principle consist of a large number of different, simultaneous activities. Is the human brain somehow able to exploit this phenomenon? I can hardly explore this eerie possibility as well as Penrose does. Readers intrigued by the thought had best buy the book.

I was inspired, however, to investigate a related question. Could human beings quantify their own intelligence in a universe whose structure goes on forever? An end to the structure of matter, either as an ultimate particle or a set of particles, seems inconceivable. By this I mean not just particles but any structure, whether energetic or even purely informational, underlying the phenomena in question.

It seems to me that physics itself may be an infinite enterprise for the simple reason that as soon as some "ultimate" structure is discovered, explaining the existence of the "ultimate" laws becomes the next problem. In any event, I would prefer to live in an infinitely structured universe. For one thing, our minds might turn out to be much more powerful than if the structure went only so far.

Computers are constructed to rule out the influence of any physical process below a certain scale of size. The algorithm must be protected from "errors." Our brains may or may not be so structured, as Penrose points out. Physical events at the atomic level might well have an important role to play in thought formation. Processes at the molecular level certainly do. One has only to think of the influence of neurotransmitter molecules on the behavior of a neuron. Furthermore, it is a well-known characteristic of nature to take advantage of physical possibilities in the deployment of biological operations. If physical structures extend to a certain level, is there some a priori reason to believe that the brain must automatically be excluded from exploiting it?

What if the brain could exploit all levels of structure in an infinitely structured universe? To demonstrate in the crudest imaginable way the potential powers of an infinite brain, I have designed an infinite computer that exploits the structure at all levels. For the purposes of the demonstration, I will pretend that the structure is classical at all scales.

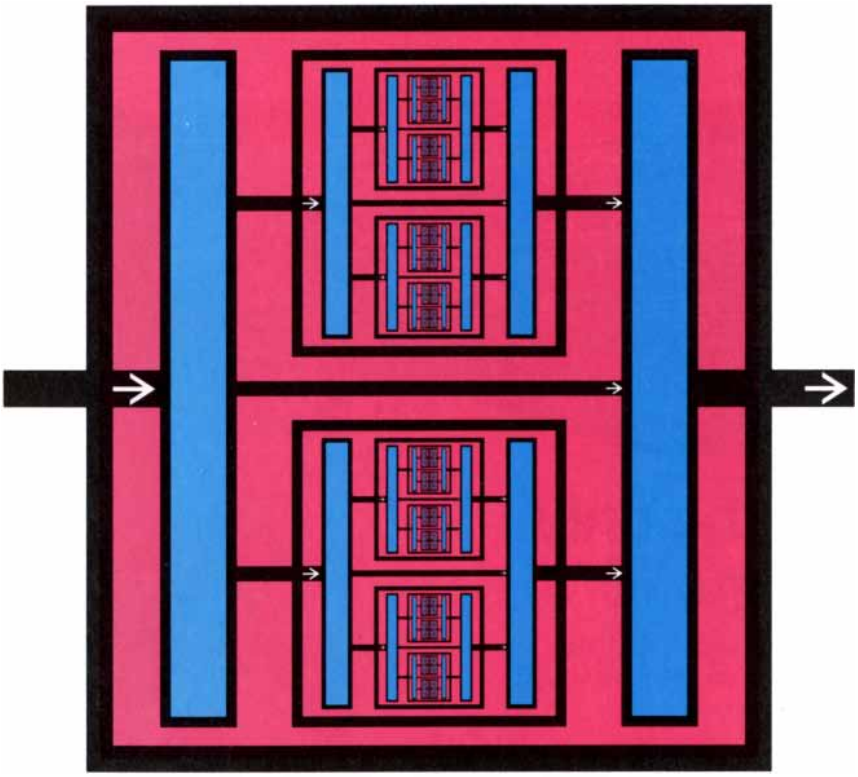
My infinite computer [*see illustration on page 142*] is essentially a square that contains two rectangles and two other, smaller squares. An input wire enters the big square from the left and passes immediately into the first rectangle. This represents a signal-processing device that I shall call a substitution module. The substitution module sends a wire to each of the two small squares and also to the other rectangle, henceforth called a message module.

The structure of the whole computer regresses infinitely. Each of the two smaller squares is an exact duplicate of the large square, but at half the scale. When a signal is propagated through the wires and modules at half the scale, it takes only half as long to traverse the distances involved, and so the substitution and message modules operate twice as fast as the corresponding modules one level up.

The infinite computer solves the famous "word problem" invented by the mathematician Axel Thue. In this problem, one is given two words and a dictionary of allowed substitutions. Can one, by substitutions alone, get from the first word to the second one? Here is an example of the problem: suppose the first "word" is 100101110 and the second is 01011101110. Can one change the first word into the second by substituting 010 for 110, 10 for 111 and 100 for 001? The example is chosen at random. I deliberately refrain from attempting to solve it.

It might happen that no sequence of substitutions will transform the first word into the second. On the other hand, there might be a sequence of substitutions that does the job. In the course of these substitutions, intermediate words might develop that are very long. Therein lies the problem. As with certain points in the Mandelbrot set, one cannot effectively decide the answer. There is no algorithm for the problem, because an algorithm must terminate, by definition. The danger is that the algorithm might terminate before the question is decided. Thue's word problem is called undecidable for this reason. No computer program, even in principle, can solve all instances of this problem.

Enter the infinite computer. The target word is given to the computer through the main input wire. It enters the first substitution module in 1/4 second. The word is then transmitted by the substitution module to the two substitution modules at the next level. But this transmission takes only 1/8



A fractal computer solves Thue's word problem

second. Transmission to subsequent levels takes 1/16, then 1/32 second and so on. The total time for all substitution modules to become "loaded" with the target word is therefore half a second.

Next, the three (or however many) substitution formulas are fed into the computer by the same process and at the same speed. This time, however, the various substitution modules at different levels are preprogrammed to accept only certain substitutions in the sequence as their own, and they are also preprogrammed always to attempt a substitution at a specific place in a word that arrives from a higher level. A recital of the distribution scheme for farming out the substitutions and their places would probably try the reader's patience, and so I shall omit it. This should not prevent those who enjoy infinite excursions from imagining how it might be managed.

The computation begins when one sends the first word into the computer. The first substitution module attempts to make its own substitution at its allotted place in the incoming word. If the substitution cannot be made in the required place, the substitution module transmits the word to the lower square in the next level down; if it succeeds in making the substitution, it transmits the transformed word to the upper square. If the substitution succeeds *and* the newly produced word matches the target word stored in the substitution module's memory, then the module sends a special signal to the message module: "success."

Each square at each level operates exactly in this manner. As I indicated earlier, it is possible to distribute substitutions (and places at which they are to be attempted) throughout the infinite computer in such a way that the word problem will always be solved. The question takes at most one second to decide in all cases: half a second for the computation to proceed all the way down to infinitesimal modules and half a second for the message "success" to reach the main output wire. If no substitution sequence exists, the absence of a message after one second may be taken as a "no" answer. Readers may enjoy pondering the infinite computer while exploiting the many (perhaps infinite) structures of their own brain.

It seems long ago when, in August of 1984, this column featured the Busy Beaver problem: if a Turing machine is allowed to have no more than n states, how many 1's can a Turing machine be made to produce before it finally halts? Turing machines are conceptual devices that read and write 0's and 1's on a tape. For each possible state a Turing machine might be in, it has a specific response to each symbol that it might read on the portion of tape that it is currently scanning. The response includes what symbol to write and which way to move the read-write head for the next cycle of action.

In the Busy Beaver problem the Turing machine is the "beaver." The question is, How busy can we make it? The question has been settled for one-, two-, three- and four-state Turing machines. Before the 1984 column the busiest five-state beaver known produced 501 1's before halting. Then, one of our readers, George Uhing of the Bronx, N.Y., discovered a five-state machine that printed 1,915 1's. Until recently, this was the world record.

Allen H. Brady of the University of Nevada at Reno reports a new, even busier beaver found by Heiner Marxen and Juergen Buntrock of the Technical University of Berlin in West Germany. The Marxen and Buntrock beaver is almost four times busier than Uhing's. It outputs 4,098 1's and undergoes 47,176,870 cycles before stopping! Can a beaver be any busier? Perhaps one of our readers can find one.

In "Computer Recreations" for this past August, I challenged readers with a puzzle from Dennis Shasha of New York University. Shasha's book, *The Puzzling Adventures of Dr. Ecco,* includes the problem of designing an Antarctic research station that must have 31 rooms. No room may have more than four doors, and the rooms should be arranged so that one must walk from any room to any other room without passing through more than six doors. I asked whether readers could devise an architecture to accommodate more than 31 rooms.

More than 100 readers sent in solutions to Shasha. Although many managed 53 rooms based on a tree-structured layout, a number of especially clever respondents noted that it was not necessary for all paths to pass through a central room. In fact, by abutting two trees so that their "leaves" are shared, these readers obtained an architecture with 70 rooms, all on the same floor. Joint proposers Eric Jordan and Eric Weeks of Downers Grove, Ill., found an even cleverer approach wherein certain "leaf rooms" could be split in two.

FURTHER READING

THE EMPEROR'S NEW MIND: CONCERNING COMPUTERS, MINDS, AND THE LAWS OF PHYSICS. Roger Penrose. Oxford University Press, 1989.

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BOOKS

Santa Claus bags a varied collection of science books for children

by Philip and Phylis Morrison

Voyagers

THE HOME PLANET, conceived and edited by Kevin W. Kelley for the Association of Space Explorers. Addison-Wesley Publishing Company and Mir Publishers, Moscow, 1988 ($39.95).

Typographically handsome and with beautiful photographs from space (owing a good deal to the craftsmanship of its talented printers in Italy), this book is as poignant as it is dramatic. Near the end there is a list of the 201 individual men and women "who have completed one or more orbits of the Earth as of 1 January 1988." (There must be a dozen more of them by now.) Many belong to their voluntary association—space explorers who were launched to a national drumbeat but who now share a clear vision of one fragile blue world inside curved horizons.

Here are about 150 glowing images made from orbit, well documented with when, where and how, assembled mostly from the take of hand-held camera shots now in Soviet and NASA archives; the editor's first criterion was the mood and the beauty of the scene, although he made sure to represent the diversity of earth forms by adding what was needed from large-format mapping cameras. Around these images he has set remarks by these articulate witnesses, each flyer being cited in the original tongue, with a translation into English (or into Russian for the Moscow edition). It is a small surprise to see texts not only in English and Russian but also in 14 other languages: Arabic, German, Hindi, Vietnamese...

The words, some direct and others poetic, often funny, span a spacious experience. Read a few of the many. Vitali Sevastyanov carries us along at orbital speed: "In the morning I did my exercises ... on the exercise bike from South America to Vladivostok, successfully overcoming the Himalayas. In the evening I took a stroll on the walking machine from Los Angeles to Lisbon, and I didn't even notice the storm in the Atlantic." Fundamentals come clear. Jeffrey Hoffman suddenly realizes where he is: "I saw a meteor go by underneath me.... That can't be a meteor. Meteors burn up ... above us.... Then, of course, the realization hit me." And Valeri Kubasov offers Johnsonian evidence for Newtonian dynamics in weightlessness: "You experience a strange dreamlike ... freedom. You can spread out ... as if soaring in the clouds. You quickly learn to avoid ... the walls of the station, though. Rubbing your bruise, you remember that your mass remains with you."

The most personal and humane of many luminous albums from space, this book is dedicated "to all the children of the world." It would certainly be welcomed in any of their homes, schools or libraries.

ARCTIC EXPLORER: THE STORY OF MATTHEW HENSON, by Jeri Ferris. Carolrhoda Books, Inc., 1989 ($9.95).

In 1880 Matthew Henson was a smart black kid on the Baltimore docks. He went to sea, to return a skilled seaman, although still the wrong color. Robert E. Peary, 30 years old, was a tall, red-headed U.S. Navy engineer; the two met across a hat counter in a Washington shop where young Henson was a new stock clerk. Peary hired Henson on the spot to act as his servant for a season of government survey in Nicaragua. Lieutenant Peary had a dream, the dream of being first at the North Pole, and Henson came to share it.

Matt Henson, "apt at anything," became indispensable to Peary. The two of them were clear that to move, even to survive, on the ice meant to be guided by Eskimo experience: Eskimo judgments, clothing, dogs, sleds. Henson was admired by the Eskimos, and he learned their ways and their tongue better than any other of Peary's many companions. The most exciting episode tells how they crossed the Big Lead on snowshoes, keeping their feet wide apart like polar bears, on thin, transparent, undulating ice forming over a mile of open sea. After 18 years of seeking the Pole on expedition after arduous expedition, Matt Henson could pose at last among four Eskimo hunters for Peary to snap the picture: the first men at the North Pole.

After 1909 Admiral Peary was a pensioned hero until his death in 1920; Henson worked as a modest Customs House clerk until he retired in 1936. Slowly Henson gained some of his due of recognition. In 1944 Congress at last gave him a medal for his old service. Old Matt and his wife Lucy can be seen here visiting President Eisenhower at the White House on the 45th anniversary of reaching the Pole. Matt died the next year, in 1955; it was 1988 before he would be reburied next to Peary in Arlington National Cemetery. In 1912 Peary's preface to Henson's own book had been explicit: "The example and experience of Matthew Henson ... [shows] that race, or color, or bringing-up ... count nothing against a determined heart, if it is backed and aided by intelligence." But America was not yet listening.

THE ATLAS OF NATURAL WONDERS, by Rupert O. Matthews. Facts on File, Inc., 1988 ($35).

Globe-trotting from west to east, from Greenwich all around by the longitudes, this book takes the sight-seeing reader at ground level to 52 special places marked on the map, stopping at each for a large, colorful photographic view. Each stop is supplemented by two or three pages of close-ups, local maps and clear descriptive commentary on land forms, life and people. Good readers at any age can join these varied arrivals, most of them at famous destinations, a few of them less frequently viewed but just as wonderful.

Lake Baikal is here, oldest and deepest of lakes, with profiles to show how much deeper it is than the transient Great Lakes, holding more water than all five of them together. In it dwell many fish species, half of them found nowhere else, often living in those dark depths on the debris that comes down from the surface waters. There are even seals, probably immigrants from the distant Arctic during interglacial times, that raise their pups in snow lairs on the winter ice.

The "porcelain" dunes of White Sands are seen in a superb photograph under that flawlessly blue New Mexico

sky; overleaf is the strange, bleached, earless lizard of the Sands. Anak Krakatau, Son of Krakatoa, is shown as it has arisen from the sea since 1952 between Java and Sumatra. A few pages recount the explosion of his terrible father a century ago; Anak will likely follow the same career one of these centuries. See the daunting ice cliff at the Ross Ice Shelf in Antarctica, the "bewitching" sugarloaf hills of Guilin in southeast China (although none of the classic paintings), the Niagara cascade and the much larger one at Iguaçu and 45 more such places, an itinerary to challenge even TV travelers. The book is bound to draw along and strengthen the world grasp of many a stay-at-home reader.

THE SIERRA CLUB WAYFINDING BOOK, by Vicki McVey. Illustrated by Martha Weston. Little, Brown and Company, 1989 ($13.95).

What is it like to be lost? Young Jesse found out one rainy day in the mountains. He sloshed through the trees on a shortcut home, but after a couple of hours of confused turnings, he had to admit he was "one small person in the middle of a huge forest and he was lost." It finally came to him that his dog was not at all lost but was cheerfully nosing about for small animals to chase. "Go home!" he ordered. She went off without hesitation; he followed, and in half an hour they were at their own clearing.

This author, a gifted teller of tales and a trained cartographer, wants to explain how private wayfinding maps are made. We all have plenty of them in the head (dogs do, too). In that cheery vein the chapters proceed. You read of desert people, jungle folk, hunters on the ice, the wonderful navigators of Polynesia and how they all managed wayfinding from clues they sensed in the environment. Games and practice are prescribed to help you use your own sensors better. Then you meet the grids we call coordinate systems, and the public maps they make possible. Latitude and longitude, pilotage and sun-shooting and contours on the map are all explained, amid real examples of how people have used them, whether in Viking ships or lost in World War II aircraft.

Nobody is perfect. What if you do get lost? Don't panic. Someone is looking for you, too. "Practice wayfinding as if your life depends on it, and enjoy the journeys that take you on your way." The broader strokes here are both fun and wise; they are of more help than the brief directions for activities, one or two of which are hard to

follow. But in all it is a thoughtful, delightfully written book for footloose readers older than 10.

The People

IN THE BEGINNING: CREATION STORIES FROM AROUND THE WORLD, told by Virginia Hamilton, illustrated by Barry Moser. Harcourt Brace Jovanovich, Publishers, 1988 ($18.95). **WHY THERE IS NO ARGUING IN HEAVEN: A MAYAN MYTH,** written and illustrated by Deborah Nourse Lattimore. Harper & Row, Publishers, 1989 ($13.95). **EARTHMAKER'S TALES: NORTH AMERICAN INDIAN STORIES ABOUT EARTH HAPPENINGS,** written and illustrated by Gretchen Will Mayo. Walker and Company, 1989 ($11.95). **WHY THE CRAB HAS NO HEAD,** an African tale retold and illustrated by Barbara Knutson. Carolrhoda Books, Inc., 1987 ($9.95). **STAR TALES,** by Ian Ridpath. Universe Books, 1988 ($19.95).

Five books, as varied as the polyglot tales they recount, present word and image about origins. The Hamilton book, its rich paintings in as many styles as the tales, tells 25 creation stories in a prose that conveys the elevation of myths evoking such sacred names as Zeus, Prometheus and Elohim. One wry story from Togo tells in a lighter mood of Spider Ananse the trickster, captain of the guards of Wulbari, God in Heaven. In the beginning there was no space to live in, for Heaven was only five feet above mother earth. The painting shows what happened. An old woman pounded her food in a mortar outside her hut with a big pole. The tip of the pole kept knocking and poking Wulbari, and "so He lifted the blue of his heavenly self just a little higher." The book has something for readers young and old and even for the read-to.

Lattimore, who works her colorful images on every page to resemble the glyphs and carvings of the Mayan ruins, orders in her own way the four creations of the *Popol Vuh:* a wordless and prayerless world of cawing and grunts, animal alone; inarticulate mud creatures washed away derisively by the summer rains; wood ones whose words grate and screech (some of them still live as the monkeys); bronzed men and women who worship gladly, prospering each spring with the aid of the Maize God. Readers in the early grades can master this book, and any others who know of the Maya will enjoy it.

The tales of earthmaking are gathered from a smaller field; they are told briefly and quietly in simple language, some in less than a page, supported by black-and-white designs and wash paintings. Somewhere to the north, an anthropologist heard long ago among the Cheyenne, the Father of All is a snow-white beaver. Whenever the people anger him, he gnaws on the pole that supports the earth. One day he will gnaw the last bit, and "the people will be no more."

The Bakongo tale is suited to the youngest readers, with its bold black-and-white drawings and borders and its brief text pages. In Zaire, Nzambi Mpungu made the earth and the sky and then the other animals, but creation was not complete until she had formed the crab, so boastful that he still scuttles shamefacedly sidelong.

The last book is rather different, a valuable library book of reference as well as a book to be read through. The myths retold here are those that pertain to the Greek and Roman constellations, known best by way of poets from Ovid to Robert Graves. Each of their constellations is addressed, not only the 48 defined by Ptolemy but also those of more modern origin among the 88 that in current usage cover the entire sky. The only inanimate icon in the zodiac is Libra, the balance; old Manilius says it is the sun sign "in which the seasons are balanced" at the fall equinox. A chapter treats a score of celestial gerrymanders that did not stick, such as the Printing Shop offered in 1801 to commemorate 350 years of Gutenberg.

THE IGLOO, written and illustrated by Charlotte and David Yue. Houghton Mifflin Company, 1988 ($13.95). **IN TWO WORLDS: A YUP'IK ESKIMO FAMILY,** by Aylette Jenness and Alice Rivers. Photographs by Aylette Jenness. Houghton Mifflin Company, 1989 ($13.95).

In about 100 pages the Yues once again describe a traditional way of life with remarkable clarity, simplicity and understanding, much aided by the detailed line drawings they include, often with cutaways and sections. Half a dozen brief chapters outline the old life of the "Real People" in their circumpolar land.

An igloo is no hemisphere of snow. The dome's profile is that of a catenary, resembling a hanging chain of links inverted and frozen. The cut snow blocks are set so that they spiral upward; igloos come left- and right-handed, depending on the builder. The dome, its inside surface sealed by a glazed film of ice, traps air warmed by bodies and oil lamps to stay about 65 degrees above the outside temperature. An igloo is entered from below, because cold drafts do not rise. The Eskimos knew both mutual help and competition; their diversions were to gamble, wrestle, play games, listen to tales, dance and feast; generally Eskimos "could not understand people doing dangerous things for excitement or competition." These ingenious and artistic people have long known how to adapt to a taxing environment by thoughtful development of a powerful technology; today they need to adapt less to the Arctic than to the white man's world.

And they are fast learning to do that, too. Aylette Jenness and Alice Rivers are old friends, who met in the little Yup'ik village of Scammon Bay on the Bering Sea 25 years ago, when Alice was a teenager. Aylette had come with her two babies to live in the village for a year or so; she is now a widely traveled author and ethnographer. Alice has not gone farther from Scammon Bay than Fairbanks.

The village has now doubled: about 60 houses—no igloos—with electric power, telephone, cable TV, clinic, gym with basketball court. Fuel oil comes by sea; light planes arrive three times a day, bringing mail and goods. Scammon Bay is still alone; an aerial shot shows no roads and no other dwellings out to the far horizon.

Alice is school cook now; her husband Billy is a successful hunter and trapper of seal and muskrat. During the right spring weeks the entire family sets up fish camp right at the shore; in the tents "it never gets dark . . . , and it's fun." They catch herring by the ton to dry for food and sell the roe to Japanese boats offshore. Two snowmobiles provide speedy winter transportation, but still the family keeps a team of eight big, hungry dogs for the sled races. Grandfather Teddy Sundown plays the drums nearly every week at the traditional dances. *Akutag* is Alice's favorite home treat; the old recipe mixes shortening, sugar, fish and berries in season.

Billy Rivers says of his children: "I'd be happy to have them travel . . .—*if* they have a job. 'Cause Outside there's many people without jobs, no home. Here it's okay, as we help each other." Alice adds: "I want them to learn other ways—outside ways. And . . . our ways, too . . . both ways." They are all working at it.

Intimate photographs and expressive conversation fit this optimistic book for a wide range of readers, certainly from age 10 up to high school. Individuals and families large and small have their troubles, in all lati-

tudes. No one's future is certain; it was oil taxes that paid for much of Alaska's large investment in housing and public services, and that essential income is likely to decline. But the Yup'ik plainly both adapt and maintain, and their resilient example may help us all.

Physical Sciences and Technology

BEN FRANKLIN STILLED THE WAVES: AN INFORMAL HISTORY OF POURING OIL ON WATER: WITH REFLECTIONS ON THE UPS AND DOWNS OF SCIENTIFIC LIFE IN GENERAL, by Charles Tanford. Duke University Press, 1989 ($33.50).

Dr. Franklin was no dilettante, but a knowing pro of science, critical of theories, canny about the details of measurement. His glorious and daring experiment with the kite was unique; it was "in character for a man of destiny" to draw lightning from the heavens. This book, full of insights and acute asides, is an amplification of one much humbler experiment of Franklin's. A teaspoonful of cooking oil he dropped on the surface of a large pond "'produced an instant calm . . . which spread amazingly . . . making all that quarter of the pond . . . as smooth as a looking glass.'"

Stilling the waves with oil is cuneiform-old. But that astonishing spread, the area increasing from a teaspoon's to half an acre, was first reported, controlled and emphasized by Franklin. In 200 pages free of jargon or burdensome mathematics, our membrane-scientist author draws the reader to what came out of the unmatched thinness of the calming layer of oil. We move past Colonial Agent Franklin in London, past the blossoming of atomic chemistry, past the key 1890 inference of molecular size, up to modern days. The history is more credible here than in many more formal sources. Tanford's subtitle makes that understandable: he examines people not only for their ideas, their institutions and their personal attributes but also with the empathy of a scientist watching a colleague through mutual ups and downs of mind and heart, sharing, as if with students, the thrust of books and papers good and bad.

Two fresh tales, then, amid more. We see young Agnes Pockels, whose simple device for changing the area of a surface layer without adding any contamination "laid the foundation for nearly all modern work with films on water," as Irving Langmuir wrote of her instrument, which he had himself adapted. Yet Agnes never even entered a full secondary school; her brother won a Göttingen physics degree, but "women had not yet the right to study," only the right to display deep interest and unquenchable talent.

The double layer of biological membranes was brilliantly if indirectly demonstrated in 1925 by the Utrecht clinical pediatrician Evert Gorter. He and a graduate student, F. Grendel, told of removing the fatty coating from a counted number of red blood cells. The area that sample covered on a water surface came to about twice the total area of the surface of those red cells. The cell coating must, then, have been a thin molecular sandwich, with water-seeking ends of molecules forming both outer faces and a mobile, oily near-fluid the filling within. The now classic few pages of results and tightly argued explanation had little immediate effect; that increase in area by a factor of two seemed not to have been accurately established.

About 50 years later, after electron microscopes and X-ray diffraction had been put to work, the bilayer model of Gorter and Grendel was recognized as the universal framework for all cellular membranes. This outstanding book for any reader past the eighth grade lets us follow for ourselves the long, twisting, tantalizing search for these deep ideas.

THE WAY THINGS WORK, by David Macaulay. Houghton Mifflin Company, 1988 ($29.95).

In structured and readable drawings, big and little, this talented illustrator has visually taken apart and reassembled hundreds of contrivances—machines that move, devices for controlling air, fire and water, sound and light, and electronics. A reader of any age can follow these diagrams and explanatory paragraphs, often reviews and sketches of the physics behind the technical feat. The author's net is spread very wide, to catch brace and bit, gun cartridge, jump jet, laser printer, microprocessor and Xerox, all at a useful first level of detail.

And that is by no means all. Across many pages, some in color, the matter-of-fact information is complemented by a continued whimsical frieze of hard-working gymnastic mammoths, while the narrator explains how work with the woolly creatures long ago led him and his mates to the invention of rafts or wheels or whatever. If elaborate whimsy bothers you at all, this book is to be avoided; most readers, particularly young ones, will enjoy the fun time after time.

"The way things work" is sensibly shown and helpfully simplified. One myth has somehow crept past both the author's physical insight and his advisers: it is quite falsely said here that nuclear reactions create energy and, alone among changes, do not "convert one form of energy into another." "The waste products ... have less mass than the fuel, and the lost mass turns into heat energy." But that is true in general; burning logs (including the oxygen they consume) or unwinding watchsprings lose mass in just the same way. The only difference is in amount. Physicists need to take the blame for this link between nuclear energy and mass, misunderstood since late 1945. The link is real, of course, but it is not at all unique to the nucleus; energy and mass are jointly conserved and interconverted in every energy change we know. This fine big book may have put the myth so memorably, by its use of a reactor-mammoth made in concrete, that it may defy correction!

FOR YOUR OWN PROTECTION: STORIES SCIENCE PHOTOS TELL, by Vicki Cobb. Lothrop, Lee & Shepard Books, 1989 ($14.95).

The frontispiece shows a balloon as a hollow hemisphere, the needle that popped it so loudly well within the original volume, 40 milliseconds into the burst. Tight-shut eyes demonstrate the speed of the startle reflex of the small boy who had burst the balloon for the fast strobe flash. Fifteen or so other big pages show a sneeze too fast, colors too red and blood cells too small to see.

The simple, factual text conveys well the idea of using photographic devices to make visible what we cannot see directly, a path to insight for readers in primary grades. This experienced author has carefully selected images that are recognizable because they are extrapolations from everyday vision.

SIMPLE MACHINES, by Anne Horvatic. Photographs by Stephen Bruner. E. P. Dutton, 1989 ($13.95). **HOW IS A CRAYON MADE?,** written and photographed by Oz Charles. Simon and Schuster, Books for Young Readers, 1988 ($9.95).

You make them work, these machines that don't need electricity, that work together or all by themselves—the simple machines. They are all in place, named and closely seen: the wheel, the inclined plane, the wedge, the screw and the lever. They blossom forth, bike pedal and sprocket, seesaw, soda-can tabs and paint-can lids, claw hammer pulling a nail, scissors. A nail seen in cut section is a wedge, and the inclined plane is seen in a roof, a ramp under a tire at the garage. There are wedges at work whenever you split an apple with your front teeth. Banal classification of the machines is not the center here, but rather an active sense of seeing them, a little hidden, in use everywhere. Corkscrews end this honest little introduction to Archimedean engineering physics for readers in the lowest grades.

There is not much that is simple about the manufacture of a couple of billion wax crayons annually in the U.S. Instead any very young reader is unerringly guided by the familiarity of the crayons themselves, their bright diagnostic color easily readable in the filter cakes at the color mill, the wax-mixing vats, the molds, the labeling machine and even the color test bench. The packing machine has eight slots, filled color by color in a strikingly ordered close packing. The final close-up of a score of filled crayon boxes completes the circle. This is an imaginative evocation of an industrial world, all from children's crayons.

POWER UP: EXPERIMENTS, PUZZLES, AND GAMES EXPLORING ELECTRICITY, by Sandra Markle. Photographs by Bob Byrd. Atheneum, 1989 ($13.95). **MORE WIRES AND WATTS: UNDERSTANDING AND USING ELECTRICITY,** by Irwin Math. Illustrated by Hal Keith. Charles Scribner's Sons, Books for Young Readers, 1988 ($13.95).

Power Up ends with a final problem: five circuit diagrams, in each of them a battery or two, a bulb or two and a wire or two. Only one will work; find it, and fix the others. That is how far you might get in this direct little book of flashlight batteries and bulbs. To begin, you try a bulb and a dry cell and some wire. The wire is homemade, out of kitchen aluminum foil and some sticky tape. Series and parallel are worked out; an active problem solving is encouraged. Fuses, household bulbs and switches are modeled and explained, although the wall plug is never used: danger. The book opens a time-tried experience of real but safe electricity for boys and girls in the early grades.

Math's book is much more demanding. The intended experimenters are middle schoolers who have some hold on electricity and are willing to solder. It too has projects in the last chapters: a remote flash unit with a transistor switch and an attractive coin-pitching game with a foil target and half a dozen buzzers and lamps.

This clear and helpful book, which offers guidance and circuits rather than step-by-step recipes, opens with a short and sensible look at the basics by way of a charged comb, a compass-and-coil meter and a lemon battery. It goes on to useful power sources, a DC power supply with dry cells and an AC supply using a step-down transformer. Soldering, wire-stripping tool and multimeter are added. Ohm's Law appears, somewhat shyly, along with the multimeter. This is the straight road to electronics, although only a little way down it.

Words and Symbols

READING THE NUMBERS: A SURVIVAL GUIDE TO THE MEASUREMENTS, NUMBERS, AND SIZES ENCOUNTERED IN EVERYDAY LIFE, by Mary Blocksma. Viking Penguin, Inc., 1989 ($18.95; paperbound, $7.95).

Numbers signify. They have a foreign policy, not only their domestic economy of $2 + 2 = 4$, so intimate and so alone. This compact, explicit, brisk book of reference explains just what numbers stand for (a few code letters come along) in more than 100 alphabetized contemporary contexts, from Alcohol to Dow Jones, Hats, Motorcycles, *p*H, Sandpaper, Vitamins and Zip Codes. Most entries offer a capsule history of the numerical system at hand, with a practical appraisal of its utility and its pitfalls.

The author is a librarian who well knows the art of consulting experts. Her material is most reliable; even so technical a matter as Time Units is well if not impeccably outlined. Useful maps and tables and lists abound. Two entries that are flawed are Light Beer and Earthquakes; those calories saved are not all taken from alcohol, and the Richter magnitudes are not quite clarified. What school library could do without a book that answers so many questions—especially the unasked ones?

FAMILY MATH, by Jean Kerr Stenmark, Virginia Thompson and Ruth Cossey. Illustrated by Marilyn Hill. Lawrence Hall of Science (EQUALS Project), University of California, Berkeley, 1986 (paperbound, $18 by surface mail).

Family Math is what it claims, a guide for parents and children to work together not on passive tasks of rote learning but in active game play, solving problems, experimenting and even discovering. The tools are many but familiar: cups and playing cards and beans, paper and pencil and scissors, for some a watch with a second hand

and a $5 calculator. What to do is neatly shown in the 100 or more activities that are laid out in this cheerfully illustrated, informal book. Here are all the patterns, diagrams, tables, rules, questions and challenges you might want, enlivened with little cartoons, like one of a young mathematician winning at coordinate tic-tac-toe.

Matter is here for children from ages five to 18, perhaps most of it for the middle school student, the one who has lots of know-how already and yet still a long way to go. The activities are graded to help choice; the intent is to allow half a dozen or so sessions, each for a friendly hour or two. High aims include the growth of confidence no less than of skill and a glimpse at how careers open in this world with math. Making almost anything economically and well, packing, shipping, selling and buying—all are matters of count, measurement, logical thought, strategy, estimation, spatial form, probability or at least plain head-and-calculator arithmetic.

This is a curriculum for informal math education, so badly needed. By the way, you play coordinate tic-tac-toe on the intersections of a 10-by-10 grid, where a row of four X's or four O's wins. The game can lead any rookie player to the big leagues of curves and graphs.

IT'S MAGIC, by Henry Gordon. Prometheus Books, 1989 (paperbound, $7.95).

The magic here described is for grade school readers. Three chapters handle "amazing effects" with cards, coins and dollar bills and numbers; one treats mental magic, and finally there is a miscellany of props, ropes, balloons, drinking glasses and more. Each chapter presents more than a dozen individual tricks, about a page for each. They are carefully written, usually in two distinct sections, one on what the audience sees, one on what the magician does.

Henry Gordon is a well-known Toronto professional magician. Don't skip his introduction, which makes it quite clear that magic effects are not mechanical—that their value as entertainment depends very much on human performance. Practice . . . and practice again.

Here is one effect from the chapter on mentalism. Someone selects a card in public. You dial a certain number and ask for the right person by name: Is Madame Zola in? Almost at once, you ask that she be called to the phone. As soon as she responds, you ask her to hold the line. You hand the phone to one of your audience and let the seer herself announce to the surprised spectator the very card just chosen. Certainly a code is hidden, perhaps in the unheard part of the telephone conversation. Can you devise one that would fit the events outlined here? If not, the book will tell you two ways; this review is not about to disobey Mr. Gordon: "Never, but never, reveal the secret."

Human skill and reason lie behind every magic trick, however it may appear to defy the order of the world. That is magic's most useful lesson—and magic is fun besides. Practice!

GOLD AND SILVER, SILVER AND GOLD: TALES OF HIDDEN TREASURE, collected and retold by Alvin Schwartz. Pictures by David Christiana. Farrar Straus Giroux, 1988 ($13.95).

His title rings like pieces of eight in an ironbound chest; this talented author can write no wrong for good readers young or old. Half of the tales here are true and documented (not every time from sources quite as primary as one might hope for); the rest are legends mixing fact and fancy, one a folktale echoed (or echoing) Chaucer. A chapter on codes, maps and signs, a few diving bells and minisubs, the grand "silver reef" from the broken galleon searched out for 19 years through old archives and in untiring dives—all justify this as a book of mathematics, technology and the worth of evidence.

One true tale of treasure in Boston Harbor is hard to top. Edward Rowe Snow heard that a lighthouse keeper, perhaps an old pirate, had maybe once buried a treasure on one of the harbor islands. An old fisherman recalled that a man from Canada had spent two weeks searching on Great Brewster and had left a note. The note was mislaid but turned up after six years. Finally Snow searched where the note had hinted, but on Middle Brewster instead. (Yes, there are four Brewster islands; New Englanders are parsimonious with names, too.) Only a dull old book was found in the old house—not much use. But a clever librarian found that page 101 had been pricked with 45 pinholes. The letters they designated spelled out nine strange words; read backward—hardly a challenging code—they began: gold is due east of trees . . . , and then said where. Months of searching with a metal detector on the right Cape Cod island eventually brought Snow a box of 316 gold coins, among them pieces of eight. The mysteries of who and how and when and why remain.

Earth and Sky

THE FIELD GUIDE TO GEOLOGY, by David Lambert and the Diagram Group. Facts on File, Inc., 1988 ($22.95).

This versatile English author and design team have here worked their will on another concise exposition in the earth sciences. This is no field guide in the usual sense but an up-to-date introduction to geology for the motivated amateur—quite suitable for readers in high school and beyond—in a small book with more page area in images than in text, mostly careful line drawings. A dozen chapters treat all the topics of the usual geology text. First come the formation of the planet and plate tectonics. Then come four chapters on rock types and their formation, with a minimum of nomenclature. The next chapters treat the changes made by rivers, sea, ice and air. Three chapters sum up historical geology; in one of them the geologic column since the Cambrian is described period by period. A closing chapter looks at mapping and collecting, mining and museum displays and geologic sites worldwide.

Take a sample spread: clocks in rocks, or chronometric dating. One page has five small drawings: a section of a dike injected into granite, a hand sample of the diabase dike being dropped into a laboratory crusher to be broken into mineral grains, a beaker with the froth that has floated out the mica grains (other grains yield to other separations), a highly diagrammatic mass spectrometer and a printout in the act. The right-hand page bears a generic curve showing the residual concentration as half-lives of time pass by, and a final sketch represents a strew of fission tracks in an etched crystal. "The more tracks, the older the crystal." One succinct paragraph tells of the accumulation of daughter elements, and four numbered paragraphs define the materials used and the range of utility for dating with potassium-argon, rubidium-strontium, uranium-thorium-lead and fission tracks. Missing: even the word or idea of the spectrometer vacuum, statistics, isotopes, or any earlier development of the modern method. An interested person can grasp the central point; a less eager reader may not.

For the dozen periods of the geologic column, uniformity of concept adds mutual reinforcement: every spread has its map, a couple of fossils, a typical site. Periods are surely easier to understand in this mode than is dating by decay. Certainly a great deal

of usable information is presented here compactly and inexpensively.

THE BIG ROCK, written and illustrated by Bruce Hiscock. Atheneum, 1988 ($12.95).

The big rock is much older than the forest around it, as the forest is older than the snow or the passing red fox or the glacial boulders that line the farm roads. This is good country for rocks, at the edge of the Adirondacks. Once the primary school reader has seen enough to know the place, the pages recount the main stages of the birth of rocks, the rise of a mountain, the coming of the sea and its animals and eventual land rise until erosion bares the underground rock at last. It remained a mountain summit until the ice came past, to sweep away and then drop the heavy boulder as the rainbow celebrated the end of the grip of ice. The forest grew around it; long ago two Native American children hid from a passing mastodon behind the same rock! The rock itself is changing slowly now; some day it may be only a lump and a heap of sand.

These colorful and detailed images, some of them rather abstract and some real, have no need for captions or legends. They are kept meaningful by the quiet and engaging text. The small book has the distinction of a true geology for the young, based on a single landmark viewed both familiarly and imaginatively.

SUNDIALS & TIMEDIALS, by Gerald Jenkins and Magdalen Bear. Nine cardboard construction models. Tarquin Publications, 1987. Distributed by Park West Publications, 238 West 72nd Street, New York, NY 10023 ($11.95 plus $1.75 postage).

With the right glue (the brand names given are not much help here in the U.S.) and with a ballpoint pen that has run out of ink to score the ruled lines that define all the models, any reader old enough to be safe and strong enough for big scissors or a mat knife can cut from these thin card pages a real working sundial. In fact, the pages yield seven different graduated sundials, plus a map cylinder for finding time in any time zone and a dial for finding time at night from the pointers.

Naturally, thin cardboard models six or eight inches high are not suited to endowing your garden with a long-lasting dial. But building any one of these, guided by text and photographs of all versions fully assembled, is at least a royal gardener's road to understanding how sundials work, given days of sunshine. (The why's of the astronomical background are not brought out.) One of the models is a nifty three-in-one: a horizontal dial, a vertical dial and an equatorial one in a single structure. It is the variety of design that gives the collection its teaching strength. North-south orientation, latitude and longitude dependence, the equation of time and the time zones are described concisely, along with simple tables. These models are made to work in a range of North Temperate latitudes. Any close examination will suggest at once—no construction is needed—what the origin of clockwise and counterclockwise must have been.

Biology

THE NEWS ABOUT DINOSAURS, by Patricia Lauber. Bradbury Press, 1989 ($14.95).

In the flood tide of good dinosaur books that swept past us this year, this colorful slender volume for grade school enthusiasts left on the record something unusual: the news that dinosaurs are alive. That is to say, they are compact of two ingredients: the bones and tracks and eggshells found in the rock and the changing ideas by which we try to understand the long-ago natural world. Lauber, an author of proved qualities, has made this remarkably clear by building her book out of small summaries that turn into surprises as soon as the reader comes to a heading in red: "The news is..."

Most living reptile mothers ignore their young; they lay eggs and leave for good. By analogy, dinosaurs were thought to have done the same. But no more. The news is that the herds of duckbills whose bones are always found near some old shore left no eggshells there and no bones of the young. They must have nested elsewhere. In time the nesting grounds were found, the nests spaced by just the length of an adult duck-billed dinosaur. Moreover, those places hold the remains not only of eggs, nests and young but also of adults: the duckbill mothers must have stayed near the nests, probably on guard. Other news even tells why we judge that the adults brought grasses and seeds to feed the young, as birds do today. These duckbills are new.

The paintings here play a part in the news; they are the lively and luminous latest efforts at reconstruction by artist-paleontologists. Better still, they include work by five different hands; these experts' dinos are not all the same. This book is the state of the art,

not just up-to-date but understandably changing.

ELEPHANTS: BIG, STRONG AND WISE, written by Pierre Pfeffer, illustrated by René Mettler. Young Discovery Library, 1988 (217 Main Street, Ossining, NY 10562) ($4.95). **TREE TRUNK TRAFFIC,** text and photographs by Bianca Lavies. E. P. Dutton, 1989 ($13.95).

A text spread near the end of the first, hand-size book is enough to indicate its quality. On the left, the trail across a green, rock-strewn Alpine meadow is filled with traffic, a long parade of elephants escorted by soldiers bearing spear and shield. It is a view of Hannibal's strong fighting elephants bound for Italy. Across the page you see a small, pink Ganesh, elephant-headed god of good fortune for schoolchildren and many others in India; the preceding pages show elephants all red and gold in glorious costume for some Indian festival. The 36 pages of short and easy text suited for the beginning reader do not neglect wild African elephants, managing a fresh and sensible show-and-tell all about elephants—their tusks, trunks, herds, tick birds, trumpeting and affection, all fueled by 300 pounds of green fodder a day. The small work is one of a French-made series that will number 120, an excellent pocket encyclopedia for small readers; a dozen or two of the books are out in English.

The vertical highway is a maple tree 70 years old, shown beautifully in its red fall foliage against a blue October sky. The author-photographer presents two dozen or so distinguished photographs of tree traffic on these big pages, along with texts of a few lines, suited for the earliest readers and indeed for the read-to. Up and down and around the trunk by night and day the living traffic flows, at all scales (real sizes are listed) and all hours—a blue jay, a daddy longlegs pair, a starling startled in her nest hole by a squirrel, an emerald katydid, a masked raccoon family. The close-up photography is sharp, bright and exciting, as are the night scenes. The squirrel family dozes off nicely as the raccoons waken: "ready to say hello to the night, the stars, and to you."

CLOSE ENCOUNTERS WITH INSECTS AND SPIDERS, written and illustrated by James B. Nardi. Iowa State University Press, 1988 ($14.95).

The bright red, chunky book is a charming, chatty field guide prepared by a research scientist, a keen arthropod-watcher himself, who sketch-

es and writes engagingly. The variety of forms he includes, their wide distribution in habitat, his enthusiasm and know-how-to-find and his big but carefully scaled drawings will give this book a strong appeal to children of all ages. Adults can read names and detail to the youngest users, who are closer to the ground and can better see the animals; most grade schoolers can follow the text for themselves, conceding a few grown-up taxonomic pitfalls.

First to be explored are the home, school and garden (and yards, edges and streetsides); then come ponds and streams, meadows and fields, trees and logs, and finally the great team of soil recyclers busy beneath our feet: pillbugs, millipedes, ants and many more. Some morning you may see a tiny, fuzzy moth appear suddenly, to strut the edge of the sink; it is a moth fly, and it "has spent the last few weeks as an egg, larva, and pupa in the depths of the drain pipe."

"The musicians of the meadow" and their instruments are worth the attention they get here. The gall midge or gall fly can be found housed on a leaf or the stem of almost any roadside goldenrod; the creature will emerge in a jar kept on your windowsill—but do not be surprised if distinct species of insects emerge from galls that look exactly alike: parasite wasps. This book has struck a first-rate balance: not so much as to daunt a learner, not so little as to lack interest.

MAMMAL, written by Steve Parker, photography by Jane Burton and Dave King, 1989. **BIRD,** written by David Burnie. Eyewitness Books, Alfred A. Knopf, Inc., 1988 ($12.95 each).

By now a dozen of this series of internationally produced visual books on particular topics have appeared, every one of them excellent. Page after page is filled with related photographs and artwork, each with a clear, concise label. The effect is that of visiting among the cases of a rich and well-arranged museum.

The book on mammals transcends most of the others. Yes, it shows skulls of rabbit and pangolin and manatee, and it shows tracks and claws and furs and skins, too. But mammals live, and these pictures show it. The pages follow a house-mouse nest from day one—pink heap of a dozen tiny bare newborns—until two weeks later the pups outgrow the nest and begin furry exploration of the world. A cat's family life is shown close up over even a longer time. Then you watch cats wash, chinchillas take dustbaths, puppies tussle and romp, hamsters stuff and unstuff their cheek pouches with delicious nuts. The same style of ordered and comparative pages here includes living mammals in action; the book has become museum and zoo all in one.

Another book of the set treats birds in much the same way: plenty of eggs and nests and feathers, but also a shot of five blue-tit nestlings, their striking yellow-ringed red mouths so dominant in the parent birds' view from above. Deposit food here!

PET MICE, text and photographs by Jerome Wexler. Albert Whitman & Company, 1989 (5747 West Howard, Niles, IL 60648) ($12.95). **PIGEONS,** by Miriam Schlein. Photographs by Margaret Miller. Thomas Y. Crowell Junior Books, 1989 ($12.95). **BOX TURTLE AT LONG POND,** by William T. George. Pictures by Lindsay Barrett George. Greenwillow Books, 1989 ($12.95). **SEA OTTERS: A NATURAL HISTORY AND GUIDE,** second edition, by Roy Nickerson. Photographs by Richard Bucich. Chronicle Books, 1989 ($12.95).

Among scores of books that tell some tale of a specific animal or plant, usually over time, we have selected four excellent examples of the genre.

Jerome Wexler has illustrated nearly 40 children's books with his intimate and meaningful photographs. This one opens with a profile shot of one urbane young mouse, held between thumb and fingers, two black patches on his white head, seen six or eight times life-size. A mouse diary shows you a small family of pups growing up.

The short book offers a full account of how to raise and enjoy pet mice (they come in a range of colors) in sickness and in health, for better or for worse, until eventually, like all living things, they die. There is a key page on population control: by the 27th day after birth you need to separate all males from females, and the book explains how to tell them apart—the first prerequisite. Biology, responsibility, affection: there is a lot to learn, and Mr. Wexler, who has been a reflective small-pet husbandman for a long time, teaches it warmly, not by assertion alone but by reason and very well.

People raise pigeons, too, and this book for readers in the lower grades spends a few pages on how homing pigeons are kept and on their heroic past in war and peace. But its real topic is that visible free citizen, the city pigeon of sidewalk, street and cornice. Wheeling city flocks appear to have no young; in fact, the young ones are hidden away in high, safe nests. A set of photographs with text shows

how the free birds rear their young, from egg to flight in under six weeks. The author, a New York City dweller, knows and admires these streetwise, speedy, spunky survivors, here seen raising their families and "making one of the nicest city sounds."

Long Pond is no place we know, and yet it is real enough, as if in a good but tiny novel. The paintings are rich and strong, trees glowing with autumn colors, the pine duff golden, very close up. The yellow-patterned box turtle with red eyes comes slowly out to bask in the sun after a cold night, then to shelter from the afternoon rain under an apple tree. Box turtles drink pond water but can't swim; this one looks around for grapes, but what he finds is some earthworms driven out of their holes by the rain. He bites their heads off to prevent their escape and prepares to eat them one by one at his slow leisure. But a swifter young raccoon has the same intention. The turtle is sealed safe; raccoon fingers cannot pry open his shell. When he opens up again, all is quiet, but the worms are gone. By luck many grapes fall, disturbed by feeding grouse. Soon the turtle is very full of grapes, and he crawls into soft, warm pine needles to close his eyes for sleep. "It has been a long day" by the pond, one quietly shared by the read-to and the beginning reader.

The sea otters of the California coastal kelp forests are possibly the most engaging animals of American wildlife. They are visibly playful, consummate swimmers, good to their young, given to floating serenely on the back, cradled in kelp, while cracking a clam by striking it against a stone held on the sturdy chest.

The text chronicles the long war between hunter and sea otter, waged without quarter once the fur trade found their beautiful dark pelts in the Pacific. The otters were reduced a hundredfold a century ago, most surviving only in the Bering Sea. Hunting (none were to be found) was stopped in 1911. They have come slowly back into the wild, and now they can be seen—still protected and still disputed by competing shellfishermen in many places along the kelpy coast. The locations are given in this authoritative and attractive guide. The skein of interrelations, war and peace alike, among otter, fur hunters, Aleuts, abalone divers, red sea urchins and industrial harvesters of the giant kelp makes fascinating reading. This entirely adult but nontechnical book is accessible to all good readers, certainly those past the seventh grade.

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ESSAY

How to control U.S. health costs

by Anthony Robbins

The vigorous debate over medical care in the U.S. seems to have little to do with the health of the American people. Public discussion of the cost of health care—dominated by considerations of containment and the size of the health industry—has not addressed the fundamental factor that underlies costs: disease itself. Critics who understandably attack the cost of intensive medical care at the end of life might concentrate as well on two strategies that are likely to improve life and simultaneously hold off unneeded expenditures: the prevention of disease and its early detection and treatment through primary care.

In the past two decades concern about deficiencies in U.S. health care has come to be dominated by alarm about buoyant costs. That problem has moved legislators and health-care administrators to devise "data dominated" payment systems limiting outlays according to various formulas, such as the diagnosis-related-group system. Such schemes have failed to control costs, but they do offer one benefit. They enable one to look at who is receiving what care for what medical problems and where care is being administered. Translated into rates of disease and medical services, these data reveal tremendous variations in medical care—variations far greater than those found in morbidity and mortality statistics.

The overall age-adjusted death rate from ischemic heart disease is 40 percent higher in the U.S. than it is in France and Switzerland. In New Mexico the age-adjusted death rate for white men 45 to 64 years of age is 301 per 100,000; in West Virginia it is 529 per 100,000. If the entire U.S. achieved the French and Swiss rate, or even the rate in New Mexico, the American people would save billions of dollars in health-care costs. (Heart disease now costs society more than $70 billion a year.)

Cancer death rates show similar variation: citizens of Utah die of cancer only half as frequently as do other Americans. This geographic variation suggests social, economic and environmental causes—causes that can by definition be controlled. Cigarette smoking, which precipitates at least 75 percent of all lung cancers, is at the top of the list, followed by such other agents of expensive death as injuries, stroke, chronic obstructive lung disease and chronic liver disease.

Are data on the medical services provided and on related outcomes similarly revealing? Except where there are local increases in a particular disease or where major regional demographic differences exist, strong variations in the number of people seeking medical advice should not be expected. Yet great differences emerge with respect to the kind of medical care received from community to community.

It appears, for example, that the number and kind of surgical procedures performed in an area correlate better with the number of surgeons and their specialties than with the variety of diseases. Where there are general practitioners and primary-care services, there are fewer operations and fewer hospitalizations. And everywhere, the number of laboratory tests and procedures that are billed as separate services has grown.

These troubling facts seem to call for the enactment of new public policies aimed at disease prevention. Indeed, the cost of preventing the most common and most costly causes of death, disease and disability is small compared with what is spent on treatment today. Disease can be curtailed simply by expanding existing preventive and educational public programs. Programs that have not reached optimal size include those devoted to immunization, fluoridation, prevention of lead-based-paint poisoning, family planning, prenatal care and control of AIDS and sexually transmitted disease.

New social and institutional strategies must also be devised to prevent certain diseases. Heart disease, the second leading cause of death, for example, has become less common over the past 15 years. Rates among middle-aged persons have dropped by 3 percent a year but, as noted above, are still 40 percent higher than rates in some other industrial countries. A national effort to reduce the consumption and marketing of foods high in unsaturated fats could accelerate the downward trend. So could a similar effort aimed at reducing salt intake.

Occupational and environmental hazards, as well as excessive drinking and cigarette smoking, explain the significant differences in cancer mortality among segments of the U.S. population. Efforts to control exposure to carcinogenic agents in the air, water, food and the workplace must be expanded to achieve primary prevention. Rates of mortality from cervical and breast cancer can be reduced by screening and early detection.

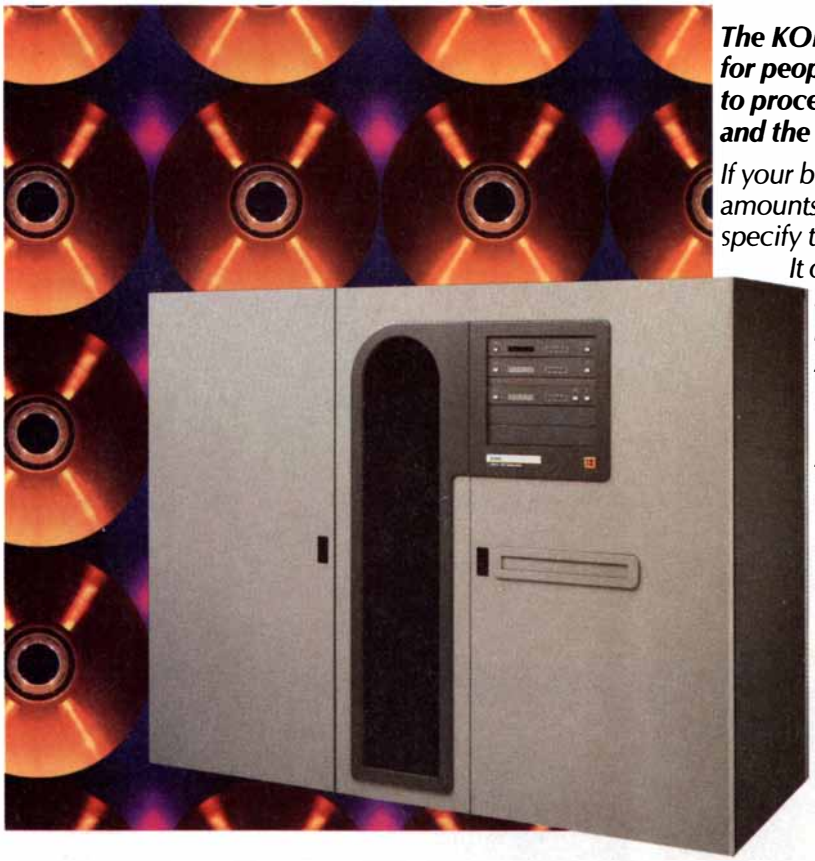
A major emphasis on primary care should complement a national effort to prevent disease. Primary care is frontline medicine, the point at which people who need medical services enter the system by consulting an internist, a family practitioner or a general practitioner. Primary care alone can provide more than 90 percent of the services people need. Limiting access to such care does not reduce expenditures. On the contrary, it means that the sick tend to get sicker, require more expensive hospital care and ultimately cost society more.

Yet the U.S. medical-care system is skewed sharply toward specialized hospital care and toward surgery and surgical subspecialties. It is not hard to identify the reason there are more surgeons per capita here than in the United Kingdom: surgeons and surgical subspecialists in this country earn from six to seven times more than primary-care doctors do, even when one takes into account proper remuneration for differences in skills and training. This economic skewing of medical talent costs more and encourages unnecessary surgery, and it fails to improve health.

How can national policy initiatives enhance primary care? They can provide incentives to insurers to cover such care, offer preferential financing to facilities that house such services and reverse the imbalance in payment schedules to discourage unnecessary procedures and surgery. We must also repair the damage that the Reagan budget cuts did to primary-care programs established to serve the poor, the young and the elderly—whether they live in cities, suburbs or isolated rural areas.

The evidence is in. Prevention and primary care are the only sound long-term ways to remedy excessive, unnecessary spending on medical care. Prevention and primary care make sense for cost containment—now.

ANTHONY ROBBINS, M.D., is professor at the Boston University School of Public Health.



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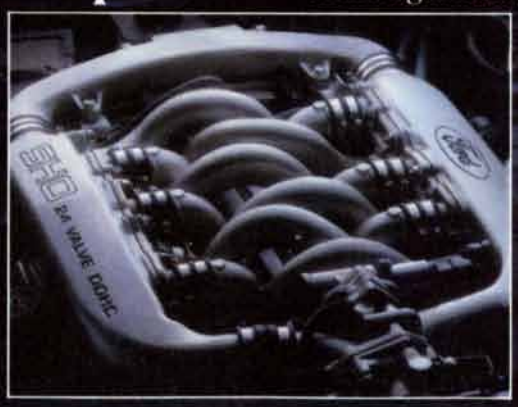

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AGE: 143.

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LAST BOOK READ: *A Christmas Carol*, Charles Dickens. "I've read it nearly every year since it came out."

LATEST ACCOMPLISHMENT: "Finally getting myself into one of these ads. But then people are always slow to recognize genius."

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