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DECEMBER 1988
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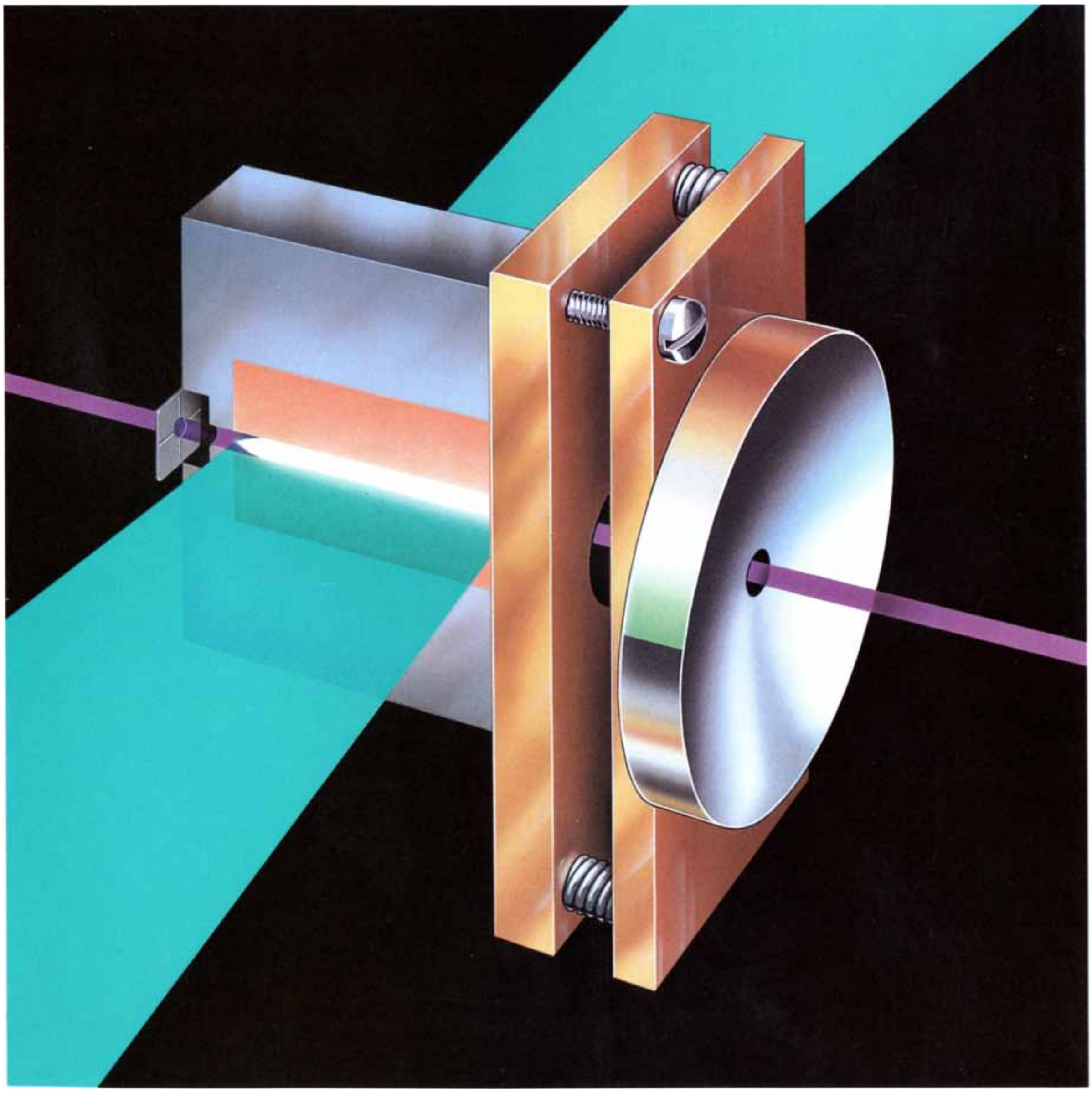
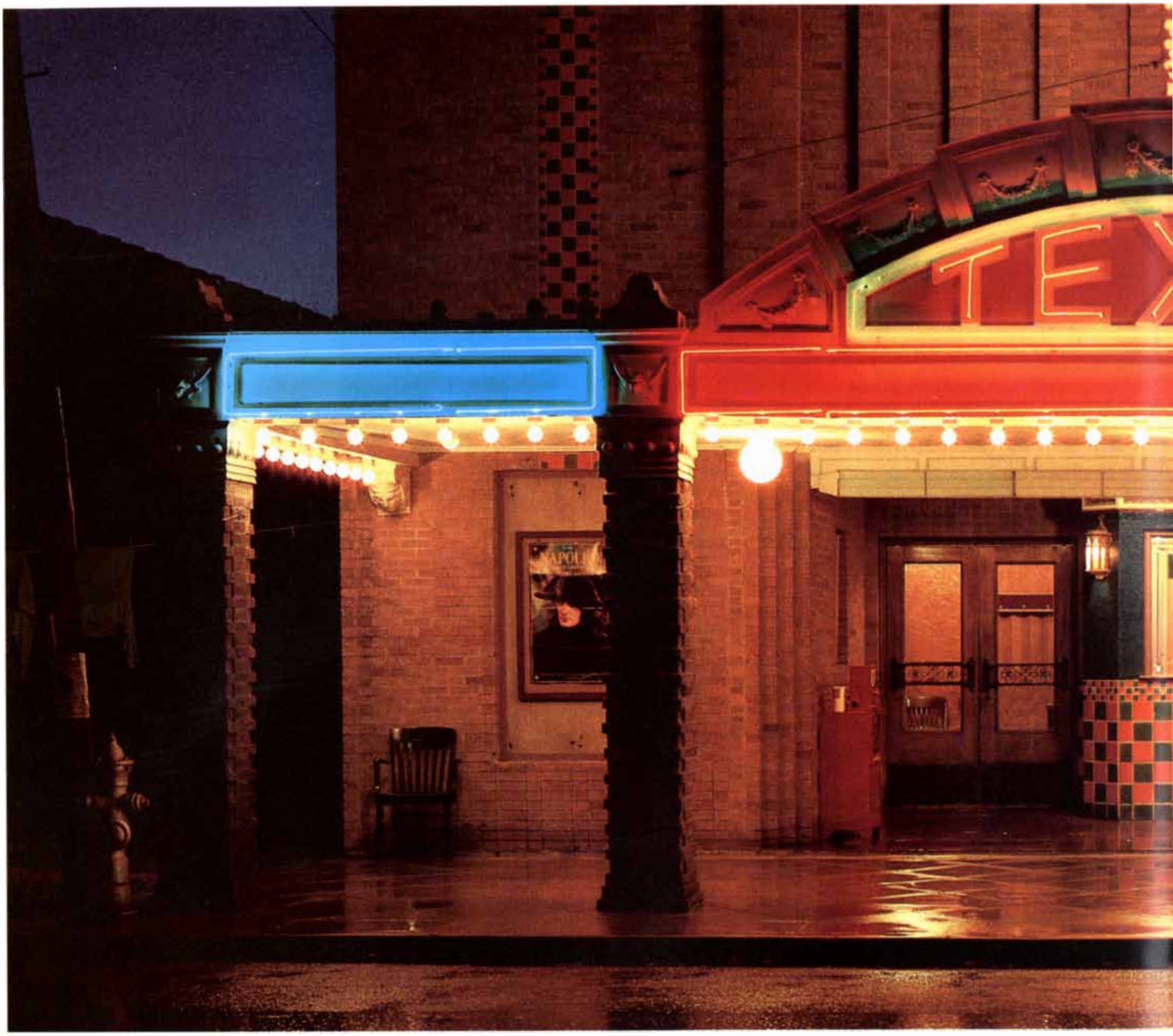
How experience shapes the brain's anatomy.

How our throwaway society can cope with trash.

How a single molecule mediates fertilization.



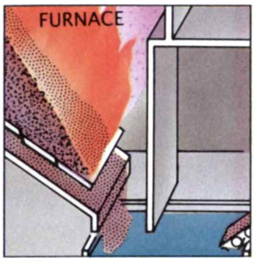
X-ray laser: *A powerful optical pulse strikes a selenium foil, which explodes and emits a beam of coherent X rays.*

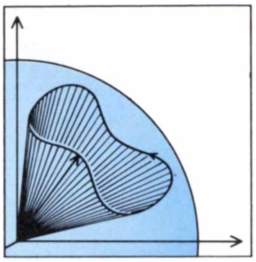


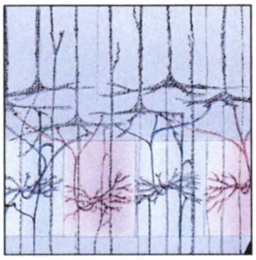
The Best Way To Watch A Movie Has Always

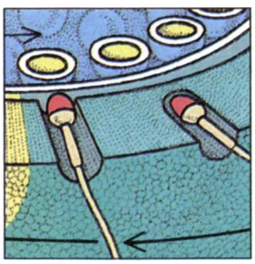
SCIENTIFIC AMERICAN

December 1988 Volume 259 Number 6







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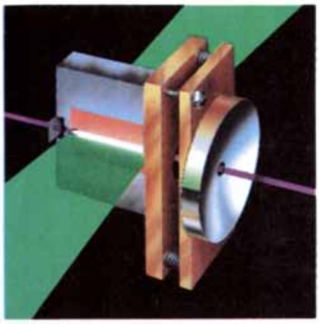

THE COVER painting, based on an illustration from the Lawrence Livermore National Laboratory, depicts the first soft-X-ray laser (see "Soft-X-Ray Lasers," by Dennis L. Matthews and Mordecai D. Rosen, page 86). A light pulse (*green*) from the world's most powerful optical laser strikes both sides of a selenium target, which is vaporized and ionized. Electrons detached from selenium atoms in the course of the ionization process strike excited selenium ions and stimulate X-ray emission.

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Cover painting by Hank Iken

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LETTERS

To the Editors:

"Dr. Atanasoff's Computer," by Allan R. Mackintosh [SCIENTIFIC AMERICAN, August], is an interesting presentation of John V. Atanasoff's early attempt to produce an electronic digital computer. The article makes it clear that he did not succeed. Mackintosh states that it is unfortunate Atanasoff did not obtain a patent on his invention—yet no patent application was filed, and the Atanasoff-Berry Computer was never capable of doing any worthwhile computation. Atanasoff left Iowa State University in 1942 without having made any arrangements to preserve the partially built computer and with no intention of ever returning to complete it.

Atanasoff deserves credit and recognition for this early attempt, but the first working electronic computers were invented by J. Presper Eckert and John W. Mauchly at the University of Pennsylvania. When Atanasoff became aware of their ENIAC project, he realized that his own earlier effort to build a computer was trivial in comparison. He never tried again, and he did not participate in the explosive growth of the computer field.

Eckert and Mauchly are true pioneers of the computer field. All the computers now in use derive from the original work they did between 1942 and 1946. In 1980 the Association for Computing Machinery honored them, and deservedly, as the founders of the computer industry. It is unfortunate that the history of the computer field has been distorted by a patent suit that ended with the judge's announcing his own opinion as to who invented the digital computer. A court of law is not the place for deciding questions about the history of science and technology. Most people who are interested in the history of computers do not deny Eckert and Mauchly the honor to which they are entitled.

Let me also comment on a few small errors in the article. Alan M. Turing did not take part in the building of the Colossus. The Colossus did not help to decipher the German Enigma code. Turing did work on the Enigma code, but the Colossus was used for a higher-level German cipher. The Colossus was one of the first large-scale electronic devices built, but usually it is not considered to be a computer. There is no reason to deny the honor of being the first electronic computer to the ENIAC, which was a spectacular achievement.

SAUL ROSEN

Department of Computer Sciences
Purdue University
West Lafayette, Ind.

To the Editors:

Saul Rosen and I agree that the construction of the ENIAC was a great achievement. It is also true that "most people who are interested in the history of computers do not deny Eckert and Mauchly the honor to which they are entitled." It requires an exceptional feat of special pleading, however, to include in this honor credit for inventing the first electronic computer.

Well before the design of the ENIAC, Atanasoff and Clifford E. Berry constructed their 1939 prototype and the 1942 Atanasoff-Berry Computer, both of which were electronic, were operated digitally and were indubitably computers. The prototype and the full-fledged machine carried out their respective functions of adding and subtracting and of calculating the eliminant between linear equations effectively and accurately by means of electronics. They proved the workability of Atanasoff's key concept of computing by means of electronic logic circuits in conjunction with a refreshable binary memory. No one had made such a device before. In any reasonable sense of the words, Atanasoff was therefore the inventor of the electronic digital computer. I find the disparagement of his efforts by Rosen and other supporters of Mauchly and Eckert unfortunate. Rosen might remember that Atanasoff left the project, which had dominated his life for much of a decade, to serve his country in a time of great need. He did so with distinction and with no thought of personal reward.

The events surrounding the construction of the Colossus are still somewhat obscure owing to the secrecy of the project, but that machine was operational well before the ENIAC and there can be no doubt that it was an electronic computer. Indeed, in its use of binary electronic logic circuits for deciphering code, the Colossus was probably closer to modern computational practice than the ENIAC, which carried out straightforward, albeit large-scale, calculations using counters and accumulators. As any owner of a personal computer knows, performing numerical calculations is only one of the functions of an electronic computer.

I am no doubt not alone in finding priority disputes rather tedious. I agree with Atanasoff when he says there is enough credit available to satisfy everyone who was involved in the development of the electronic computer. But Mauchly's blatant plagiarism of Atanasoff's ideas, and the constant efforts of Mauchly, Eckert and their supporters to belittle Atanasoff's achievement, have distorted the historical record in a way that demands correction. Only when this matter has been set straight can the impressive contributions of Mauchly and Eckert be placed in their true perspective.

ALLAN R. MACKINTOSH

NORDITA
Copenhagen

To the Editors:

I was amused to read in "50 and 100 Years Ago" [SCIENTIFIC AMERICAN, July] that a writer in an 1888 issue of *La Nature* remarked that the laying out of streets at right angles rather than "diagonals" required people to walk farther by 40 percent, because the sum of two sides of a square is 40 percent longer than the diagonal. I guess it never occurred to the writer that after the streets are laid out in diagonals instead of squares, the diagonals will intersect at 90 degrees, and you are right back where you started, except that the streets are now reoriented by 45 degrees and the blocks are shorter by 30 percent. I wonder if the editors of *Scientific American* spotted the problem 100 years ago. Either way, how far you will have to walk depends on where you are coming from and where you are going.

ERVIN J. HALVORSON

Sioux Falls, S.Dak.

EDITOR'S NOTE

The figure on page 70 of the May SCIENTIFIC AMERICAN is based on one from "Human Tumor Necrosis Factor," by Bharat B. Aggarwal and William J. Kohr, in *Methods in Enzymology*, Volume 116, pages 448–456; copyright © 1985 by Academic Press, Inc.

50 AND 100 YEARS AGO

SCIENTIFIC AMERICAN

DECEMBER, 1938: "What a sorry spectacle the earth has been during the year now rapidly drawing to a close. Individually and collectively the peoples of the world have behaved very badly indeed. Spain is still involved in a blood-letting orgy that provides the stage for war rehearsal by outside nations and a training ground for their soldiers. In China there is a constant enlargement of the 'incident' in which Japan has killed hundreds of thousands of Chinese and destroyed the homes of millions. The year in Europe has seen the rape of nations by what has been called the new 'stand and deliver' diplomacy."

"Castor oil and coal appear to be the 'silkworm' from which the silk stockings American women will wear tomorrow may be made. With these basic ingredients, chemists are now fashioning in their test tubes a viscous fluid that can be drawn into fibers that are finer and stronger than natural silk and have amazing elasticity. In the posthumous patent of the brilliant du Pont chemist Dr. Wallace Hume Carothers, just granted by the U.S. Patent Office, is revealed this strange fiber that gives promise of being silk's crucial rival in the hosiery field."

"Medical scientists are preparing for the day when whole organs—livers, kidneys, spleens, perhaps hearts—may be transplanted successfully. But today an organ transplanted from one warm-blooded body to another almost invariably degenerates, because it undergoes an ill-understood self-digestion, or autolysis. When the cause is found, together with a means of removing it, then old organs can be traded for new—new, healthy organs probably taken from the quickly dying."

"The daily record of the vibrations of the ground under New York City includes some vibrations caused by traffic, some by blasts, some by earthquakes and some by what we might call the natural heart-beat of the earth. If there were no traffic in New York and no inhabitants within miles of it, the ground would still have a certain throbbing. The full cause is not known but the generally accepted cause is the action of the surf on the coast."

SCIENTIFIC AMERICAN

DECEMBER, 1888: "Over the telegraph comes the announcement of the financial collapse of the Panama Canal Company, due to its failure to negotiate the further sale of its bonds and its inability to meet the now gigantic calls upon it for interest and expenses. Whether any new arrangements can be made to prosecute and complete the great work is questionable."

"The type writer takes rank as one of the principal inventions of the age. In almost every office in every large city may be found one or more of these now indispensable machines. The SCIENTIFIC AMERICAN makes use of these machines in its editorial work, in its correspondence, and in its patent business. The type writer has furnished profitable and pleasant employment for thousands of men and women. It has proved a great educator, elevating the standard of letter and manuscript writing, often effecting the combination, in one person, of author, compositor, printer, and proof reader."

"C. W. Oldreive lately accomplished the task of walking on the water of the Hudson River from Albany to New York. Distance about 150 miles, wager $500. His average progress was twenty-four miles a day. He always went with the tide. The shoes he wore are of cedar lined with brass. They are five feet long and a foot wide."

"In the duel scene in Gounod's *Faust* will be found a striking electrical effect. The soldier Valentine engages Faust; Mephistopheles stands by, his sword drawn, to aid Faust. The poles of a battery are connected under the stage with copper plates sunk into the flooring where the duel takes place. Copper nails, one driven into a shoe of Valentine's, the other in that of Faust's, connect up with the floor plates whenever they stand upon them, and wires running up the legs and body of each and then down their several sleeves end in a small plug inserted in the hilt of each sword. Thus every time Mephistopheles interposes his own sword and strikes up the contending weapons, which are then brought in contact, the sparks fly furiously, and there are those weird, crackling, sizzling sounds heard in lightning as well."

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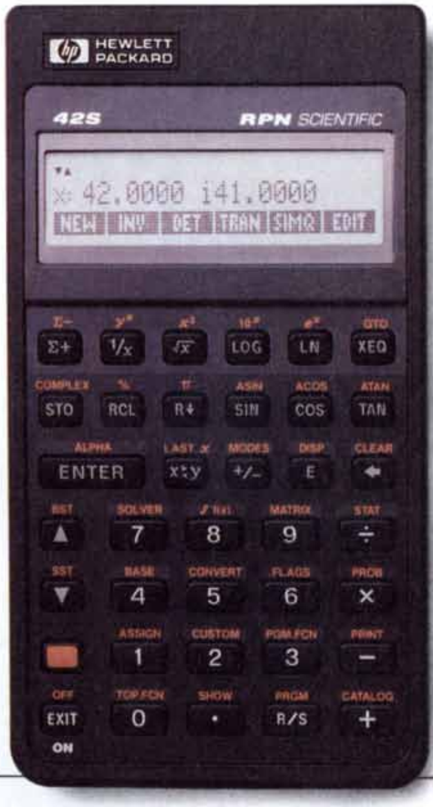

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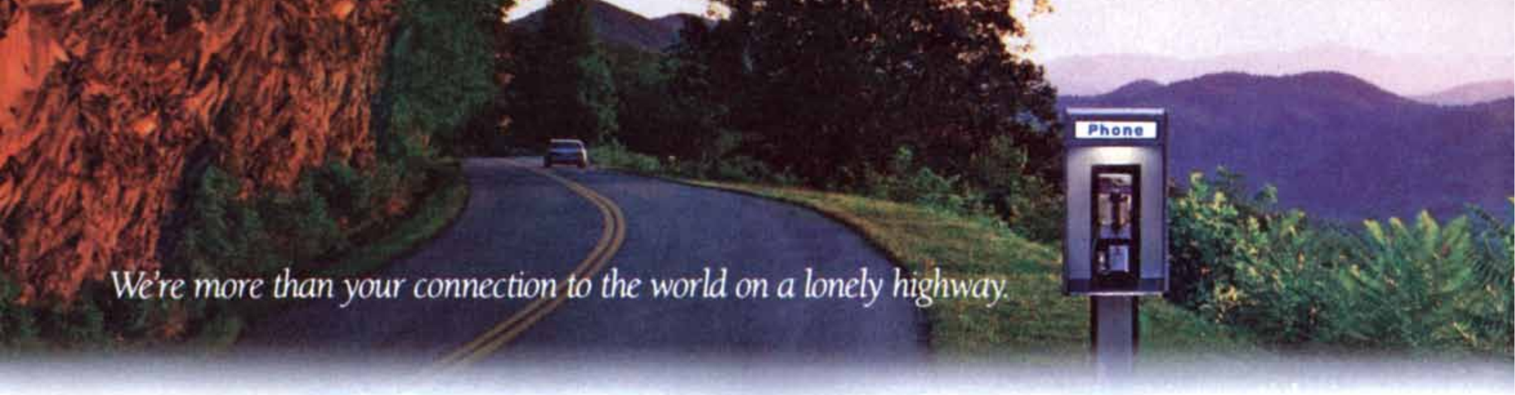
HEWLETT PACKARD



With a first name like Bell, it's no surprise Bell Atlantic is in the telephone business. But what is surprising is how much more than telephone service Bell Atlantic provides businesses around the world.

Did you know, for example, thousands of businesses come to us every year to help them find better ways to manage their information? What they've discovered is Bell Atlantic has the people and the technological expertise to design voice and data networks to meet their individual needs.

Here's something else you should know about us. We're the leading independent computer-maintenance organization in the world. To our over 45,000 customers we're known as Sorbus.SM And we service over 3,000 makes and models of computers and

Most of is unheard

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THANK YOU, PAINEWEBBER.

When PaineWebber needed a computer-maintenance source that could increase their computer uptime without letting them down, they sought out Bell Atlantic's Sorbus. Today, Sorbus maintains over 500 IBM terminals in PaineWebber's metropolitan Manhattan offices alone, including printers needed for buy-and-sell orders and late-breaking news. Because Sorbus has a dedicated field engineer, on-site maintenance, in most instances, is performed in less than one hour.*

*IBM is a registered trademark of International Business Machines.

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SCIENCE AND THE CITIZEN

Fertility Rites

Controversy and liability are limiting contraceptive options

Recently the French company Groupe Roussel-UCLAF made the headlines when it declared that, in response to "public outcry at home and abroad," it would halt distribution of a pill that safely induces abortion. That announcement sparked even more vehement protests and the French government, which had approved the drug a month before, promptly overruled the company's decision. No such clamor greeted the Upjohn company's decision a year ago to phase out one of the three abortifacients it has marketed in this country for more than a decade. Upjohn claims low demand and the availability of alternative products justify its action. But some industry observers say Upjohn's decision, like Roussel-UCLAF's, reflects the perils of reproductive research in the 1980's. Straightforward science has become tangled in a thicket of economic, political and social complications. Fertility experts say Americans in particular are being denied options in reproductive technology that have been available for years in many other countries, while the prospect that this country will lead a revolution in contraceptives grows increasingly unlikely.

Upjohn has weathered a persistent boycott by antiabortion groups in order to sell its abortifacients in the U.S. Judged safe and effective by the Food and Drug Administration in the 1970's, the drugs, which contain hormones called prostaglandins, are indicated for use in the second trimester of pregnancy. The products have other indications, but family-planning experts say the injectable prostaglandin Upjohn pulled from the market was the one most commonly used to induce abortions. Upjohn is careful to distance the two prostaglandins that it still sells in the U.S. from Roussel-UCLAF's abortifacient, a drug known as RU-486. In September, RU-486 was approved in France and China for use in the first trimester; it is a potential candidate for a morning-after pill.

Many family-planning experts think right-to-life activists would succeed in throttling any attempts to sell RU-486 in this country. Upjohn's prostaglandins may have survived such opposition because activists were distracted by a more heated skirmish over the company's injectable contraceptive, Depo-Provera. In the 1970's evidence that the drug caused tumors in beagles created an uproar that scuttled the company's bid for approval. Subsequent reports have cast doubt on the evidence, but the FDA has held firm.

While Depo-Provera remains mired in controversy here, six million women in more than 90 countries outside the U.S. are using some form of injectable contraceptive. In a dozen countries women can also receive hormone implants that afford protection from pregnancy for five years. "American women have to make do with the last generation of contraceptives, while the rest of the world moves ahead," says Sheldon J. Segal, director of population sciences at the Rockefeller Foundation.

In this country, public outcry is just one of the factors discouraging contraceptive development. The multimillion-dollar judgments against G. D. Searle & Co. and the Ortho Pharmaceutical Corporation and the $2.5-billion Dalkon-shield settlement with the A. H. Robins Company, Inc., are fearful precedents for a would-be manufacturer. The FDA requirements for contraceptives are more stringent than those applied to drugs used to treat disease. Years of animal testing can push the cost of developing a new contraceptive up to $50 million or more, and every year spent studying monkeys is one less year a company can claim patent protection on the market.

It is alarming but not surprising, then, that only one U.S. company is actively pursuing contraceptive research. In the early 1970's at least eight American companies did so. Nonprofit organizations and Government laboratories have been struggling to pick up where the other seven left off. The National Institute of Child Health and Human Development funded many of the studies that led to the approval of the cervical cap earlier this year, and a nonprofit group, the Population Council, is sponsoring an application for the implantable contraceptive, Norplant.

Assuming these groups gain FDA approval, they still have to find commercial firms willing to manufacture and market their drugs. "Even when you do the research yourself, a lot of companies don't want to be bothered," says Richard Lincoln, a senior fellow at the Alan Guttmacher Institute.

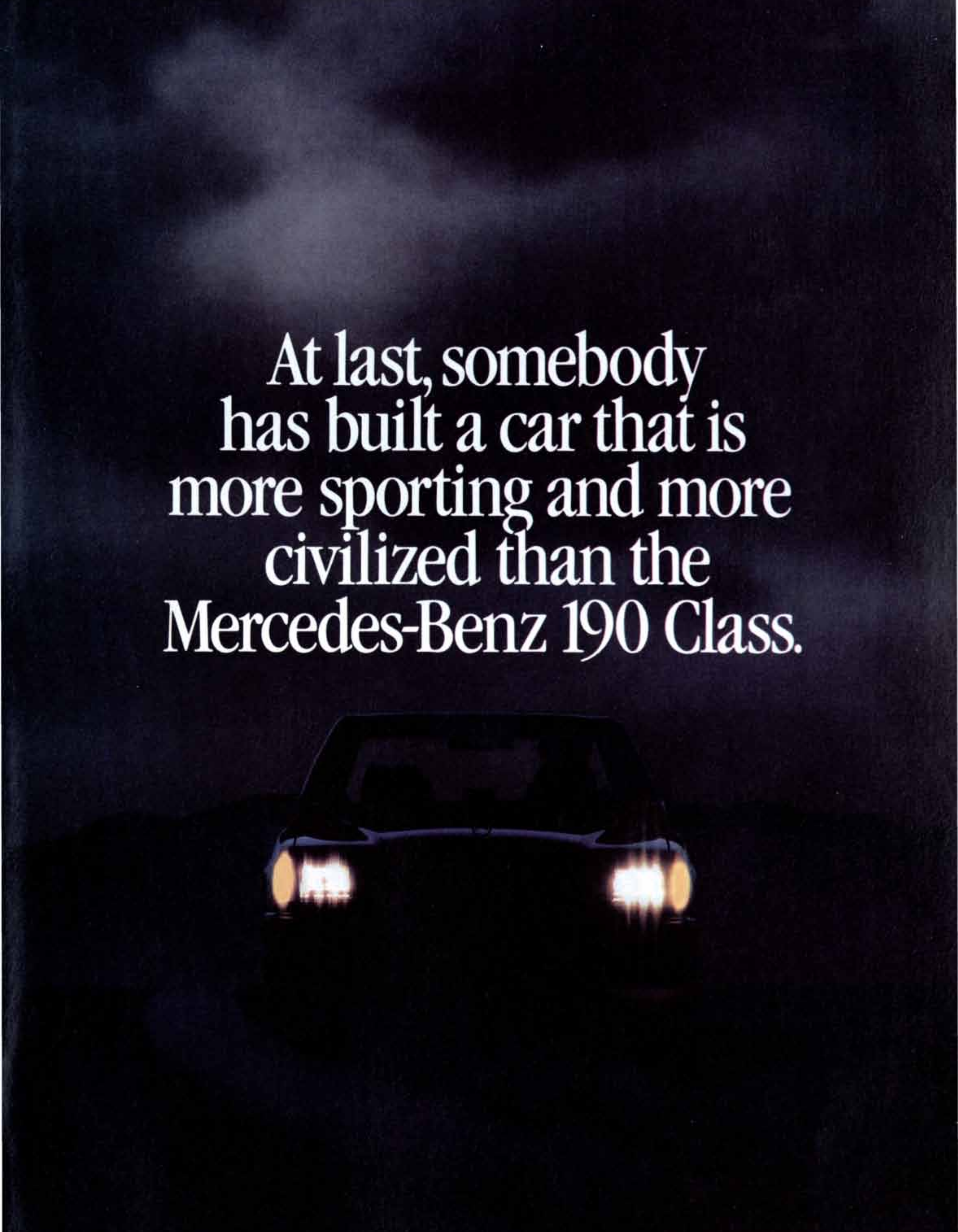
Lincoln also says the low birthrate in this country has veiled the urgency of the issue. But contributing to that low rate are the 1.5 million abortions that occur every year—a full fourth of all pregnancies and one of the highest abortion rates among developed countries. "Our ability to control pregnancy in this country," Lincoln says, "is rotten."

New contraceptives would not eradicate the problem of unwanted pregnancy, but they could help. This spring a working group at the National Academy of Sciences' Institute of Medicine plans to publish an appraisal of measures that could be taken to improve the climate for contraceptive innovation. Some observers fear that, unless the public perceptions that prompted Roussel-UCLAF's decision can be changed, the panel's recommendations will have little impact. *—Karen Wright*

After *Discovery*...

The future for space science looks bright—or does it?

When trying to guess the prospects for U.S. space science over the next decade or so, into whose crystal ball should one look? Lennard A. Fisk's is exceptionally clear and bright, if a bit rose-colored. "We should be entering an unprecedented period of activity for space science," says Fisk, who heads the National Aeronautics and Space Administration's office of space science and applications. "Some of that is an artifact of all the backlog" resulting from the *Challenger* accident, he adds, "but we want it to continue, and I think that will occur."


At last, somebody has built a car that is more sporting and more civilized than the Mercedes-Benz 190 Class.

The immediate source of this optimism is obvious. On September 29 NASA's space-shuttle program, shut down for two years and eight months, resumed again as the *Discovery* lifted off from the John F. Kennedy Space Center. That same day Canada, Japan and the European Space Agency agreed to chip in some $8 billion to help the U.S. deploy a space station—recently dubbed "Freedom"—by the mid-1990's. These twin events, Fisk says, are particularly auspicious for studies of how living and nonliving things behave in a weightless environment. Over the next five years 17 shuttle flights will be devoted to "Spacelab" missions, in which materials processing and biological experiments are carried out. This research will lay the groundwork for more sophisticated microgravity research to be done on the space station.

The resurrection of the shuttle program also means that several scientific spacecraft that have been languishing in warehouses for the past few years should soon be in service. These spacecraft, which were designed for transport by the shuttle and cannot be launched by any other means, include the Venus mapper *Magellan* and the *Galileo* mission to Jupiter, scheduled for liftoff next year, and the *Hubble Space Telescope*, the *Ulysses* solar observatory and the *Gamma-Ray Observatory*, all slotted for 1990. Noting that the White House has banned launches of commercial satellites by the shuttle and that the Pentagon is developing its own launching capability, Fisk maintains that NASA should be able to meet these launch dates.

Nevertheless, to allay the concern of space scientists that their projects are much too dependent on the vagaries of the shuttle, NASA has taken steps to obtain unmanned rockets for future missions. "Any spacecraft that can be lifted into space by a rocket rather than by the shuttle will be," Fisk remarks. NASA is buying rockets for launching the *Cosmic Background Explorer* next year, the *Extreme Ultraviolet Explorer* in 1991 and the *Mars Observer* in 1992, to name a few examples. The agency is also procuring rockets for smaller scientific missions that can be mounted quickly, to monitor a new supernova, perhaps. "We hope to have two of these [small missions] a year, forever," beginning in 1991, Fisk says.

To ensure that its space-science program will be amply supported into the next century and beyond, NASA will try to initiate at least one major, long-term project per year. The agency has received a "tentative go-ahead," Fisk notes, for an X-ray observatory that could be launched by 1995. Fisk's office has recommended giving high priority to a combined asteroid-Saturn probe, a multisatellite earth-observing system and an infrared observatory. Most of these plans depend, of course, on the largesse of the Administration and Congress. Again, Fisk professes optimism, noting that space science fared proportionately better in the fiscal 1989 budget than other NASA programs. "Support from Congress and the Administration is quite good."

James A. Van Allen of the University of Iowa, discoverer of the radiation belts that bear his name, applauds the goals set forth by Fisk but questions whether they are realistic. As long as NASA remains committed to large, manned programs, Van Allen suggests, the smaller, unmanned scientific missions will be most vulnerable to budget cuts. He warns that the space station, like the shuttle, may become "a real albatross," consuming a disproportionately large share of the agency's budget while contributing little to space science. Thomas M. Donahue of the University of Michigan, who heads the National Academy of Science's Space Science Board, concurs. "A lot of us are fans of the manned programs," he says, "but we just don't see much use for having humans doing space science." —*John Horgan*

Radon Retried

Its danger and the value of remedies are both in dispute

The quiet invasion of radon has touched off a strident argument. In September the Environmental Protection Agency warned that the gas, which seeps from the soil into millions of houses around the country, may cause some 20,000 lung-cancer deaths in the U.S. every year. Many health physicists disagree. One former head of radiation standards at the EPA, William A. Mills, accuses the agency of making "misleading" pronouncements that exaggerate both the danger of radon and the potential for reducing it. Meanwhile a new study of radon and cancer risk challenges basic assumptions about the danger of low-level radiation.

Radon is produced by the decay of uranium naturally present in some rocks and soils. When it is inhaled, it deposits its own radioactive-decay products in the lungs. High radon levels, found in uranium mines, for example, have been shown to cause lung cancer, and low concentrations have been assumed to increase the risk of cancer by an amount proportional to the radiation dose.

A national health advisory issued by the Public Health Service in September urged that most houses be tested for radon and suggested that ones with a measured level of more than four picocuries per liter have seals and vents installed in their lower stories to reduce radon accumulation. A new EPA survey of seven states indicates that nearly one in three houses in those states has radon levels above the four-picocurie "action level."

Ralph E. Lapp, a radiation-safety consultant, charges that in issuing the advisory "the surgeon general has been ill-advised." He maintains that the EPA overestimates the risk by a factor of 2.5, because the measurements are made under conditions that inflate the readings: in winter (when windows are closed) and in basements (where the gas accumulates). His proposed action level for houses—10 picocuries per liter—would drastically reduce the size of the problem. Lapp also notes that smokers account for 85 percent of the deaths attributed to radon, since smoking worsens radon's effect. He argues that even the EPA's stringent action level would save no more than 300 nonsmokers per year. The Government, he says, should not set a low radon standard primarily in order to protect smokers, who knowingly accept health risks.

Lapp believes the EPA adopted the four-picocurie limit to save political face: it had proposed that level for houses near uranium tailings some years ago, and expensive measures have been taken to comply with it. In calling for a less stringent standard, Lapp is supported by Mills, who adds that the EPA failed to make clear that many of the 20,000 deaths it attributes to radon result from very low concentrations of the gas, which ordinary vents and seals cannot eliminate.

The assumption underlying the concerns, that risk is proportional to radiation dose at low levels, is challenged by a study done by Bernard L. Cohen of the University of Pittsburgh. Cohen maintains his study is the first to test the assumption rigorously. When he examined lung-cancer mortality and average radon exposure in 411 counties across the U.S., he found that mortality is significantly lower where radon exposure is high—the opposite of what is expected.

Cohen has eliminated several "confounding factors," and the pattern seems robust. He suggests that an explanation may lie in "hormesis": the notion that low doses of radiation might actually protect against cancer. Jerome S. Puskin of the EPA, in contrast, thinks the data might be explained by some confounding factor that has yet to be recognized.

The EPA has no plans to revise its radon standards. Puskin says the action level would be even lower than four picocuries if that were practical. But Robert E. Alexander, president of the Health Physics Society, says he is "very suspicious" that the risks from radon have been overplayed. The organization has convened a working group to determine the professional consensus. —*Tim Beardsley*

PHYSICAL SCIENCES

The Cygnet Turns Phoenix

Hercules X-1 joins Cygnus X-3 as emitter of cosmic mysteries

At a time when accelerators are unable to produce the Higgs boson and other expected fundamental constituents of matter, the cosmos is doing quite well at providing the unexpected. The story begins in 1983 when a research group at the University of Kiel in West Germany reported that cosmic-ray showers coming from the general direction of Cygnus X-3, the brightest X-ray source in our galaxy, seemed to contain roughly 10 times the number of muons they expected. Muons are common subatomic particles, about 200 times more massive than electrons but otherwise identical with them.

The Kiel report was known only to specialists until 1985, when several research groups that had been operating proton-decay detectors underground announced fluxes of muons on a direct line of sight from Cygnus X-3 that were much larger than muon fluxes from other directions in the sky. Moreover, the greatest muon signal was received during the biggest cosmic-ray shower from Cygnus X-3 ever recorded.

At these announcements the usual corridor speculation among physicists also jumped far above normal background noise. Why? Cosmic-ray showers are initiated when any of a number of particles—usually protons—impinge on the earth's upper atmosphere to produce a cascade of secondary particles, including muons, which are the particles actually detected by the cosmic-ray detectors. Muons, however, are unstable: their lifetime is about six milliseconds at the energies at which they were apparently being detected. Cygnus X-3 lies at a distance of about 40,000 light-years. It is therefore impossible for muons to travel from Cygnus X-3 to the earth without decaying; those recorded must have been secondary particles produced near the detector by some other, primary particles.

The problem was an acute lack of obvious candidates for the primaries, whimsically named cygnets. Any primary must be electrically neutral; otherwise the magnetic field of the galaxy would deflect it far from the observed straight-line trajectory between Cygnus X-3 and the earth.

Neutrons were ruled out because, although they are electrically neutral, they too are unstable and would decay during the 40,000-year flight from Cygnus. This left photons and neutrinos, but no known reaction between photons or neutrinos and detectors produces the number of muons that were being reported. In 1985 physicists resorted to the ultimate in exotica to explain the observations: Cygnus X-3 is a quark star, emitting small, neutral chunks of strange-quark matter—the cygnets.

As so often happens, the proton-decay detector results faded into oblivion for want of replication. Now, however, collaborators from the University of Maryland at College Park, George Mason University, the Los Alamos National Laboratory and the University of California at Irvine have reported similarly perplexing observations of a July 1986 cosmic-ray shower from Hercules X-1.

Like Cygnus X-3, Hercules X-1 is a compact binary system consisting of a neutron star and a companion of several solar masses. Like Cygnus X-3, it is a strong emitter of X rays and ultrahigh-energy photons and is associated with cosmic-ray showers.

In the 1986 shower 17 bursts from Hercules X-1 were detected, whereas the normal background level would have been approximately three. The investigators estimate that the probability of this being a random fluctuation in the background is about .0001. Furthermore, the number of muons detected in the showers is at least an order of magnitude more than the number produced when high-energy photons are the cosmic-ray primaries, and somewhat more than the number produced in proton-initiated showers.

Although the new results are independent of the old ones, the questions they raise are the same. Apparently the cygnet, having vanished three years ago, has risen from its own ashes. Speculation is already running rampant. —*Tony Rothman*

Theory-resistant
New superconductors yield their secrets reluctantly

To a reporter covering the field of superconductivity lately, the pattern is familiar. A press release from some research institution announces: "New theory explains high-temperature superconductors!" When the reporter interviews other theorists, they firmly demur. The theory may be interesting, they say, but it is also highly speculative, as are all the theories advanced so far.

Indeed, nearly three years after experimenters discovered a strange class of copper-oxide ceramics that at unprecedentedly high temperatures offer no resistance to electricity, theorists are still struggling to provide an explanation. The effort has led them to reexamine many basic views on solid-state physics, according to Theodore H. Geballe of Stanford University. "Several years ago," he says, "we thought we understood most of this."

Conventional superconductors, Geballe explains, are metals that conduct well even above their critical temperature (at which they become superconducting). The metals have an abundant supply of free electrons that can flow isotropically, in any direction. Superconductivity occurs when, at very low temperatures, minute acoustic vibrations called phonons bind the free-flowing electrons into pairs, making them virtually immune to scattering.

Apparently electrons pair off in the new ceramic superconductors, but the binding mechanism seems to be much stronger than the phonon interaction. Tests have also shown that the electrons flow not isotropically, as in metals, but primarily along the copper-oxide layers, which are sandwiched between combinations of other elements. Above their critical temperature the ceramic compounds conduct like "poor metals," in the words of one theorist; if the proportion of elements in the compounds is only slightly altered, moreover, they behave like semiconductors or even insulators, whose electrons are tightly bound rather than free-flowing.

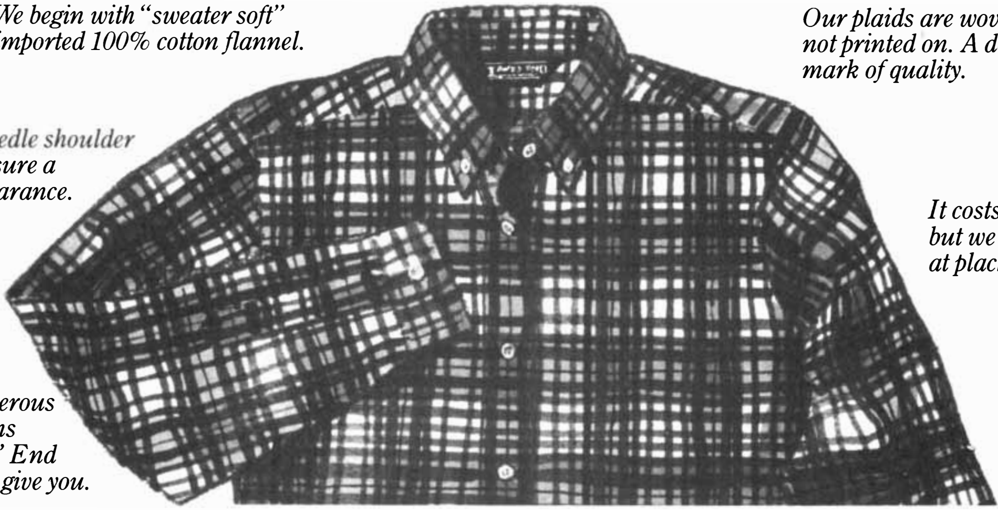
This latter property, Geballe notes, evokes a more familiar solid-state effect: some insulating materials, when doped with tiny amounts of other elements, abruptly become good conductors. By reexamining this phenomenon, Geballe says, physicists may gain insights into high-temperature superconductivity. Philip W. Anderson of Princeton University, who in 1977 won a Nobel prize for his work in solid-state physics, agrees. He suggests, furthermore, that the same mechanism that "pins electrons down" in the insulating phase of the ceramic compounds may bind the electrons into scatterproof pairs in the superconducting phase.

Atomic "spin" may play a role in superconductivity at high temperatures, but no one knows just how

MILLIMETER-WIDE SINGLE CRYSTALS of the high-temperature superconductor yttrium barium copper oxide were grown by Lynn Schneemeyer of the AT&T Bell Laboratories. Workers probe crystals for clues to the material's behavior.

Anderson's pronouncements about high-temperature superconductivity have held up better than most. What is perhaps his fundamental prediction—that a property known as spin, which makes charged particles behave like tiny magnets, plays a crucial role—has been supported by experiments done by Robert J. Birgeneau of the Massachusetts Institute of Technology and Gen Shirane of the Brookhaven National Laboratory. After probing single crystals of a copper-oxide superconductor with neutrons, the workers found that both the copper ions and the positively charged holes associated with the oxygen ions have spins, aligned in a complex spiral pattern. No evidence has linked this phenomenon to superconductivity directly. Nevertheless, a growing body of data suggests that "any theory ignoring spin will be incomplete," says Patrick A. Lee of M.I.T.

Can a single theory embrace all the new superconductors? Dozens have now been identified, ranging from the original lanthanum barium copper oxide discovered by IBM workers, which superconducts at 28 degrees Kelvin, to a thalium barium calcium copper ox-



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ide that superconducts at 125 degrees K. The picture became even more complicated this past spring when workers at the AT&T Bell Laboratories found a compound—barium potassium bismuth oxide—that superconducts at 30 degrees K. Unlike all the other compounds, the material lacks copper, it has an isotropic rather than a layered structure and it exhibits no localized spin. A comprehensive theory may have to incorporate many different pairing mechanisms, according to Geballe. Superconductivity appears to be "like water running down a hill," he says. "There are many paths it can take."

For this reason, among others, most investigators doubt whether any theory can establish the upper limit for the critical temperatures of superconductors. One attempt to do just that has gained much attention recently. The *New York Times* devoted a front-page story to a prediction by workers at the California Institute of Technology that critical temperatures will never surpass 250 degrees K., well below room temperature. "It's irrelevant to my work," says Robert J. Cava, an experimentalist at Bell Laboratories who believes room-temperature superconductivity is attainable. "Anyone who sets an upper limit is only saying where his ideas stop being effective." —*J.H.*

Factoring Googols

Computers on three continents factor an elusive number

Networking through more than 400 computers in the U.S., the Netherlands and Australia, a team of computer scientists has shattered all previous records by finding the two large, prime factors for a 100-digit number. The accomplishment, which was one of the largest parallel-computing projects ever undertaken, has begun to threaten the security of some cryptographic codes used by governments, banks and industries.

To factor the 100-digit number the project organizers, Mark S. Manasse of the Digital Equipment Corporation (DEC) in Palo Alto and Arjen K. Lenstra of the University of Chicago, implemented a method devised by Carl Pomerance of the University of Georgia. This method, known as the quadratic sieve, discovers factors by finding two numbers that when squared and divided by the original number have the same remainder. To find the factors of 15, for instance, the method would reveal that 8 and 2, when squared and divided by 15, both leave a remainder of 4. Once the two numbers are found, the factors can be computed. In this case 2 is subtracted from 8, leaving 6. If 6 is then subtracted from 15 as many times as possible without producing a negative number, the final result is 3, which is indeed one of the prime factors of 15. Although factoring small numbers by the quadratic-sieve method is a slow process, this method factors large numbers faster than any other method yet devised.

Another advantage of the quadratic sieve is that many different computers can share the task of finding factors. A computer at DEC handled the bulk of the task of factoring the 100-digit number while computer centers in the U.S., the Netherlands and Australia shared the rest of the calculation. On the 26th day of the project Manasse and Lenstra had accumulated enough data to factor the 100-digit number, which is equal to $11^{104} + 1$ divided by $11^{8} + 1$, into prime factors 41 and 60 digits long.

The ability to factor numbers that large may enable decipherers to break some codes from a widely used cryptographic system created by Ronald L. Rivest, Adi Shamir and Leonard Adelman of the Massachusetts Institute of Technology. The Rivest-Shamir-Adelman (RSA) system is based on the fact that, although large prime numbers can be computed easily, factoring the product of two such numbers has been infeasible. Every user of the RSA system chooses two large prime numbers and publishes the product. A message is converted into a string of numbers by some conventional method and is then encoded by a mathematical operation based on the published number. A message can be decoded only by a second operation based on the original prime numbers. If the published number can be factored, however, the message can be deciphered. To keep a system secure, users must choose prime numbers sufficiently large to ensure that the published number cannot be factored.

Following Manasse and Lenstra's project, many organizations may reconsider the security of their codes and choose larger numbers. In 1977 Rivest calculated that a 125-digit code that consisted of two 63-digit primes would be secure. The time required for the fastest computers of that year to break a 125-digit code would have been 40 quadrillion years. A system similar to the one employed by Manasse and Lenstra, the workers say, could break such a code in one year. —*Russell Ruthen*

BIOLOGICAL SCIENCES

High Rate of Return

Fire-ant sperm banks yield one worker for every three sperm

For a human female, the thought of engaging in sex just once in order to produce children for the rest of her life may seem a little cold-hearted, albeit efficient. But for ants and other social Hymenoptera, such as bees and wasps, it is a way of life. In the social Hymenoptera mating takes place only on one occasion, and in less than an hour a female must store all the sperm she will ever need.

Consider the efficiency with which she parcels out her sperm supply. Walter R. Tschinkel and Sanford D. Porter of Florida State University determined that on the average fire-ant queens expend about three sperm for every adult worker they produce. Even for insects such ratios are astounding; the honeybee queen, for example, expends from 20 to 30 sperm per egg. The number released by mammals is astronomically higher: each time a human egg is fertilized, the male re-

FIRE-ANT QUEEN, surrounded by workers, expends about three sperm for every adult worker produced, an efficiency of sperm utilization that is among the highest in the animal kingdom. The photograph is by Walter R. Tschinkel.

leases from 200 million to 600 million sperm. The horse produces from four to nine billion sperm per ejaculation and the pig as many as 20 billion sperm.

The investigators, who describe their findings in a recent issue of *Annals of the Entomological Society of America,* obtained their data from a fire ant (*Solenopsis invicta*) known to mate only once during the nuptial flight. Newly inseminated queens were collected and the sperm in the spermatheca, a specialized sac in the reproductive tract that stores sperm, were counted.

By dividing the number of sperm (seven million on the average) in the spermatheca by the total number of workers produced (about 2.6 million) over the seven-year life span of the queen, Tschinkel and Porter found that the queen releases approximately 2.6 sperm for every worker. The efficiency of sperm utilization is probably even greater than that, Tschinkel says, because he and Porter did not account for preadult mortality in their estimates of the number of workers produced by a queen. If mortality at any stage prior to adulthood is high, the ratio may drop to only one or two sperm per egg.

Do any other species make comparably efficient use of sperm? The nematode *Caenorhabditis elegans* produces only one sperm per egg, but the species is hermaphroditic and both gametes are therefore produced at the same time and place. How is it that a fire-ant queen is able to regulate her sperm supply so efficiently? No one knows for certain. "It isn't a subject that's received much attention," Tschinkel says. *—Laurie Burnham*

Electronic Ark

Biologists mobilize to chart vanishing species

Alarmed by the prospect that much of their subject material will disappear, biologists are stepping up their campaign for an effort to catalogue plants and animals threatened by deforestation and development. They are also starting to weigh the daunting logistics: computers will have to be used on a large scale to cope with the data generated by such an enterprise.

The biologists' pleas are not going completely unheard. In October, Congress passed a joint resolution urging the president to pursue "vigorously" discussions on an international agree-

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ment to protect biological diversity. Meanwhile the National Science Board, the policymaking body of the National Science Foundation, has instituted a task force on the subject.

The Smithsonian Institution is considering establishing a National Center for Biological Diversity, described by Stanwyn G. Shetler of the National Museum of Natural History as a think tank that would study ecological processes and plan strategies for biological sampling in threatened areas. Although it was first proposed as a domestic initiative, Shetler believes the center should have an international focus. He thinks part of its task should be to foster local expertise in developing countries.

Motivating such initiatives is the growing alarm over the destruction of tropical forests, which are home to the majority of the earth's species. Most of the species have never been described, and estimates of the pace of destruction are becoming increasingly dire. According to Thomas E. Lovejoy of the Smithsonian, between 50 and 100 acres of tropical forest are being destroyed every minute. Lovejoy's figures, based on recent remote-sensing studies, are substantially higher than estimates made a few years ago.

Even as species vanish, biologists are falling behind in cataloguing existing museum collections. Shetler points out that in the U.S. alone there are many taxonomic groups for which "we don't even have a basic identification manual." Early proposals to catalogue diversity concentrated on the logistics of an emergency mapping effort, but they "miss the mark fundamentally on the need for an information base," Shetler says.

There may not be enough taxonomists for the task ahead, according to W. Franklin Harris of the National Science Foundation. The number of new Ph.D.'s in taxonomic disciplines is declining; anecdotal evidence suggests that molecular biology is taking students away from taxonomy.

Workers are looking to computerized data bases as a way to reduce the need for staff and to speed the compiling and exchanging of information. "Computerization is the only conceivable way of getting it done," says Peter Raven of the Missouri Botanical Garden.

The Association of Systematics Collections (ASC) met recently in Washington to consider the demand for computing. According to George M. Davis, one of the organizers, fewer than 10 percent of the specimens in U.S. collections are now catalogued by computer, and yet the total number of specimens is increasing by about 11 million, or 5 percent, per year. Moreover, the number of requests for information is expected to increase. "We are at a critical juncture," Davis says. The ASC hopes that major portions of U.S. collections will be accessible by computer within 10 years, but the organization has yet to estimate the cost of the needed computing capacity. —*T.M.B.*

Unscientific Americans

School science remains a national humiliation

A new study published by the Educational Testing Service (ETS), *The Science Report Card,* gives U.S. students poor grades for their understanding of science. The study, which is a continuation of the National Assessment of Educational Progress, a Congressionally mandated inquiry, concludes that only 41 percent of 17-year-olds have "some understanding of the design of experiments or any degree of specialized knowledge across the subdisciplines of science." Just one in 13 of the 17-year-olds attains "any degree of sophisticated understanding," according to the ETS—a proportion that is "substantially smaller than that needed for the future work force."

The study was based on a sample of some 13,000 primary- and secondary-school students. Performance at the level of "some understanding" was indicated if students could "analyze scientific procedures and data" by recognizing, for example, that the amount of water an object displaces can serve as a measure of its volume. Another question at the same level was: Why are marine algae usually found only in the top 100 meters of the ocean? (Answer: They can live only where there is light.)

In order to demonstrate an ability to "integrate specialized scientific information"—and thereby perform at the "sophisticated" level—a student was challenged, for instance, to predict the direction of a vertical pole's shadow in the morning in the central U.S. or to identify the densest among four objects, given their masses and volumes.

The tests did uncover some encouraging trends: compared with scores from 1982, the results showed some improvement at all ages tested (nine, 13 and 17 years), although only among nine-year-olds did achievement regain its 1970 level. Black and Hispanic students, together with students living in the Southeast, registered the largest gains. Nevertheless, black and Hispanic 13- and 17-year-olds are still, on the average, four years behind white students. Females did not perform as well as males, particularly in physics.

On the whole the ablest students showed no improvement since 1982, and their number did not increase. One reason for the basically poor results may be the small amount of time schools devote to teaching science: the study reports that half of seventh-grade teachers and 45 percent of 11th-grade teachers spend less than three hours per week on science.

The new study makes no comparisons with other countries. A survey published earlier this year by the International Association for the Evaluation of Educational Achievement found that among students in the upper grades of secondary school in 13 countries, U.S. science students rank last in biology and lag badly in chemistry and physics. Some experts, however, fault that survey for failing to make adequate allowances for varying teaching practices. The ETS will weigh into the debate on international comparisons in January, when it will publish the results of a comparison between U.S. 13-year-olds and those in five other countries. Reviewers say the study is likely to confirm the bleak picture. —*T.M.B.*

MEDICINE

Embryonic Questions

The experimental use of fetal tissue sparks bitter debate

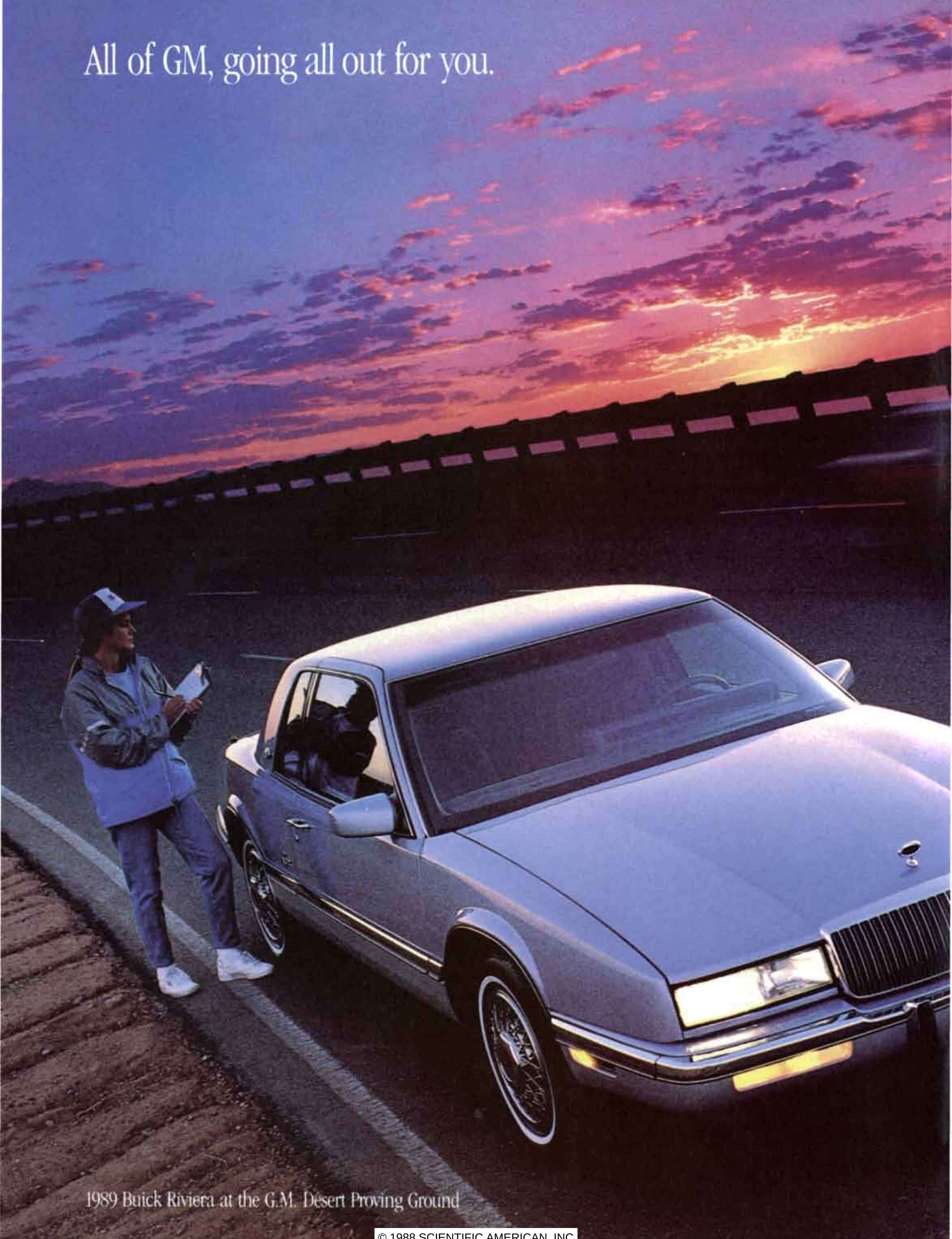
Experiments in which tissue from the brains of aborted fetuses has been implanted into the brains of Parkinson's-disease victims have reportedly yielded a few beneficial results. Whatever their outcome, the procedures have placed the experimental use of fetal tissue (which has been accepted for 30 years) squarely in the middle of a sharp policy debate.

The Parkinson's experiments have been carried out in Sweden, Britain and elsewhere but not in the U.S. When investigators at the National Institutes of Health decided to seek approval for such experiments earlier this year, they set off a Government inquiry that could have far-reaching implications.

In response to the workers' request, Robert E. Windom, assistant secretary for health, framed 10 questions that probe whether and under what circumstances investigators might use human fetal tissue in research and asked the NIH to appoint a panel of consultants to consider them. Under the chairmanship of Arlin M. Adams, a retired Federal judge, the panel spent several days in September and October taking testimony and weighing the questions.

Windom put most research on fetal-tissue transplantation on hold pending the outcome of the deliberations. Members of the consultants panel were therefore startled when immediately before their first meeting news reports revealed that Gary L. Bauer, assistant to the president for policy development, had drafted a proposed executive order stating it should be Government policy that "an unborn or newborn child who has died as a result of an induced abortion shall not be used for purposes of research or transplantation." By apparently ruling out Federal support for all such research, the proposal seemed to undercut the panelists' role. Embarrassed, the White House quickly dropped a request that the Secretary of Health and Human Services promptly review the proposed executive order.

That contretemps behind it, the panel has reached tentative conclu-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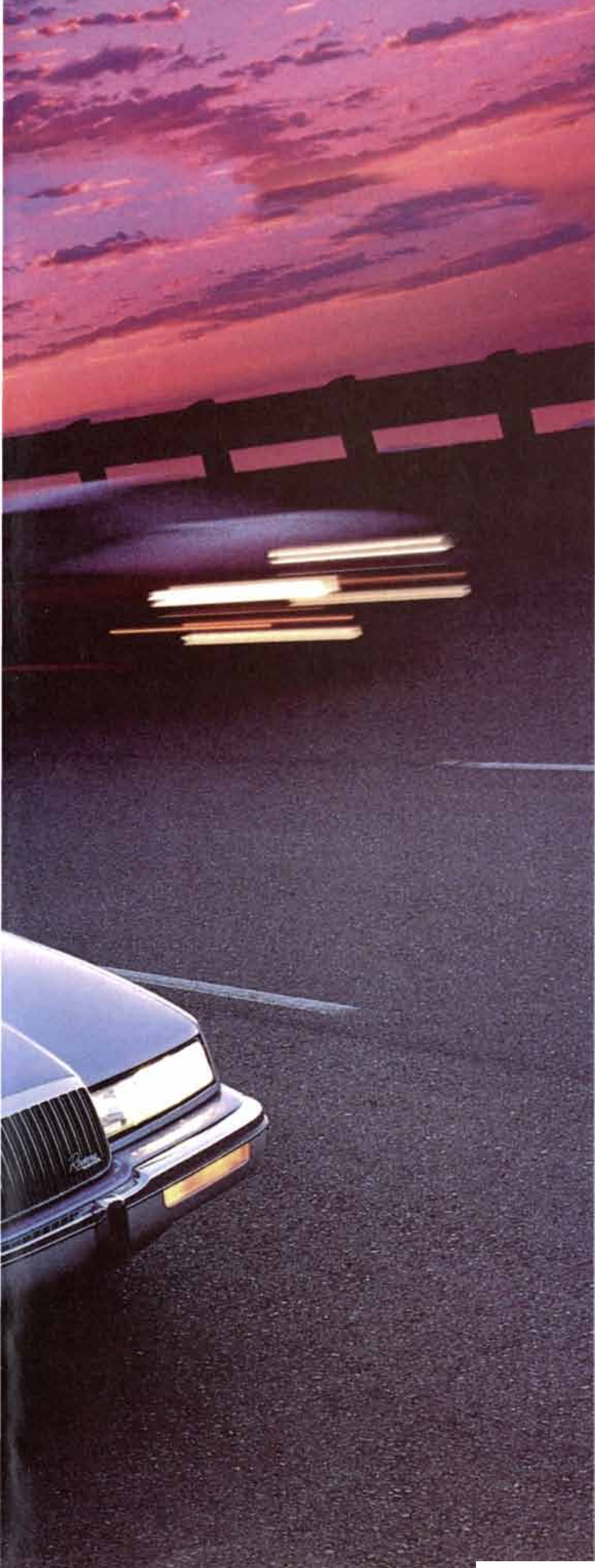


sions, subject to confirmation by a poll of its members. The central one is that the use of aborted fetal tissue is under existing circumstances "acceptable public policy." But two members of the consultants panel, James Bopp, Jr., a lawyer with experience in abortion litigation, and Rev. James T. Burtchaell, a theologian at the University of Notre Dame, issued a lengthy dissenting statement in which they argued that the Government would be in moral complicity with abortion if it sanctioned such research.

In contrast, most panel members agreed that the use of fetal tissue for research or therapy could be governed by strict protocols. These would ensure that it would never be an incentive for a woman to have an abortion or to delay the procedure in order to give the fetus time to develop. The consultants also agreed that fetal-tissue use should be sanctioned only with the fully informed consent of the pregnant woman. For most panel members the central concern was whether it is possible to devise protocols that will insulate the securing of informed consent from the decision to have an abortion.

The panel made several tentative recommendations to that end. It agreed that obtaining informed consent for the use of fetal tissue, and even providing preliminary information about donating fetal tissue, should be deferred until after the decision to have the abortion.

One fear was that some women might be tempted by financial inducements if the demand for fetal tissue grows: hence the consultants recommended that fees be made illegal. In order to dispel the specter of women deciding to become pregnant in order to donate fetal tissue to friends or family, the consultants recommended that the Government not support experimental transplants of fetal tissue provided by anyone known to the beneficiary. Bopp believes such safeguards are insufficient: he argued that by allowing the use of fetal tissue "you provide a noble reason to have an abortion."

Speaking for the majority of the panel, Daniel Robinson, chair of the department of psychology at Georgetown University, said that allowing the use of fetal tissue in research did not imply ethical approval of abortion. Here the dissenters part company with the majority: Bopp and Burtchaell believe there can be no "moral autoclave to sterilize the tissue ethically."

The panel's final recommendations will eventually go to the director of the NIH, and thence to Windom. In the meantime some 500 antiabortion physicians and ethicists have signed a petition urging the president to implement Bauer's proposed executive order forthwith.

The situation may grow still more charged: the panel agreed that experiments with animals already justify attempts to implant human fetal tissue into patients with juvenile diabetes, as well as Parkinson's. Other diseases might follow. —*T.M.B.*

Memories of Mother

Does the immune system allow transplants that seem familiar?

For many patients who require a kidney transplant a compatible donor cannot be found. Recent observations of transplant candidates brighten the outlook for victims of kidney disease by raising the possibility that the pool of compatible donors can be enlarged.

The pool of donors is limited by the immune system's propensity to destroy tissue it regards as "not self," or foreign. On any transplanted organ the principal immunological feature to which a recipient's immune system responds is the cell-surface proteins known as class I histocompatibility antigens, half of which are inherited from each parent. Because there are dozens of different class I antigens in a population, it is hard to find donor organs with class I antigens that are identical with those of the transplant recipient. A perfect match is not always essential, but it is deemed necessary for the 15 percent of kidney-transplant candidates who develop highly sensitized immune systems as a side effect of repeated blood transfusions or of an earlier rejected transplant. Such patients produce antibodies against most class I antigens that are not identical with their own.

Frans H. J. Claas, Jon J. van Rood and their colleagues at the University of Leiden tested the blood serums of such highly sensitized patients in order to see whether they would tolerate a transplant bearing class I antigens that were a close match but not a perfect one. The workers, who describe their research in *Science*, learned that for most of the patients it was possible to find one or more antigens that did not cause an immune response. The transplants were done, and a high proportion were accepted.

Only later did the investigators realize that the mismatched antigens the patients tolerated were, in 15 out of the 26 cases studied, antigens that were carried by the patients' mothers but were not passed on to their offspring. There was no corresponding similarity to paternal antigens.

The workers suggest that during pregnancy maternal cells find their way into the bloodstream of the fetus, whose developing immune system "learns" to tolerate the maternal cells' class I antigens as if they were its own. The immune system's "memory" of the maternal antigens apparently lasts into adulthood.

The discovery, if confirmed in more extensive studies, "has the potential of having a very profound impact on the way we practice clinical renal transplantation," according to Richard J. Glassock of the University of California at Los Angeles School of Medicine. Claas and van Rood's preliminary results suggest that perhaps 30 or 40 percent of highly sensitized patients, who are now unlikely ever to find a suitable donor organ, might be able to receive mismatched organs bearing maternal antigens. The discovery might make identifying donors for other organs easier as well. *—T.M.B.*

Ghost in the Machine

A data base compiles human anatomy slice by slice

The human body is taking shape in an image-processing computer in Colorado, as workers construct what they believe will be the first three-dimensional data base of the human body. The computerized anatomy, capable of showing the human body from every imaginable point and angle, may eventually be made widely available, perhaps on optical disks. It should be a boon for medical students, surgeons and radiologists, among others.

To generate the data base, David G. Whitlock and his co-workers at the University of Colorado Health Sciences Center in Denver have been photographing successive planes of a frozen cadaver as thin slices of tissue are removed by a special milling machine. Each photograph is then digitized and stored in an image-processing computer. So far the investigators have sectioned, photographed and digitized a pelvis and a knee.

The milling machine, devised by Whitlock and his colleagues, can remove slices as thin as a quarter of a millimeter. When views separated by such thin sections are assembled into a three-dimensional image, the intervals become indistinguishable. The result is a complete three-dimensional reconstruction of human anatomy, detailed enough to reveal individual bundles of muscle fibers.

Such detail, which the computer can re-create in natural color, could help surgeons to plan operations. It could also provide doctors with a base line for interpreting images of live patients obtained with techniques such as nuclear magnetic resonance. Because the computerized anatomy makes possible detailed examination of the paths of muscles, it could also lend itself to mechanical analyses of joint function. The National Football League has expressed interest in the data base, thinking it might lead to better treatments for joint injuries. Workers at the National Aeronautics and Space Administration who are developing electronic muscle-stimulating devices to restore movement to paralysis victims may use the data base to determine which muscles are crucial for specific movements.

Whitlock is now marking and coloring individual muscles in the data base so that a user can ask the computer to highlight a specific muscle. At the moment the muscles must be marked by hand, employing animation techniques originally developed by the Walt Disney Studios. Victor M. Spitzer, another worker on the project, says the group hopes eventually to develop algorithms that will enable a computer to trace and highlight features, such as a single nerve or artery, at the user's request. *—T.M.B.*

HUMAN KNEE JOINT is laid bare in a three-dimensional image produced from a computerized data base at the University of Colorado at Denver.

NOBEL PRIZES

Physics

Three Americans honored for 1960's neutrino experiment

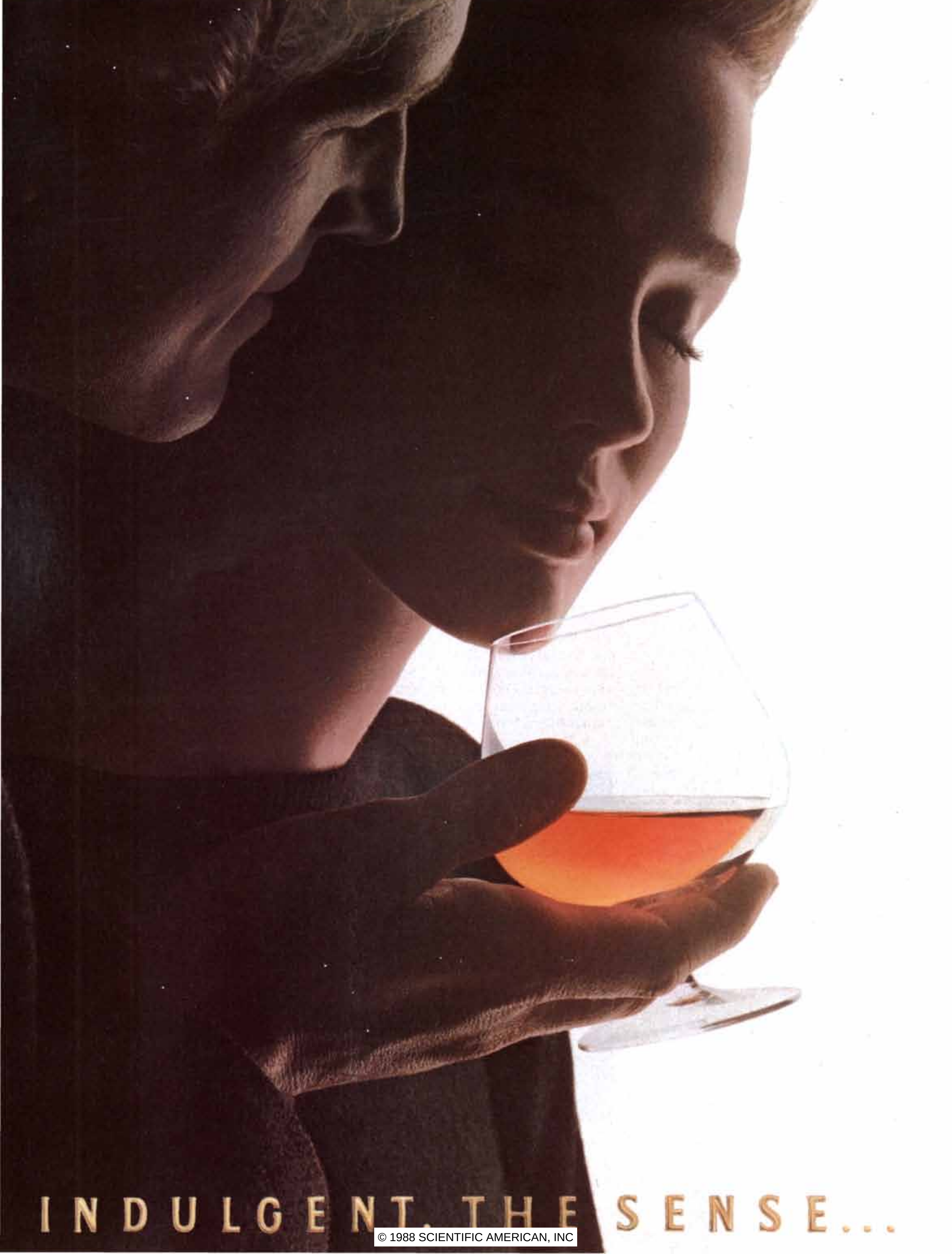
In his 1960 poem "Cosmic Gall" John Updike wrote: "... like tall / and painless guillotines, they fall / down through our heads into the grass. / At night, they enter at Nepal / and pierce the lover and his lass / from underneath the bed—you call / it wonderful: I call it crass."

The subject? Neutrinos, naturally, those wraithlike particles that play so weighty a role in modern physics. They began as creatures of theory: Wolfgang Pauli suggested in 1931 that some unseen particle must account for a deficit of energy observed in the output of a form of radioactivity called beta decay. Soon thereafter Enrico Fermi came up with the name "neutrino." Finally, in 1956, Frederick Reines and Clyde L. Cowan confirmed that one type of neutrino—associated with electrons—actually existed.

By the time Updike published his poem, however, theorists were becoming increasingly dissatisfied with their understanding of the so-called weak nuclear force, which is implicated in radioactive decay. Some theorists suspected that more than one neutrino might be involved. An experiment that produced a beam of high-energy neutrinos could help to clear up the mystery, but no one knew how to achieve that goal. For solving the problem, Leon M. Lederman of the Fermi National Accelerator Laboratory, Melvin Schwartz of Digital Pathways, Inc., and Jack Steinberger of the European Center for Nuclear Research have won the 1988 Nobel prize for physics.

The three collaborated while they were at Columbia University in the early 1960's. Using an accelerator at the nearby Brookhaven National Laboratory, they hurled protons at a target of beryllium; the collision yielded a dense beam of particles, some of which decayed almost immediately into neutrinos. A 45-foot-thick wall of steel slabs salvaged from U.S. warships filtered out all the particles except the neutrinos, which passed through the wall and into a detector.

Over an eight-month period in 1961 and 1962 the accelerator generated an estimated 100 trillion neutrinos;


INDULGENT. THE SENSE...

the detector recorded only 51 of them. The events were still sufficient for the workers to confirm that indeed there were at least two types of neutrino: the electron neutrino and another type associated with much heavier negatively charged particles called muons [see "The Two-Neutrino Experiment," by Leon M. Lederman; SCIENTIFIC AMERICAN, March, 1963]. This finding, together with others from later neutrino-beam experiments, helped theorists to realize that the weak nuclear force and electromagnetism are two aspects of the same effect, known today as the electroweak force.

A crucial question remains to be answered by future winners of a Nobel prize. Do neutrinos have mass, and if they do, could the gravitational attraction of myriad neutrinos keep the universe from expanding forever and becoming a cold, dark void? Now that would be wonderful. —*J.H.*

Chemistry

Germans win for illuminating an engine of photosynthesis

First there is light, sunlight to be precise. It bathes a field and the grass grows. A steer eats the grass and fattens. Then a human being eats the steer.

All life depends for survival, ultimately, on photosynthesis, but until recently the machinery of the process has remained obscure. For unraveling the structure of a complex of proteins that serves as the engine for photosynthesis in some bacteria, Johann Deisenhofer of the Howard Hughes Medical Institute, Robert Huber of the Max Planck Institute for Biochemistry and Harmut Michel of the Max Planck Institute for Biophysics have received the 1988 Nobel prize for chemistry.

The complex of proteins lodges in the outer membrane of the bacterium and extends from there both into and outside the cell. Such proteins, called membrane-bound proteins, contribute to many biological processes involving the transport of energy across cell walls. Biologists have not been able to determine the structure of most membrane-bound proteins because they are extremely difficult to prepare in the crystalline form required for X-ray crystallography.

In 1982 Michel did what many workers had considered impossible: he grew crystals of the membrane-bound proteins that act as the photosynthetic engine of a group of bacteria called rhodopseudomonads. Over the next three years Huber and Deisenhofer, who was then at the Max Planck Institute for Biochemistry, probed the crystals with X rays. Eventually they pinpointed the position of all 10,000 or so atoms in the protein complex.

This knowledge has already provided insights into how plants and algae as well as rhodopseudomonads carry out photosynthesis. The work may also help investigators to understand the role that membrane-bound proteins play in diabetes, cancer and other diseases. —*J.H.*

Physiology or Medicine

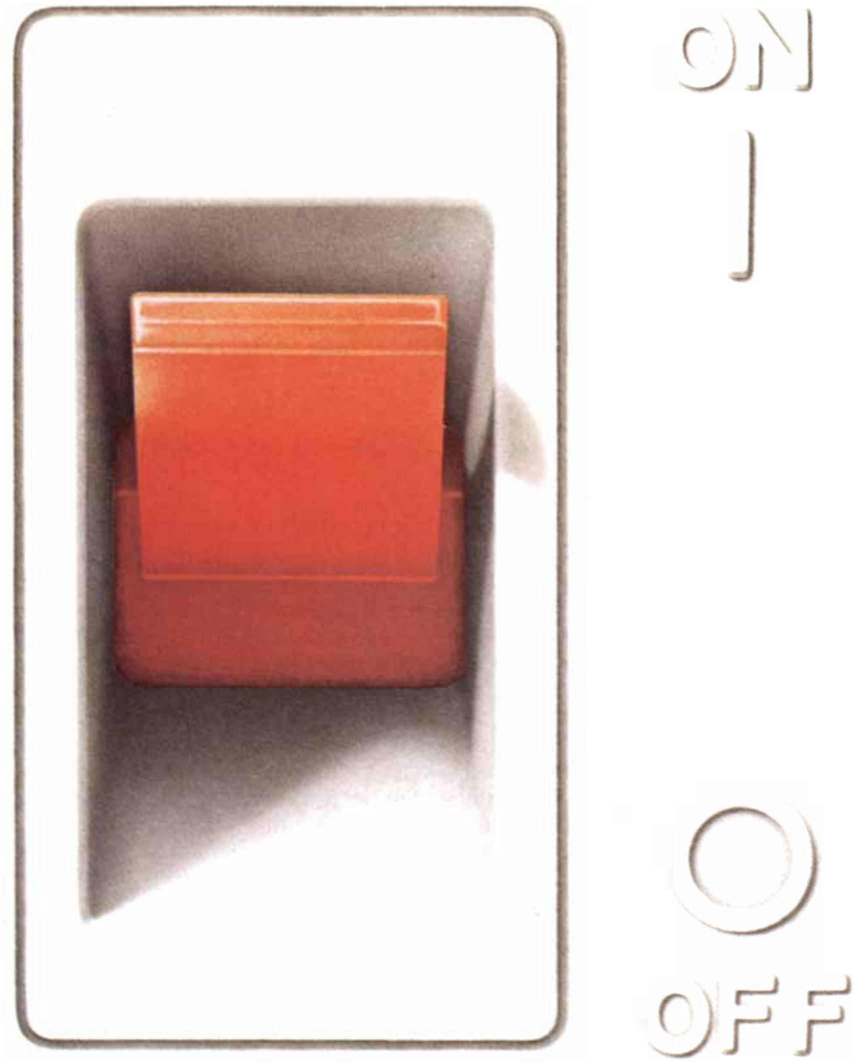
Pioneers in the development of drugs are honored

One can seek more effective treatments for disease in two basic ways: by trial and error or by building up a basic understanding of human biochemistry. The former method has dominated the search during most of humanity's history. The latter has only recently become possible. It is for this type of work that Gertrude B. Elion and George H. Hitchings of the Burroughs Wellcome Company and James W. Black of the University of London's Rayne Institute were awarded the 1988 Nobel prize in physiology or medicine.

Working together at Burroughs since 1945, Elion and Hitchings have sought to elucidate differences in the structure and function of normal cells and of cancer cells, bacteria, viruses and other pathogens. Their insights enabled them to design drugs—for leukemia, malaria and pneumonia, among other diseases—that disrupt pathogenic biochemistry but not that of healthy tissue. Their research helped others to develop acyclovir, a treatment for herpes, and the AIDS drug azidothymidine (AZT).

Black has focused on the interaction of various chemicals in the body with receptors on the surface of nerve and muscle cells. His research helped him to develop drugs called beta-blockers, used to treat high blood pressure and other heart-related disorders, and H-2 receptor-antagonists, widely prescribed for ulcers.

The Nobel committee praised the methodology of Elion, Hitchings and Black in addition to their creation of specific drugs. "While drug development had earlier mainly been built on chemical modification of natural products," the committee stated, the Nobelists "introduced a more rational approach." —*J.H.*



is incorporated in IBM's one-million-bit memory chips, the first of that density used in a computer. The world's fastest, most reliable chips, they retrieve information for customers in billionths of a second.

And IBM engineers invented the world's most sophisticated device for connecting and cooling computer circuitry. This helps increase speed and ensures reliability even when customers' computers perform many millions of computations per second.

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SCIENTIFIC AMERICAN December 1988 Volume 259 Number 6

Managing Solid Waste

Poor disposal practices have taxed the U.S. economy and environment. Municipalities should construct better incinerators and landfills and support active resource-conservation and recycling programs

by Philip R. O'Leary, Patrick W. Walsh and Robert K. Ham

America is a throwaway society. From both industrial and municipal sources, the U.S. generates about 10 billion metric tons of solid waste per year. Every five years the average American discards, directly and indirectly, an amount of waste equal in weight to the Statue of Liberty. Municipal solid waste alone accounts for 140 million metric tons per year. The municipal solid waste produced in this country in just one day fills roughly 63,000 garbage trucks, which lined up end to end would stretch 600 kilometers, the distance from San Francisco to Los Angeles. The repercussions of our waste habits, however, stretch to every city. Let us demonstrate by example.

PHILIP R. O'LEARY, PATRICK W. WALSH and ROBERT K. HAM study solid-waste disposal at the University of Wisconsin at Madison. O'Leary is assistant professor of engineering, teaching waste management. After earning his B.S. and M.S. at Wisconsin, he worked for the Wisconsin Department of Natural Resources and then until 1979 directed environmental projects for McMahon Associates. Walsh is assistant professor of agricultural engineering. He received his B.S. at Purdue University, his M.S. at the Massachusetts Institute of Technology and his J.D. from Wisconsin. From 1977 to 1981 he served in the Wisconsin Department of Justice and continues to work with local governments as a waste specialist. Ham is professor of civil and environmental engineering. He got his B.S. at the University of Minnesota and his M.S. and Ph.D. from the University of Washington. He has taught and studied waste issues for 20 years.

Like many urban areas, Philadelphia wallows in waste while dumps brim to capacity, while incineration hazards are debated and while resource-conservation and recycling programs develop slowly. The plight of the cargo ship *Khian Sea* attests to waste-disposal problems in Philadelphia. Carrying 13,000 metric tons of incinerator ash, the *Khian Sea* set sail for a dump in the Bahamas on September 5, 1986. It returned to Philadelphia 18 months later with most of the ash still on board. The Bahamas, the Dominican Republic, Honduras, Haiti and Guinea-Bissau on the west coast of Africa all denied the *Khian Sea* permission to dispose of the waste. Haiti maintains that 3,000 metric tons of ash were defiantly dumped on its beaches. On May 22, 1988, the *Khian Sea* left harbor again and has still not found a dump site as of this writing.

Like many rural areas, Marquette, Mich., discovered that discarding solid waste in an environmentally safe manner is an expensive ordeal. In 1983 the dump serving the 23,000 Marquette residents was closed because it violated a new state environmental law. The town "temporarily" shipped its solid waste to the closest legal landfill, 165 miles away. Marquette's garbage collectors traveled more than six hours every day to transport the town's 40 metric tons of waste; this more than tripled the town's disposal costs. Although land is plentiful and inexpensive around Marquette, the aversion of nearby municipalities to new landfills and Marquette's desire to preserve its land and water resources delayed construction. This month, some five years later, Marquette may finally open a landfill that surpasses state environmental specifications—but it costs just as much as dumping waste 165 miles away.

From antiquity to modern times, the primary strategy for disposing of solid waste has been to dump it on land. In 1986 the Environmental Protection Agency (EPA) determined that more than three-fourths of all municipal solid waste was deposited in the nation's 6,000 municipal landfills. The tradition of land disposal, however, is losing adherents. Communities near present and proposed landfill sites have always been concerned about the reduction of property values and the smell and sight of garbage; now they also worry about physical harm to themselves from landfill gases, microorganisms and toxins.

In response many state environmental agencies and the EPA have legislated or proposed regulations that greatly increase standards of landfill design and performance to protect people and the environment from pollutants. These regulations have closed or will soon close many landfill sites and have limited the construction of new sites. Within the next five years 1,200 landfills are scheduled to close, although in areas where alternatives are not available some may be allowed to expand. Moreover, only 563 landfills were opened from 1981 through 1986—a 35 percent decrease from the five-year period a decade earlier. As a result of the decrease in landfill capacity and the expense of pollution-control features, the cost of building and operating landfills has increased significantly. In some municipalities, particularly in the Northeast, fees for dumping municipal garbage have doubled and tripled in one year.

A municipality can lessen its dependence on landfills and alleviate waste-disposal problems by establishing an integrated solid-waste management system that minimizes environmental risk—all within the limits of the municipality's financial resources. A viable system would include resource-conservation programs to reduce the creation of waste, resource-recycling programs to reprocess waste into useful goods, incinerator technologies to reduce the volume of waste and new landfill technologies to dispose of residual waste in an environmentally sound manner. In the past Americans have been inattentive to disposal alternatives and have squandered resources. Over the next decade careful planning and changing attitudes will be necessary to avert a garbage crisis.

The impetus for the developing crisis arises from the sheer volume of solid waste produced by the U.S. population, but the environmental challenge of all waste-disposal problems arises from the heterogeneous composition of solid waste. Although solid waste from each municipality varies significantly owing to differences in climate, season, social attitudes and economic characteristics, independent research sponsored by the EPA has found that on the average more than 50 percent by weight of solid waste is accounted for by paper, paperboard and so-called yard wastes; nearly 40 percent by metals, glass, food wastes and plastics and 10 percent by wood, rubber, leather, textiles and other inorganic materials. Once these materials are mixed together a disposal method must be designed that accounts for a variety of chemical and physical conditions. When these materials are kept sorted, they can be reduced most efficiently.

The two best alternatives for waste reduction are therefore resource conservation and recycling. Resource conservation is simply the minimizing of the materials needed to complete a particular task. This can be accomplished by many different institutions. Industries can develop better packaging methods and product designs that minimize materials, and they can strive for product durability so that longer periods elapse before goods become wastes. Consumers can accel-

SEAGULLS SCAVENGE as trucks dump trash in Lyndhurst, N.J. This landfill is one of about 600 that have closed in the past three years. Safe and economical technologies for landfills, resource conservation and recycling can avert a garbage crisis.

erate these changes by choosing reliable, nonwasteful products. Governments can reinforce consumer convictions by banning certain types of packaging, assessing taxes on the use of selected materials and developing educational programs to help consumers make intelligent waste decisions. Resource conservation is not practiced widely, but it should be an important part of all integrated waste-management systems.

Resource recycling is the collection, separation and reclamation or composting of wastes such as paper, glass, metal, plastics and vegetation. More than 75 percent of the municipal solid waste in the U.S. is recyclable material, but this percent of recycling has not yet been attained owing to deficiencies in technology, public cooperation and markets. Even today a successful recycling program can achieve 30 percent and eventually reach 50 percent.

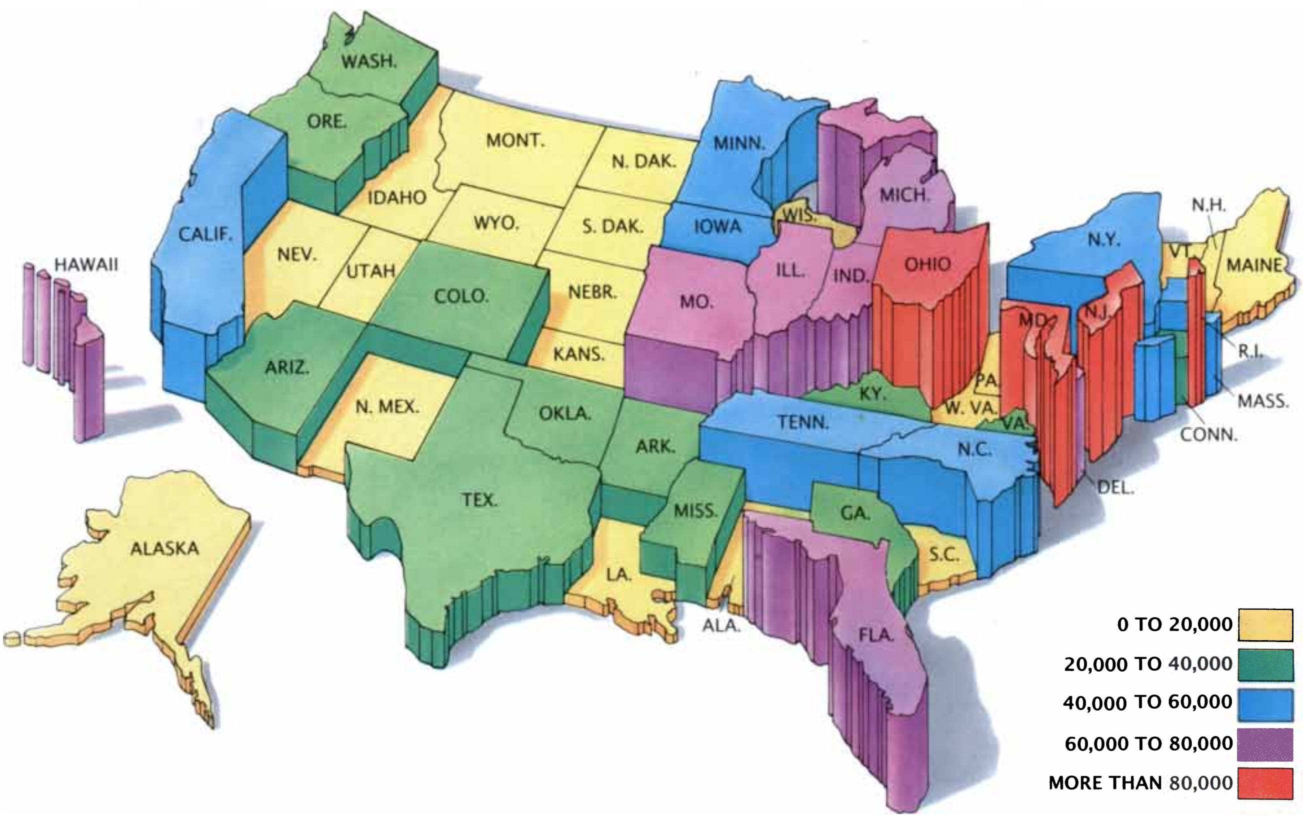
Waste administrators have devised many mandatory and voluntary programs that divide the responsibility for sorting and collecting these recyclable materials between municipality residents and waste contractors. The way these programs are implemented can greatly affect community participation and cost. Voluntary programs have often failed to achieve substantial long-term participation. In some cases, however, community interest has been maintained by incentives such as cash prizes for participation, refundable deposits on specific purchases and surcharges on garbage bags for nonrecyclable materials. Mandatory programs may achieve greater participation, but they may also result in public antagonism and illegal private dumping.

Recycling programs are most successful when they are made convenient for residents. At one extreme, contractors can collect all municipal solid waste and sort out the recyclable materials. If labor and equipment expenses are prohibitive, residents can separate the recyclable materials and contractors can provide convenient pickup schedules and special bins for recyclable materials.

Some successful and innovative recycling programs are noteworthy. Many municipalities have tried a program in which residents sort recyclable materials into color-coded containers and set them out next to the rest of their trash. Garbage collectors put the recyclable materials into the appropriate bins in their truck and the rest of the trash into a compactor compartment. Because the colored containers are highly visible to neighbors, more residents feel obligated to take part. Even with voluntary container programs, household participation rates of 80 percent have been achieved.

Marin County, Calif., has a voluntary program that recycles 22 percent of its municipal solid waste. Each participating household pays $1 a month to support the program and receives a special container for recyclable materials. Wilton, N.H., diverts and recycles 44 percent of its total solid waste, which amounts to 270 kilograms per year for each of the town's 8,500 residents. The town started the mandatory program in 1979 and allows residents to put their recyclable materials at curbside or take them to recycling centers. The town collects everything from glass, metals and paper to hazardous household wastes; it has saved about $50,000 in waste-disposal costs per year and gained about $25,000 from the sale of recyclable materials.

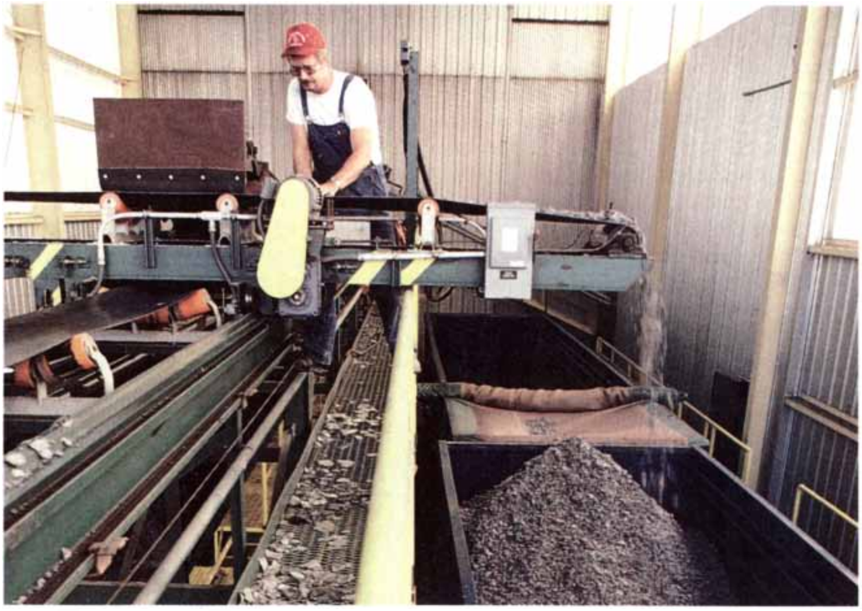
A rapidly expanding part of resource recycling is composting. Yard and food wastes are collected and put in piles or windrows, where they de-



POPULATION PER LANDFILL for municipal solid waste is shown based on 1986 data from the Environmental Protection Agency. Waste discarded by residents often overburdens landfills. Laws and public opposition limit the number of new sites.

compose aerobically and are greatly reduced in volume. Composting of all municipal solid waste is also an option. A mixture of highly organic solid waste can be prepared by a shredder and a metal separator and then put in windrows or vessels. Water or sewage sludge is combined with the mixture to achieve the appropriate moisture and nutrient content. Windrow composting is the commonest method, but mechanical systems that enhance mixing and aeration of the compost mixture are also available. After a final screening for impurities the stabilized mixture is reduced to one-third the weight of the original solid waste. Some question remains about whether the levels of metals and toxic materials in the compost are environmentally acceptable.

New technologies and community participation are not necessarily the key to economical resource recycling. Municipalities must also be able to market their recyclable materials to a processing facility, where materials are converted into useful products. Newsprint is transformed into new newsprint and corrugated paper; glass and aluminum are reprocessed into food containers; plastic milk jugs are remanufactured into plastic pipes; scrap iron is converted into steel, and compost is added to soil. Some administrators have mistakenly assumed that recycling programs will pay for themselves with the revenue generated by the sale of the materials. Unfortunately the demand for these items changes from month to month, so that the market value of raw recyclable materials fluctuates greatly. It may be necessary to pay a processing facility to accept materials, but the cost may still be less than the cost of discarding them in landfills. The markets are expected to stabilize as the recycling industry grows. In the meantime some states are attempting to expand the market by requiring government agencies to buy products made from recycled materials, and states are giving tax incentives to businesses that incorporate recyclable materials in their manufacturing processes. In relation to the entire integrated waste-management system, resource-recycling programs can be started quickly and are the least expensive option.



RECYCLING of paper can significantly reduce the amount of waste. This recycling plant shreds paper that is later converted into paper towels, newsprint and flowerpots.

The function of incinerators in the waste-management system has always been to burn solid waste to reduce volume, but the utility of incinerators has changed with time. Originally incinerators exhausted all combustion gases and particles directly to the atmosphere, but when air-pollution laws were enacted in the 1970's, incinerators became less economical because costly particle-control systems had to be introduced. Some incinerators were adapted to meet air-pollution requirements, but many facilities had to be closed. Recent increases in landfill costs have offset the costs of pollution control and advanced incinerator technology and have again made incinerators an economical alternative.

Another incentive for developing new incinerators is that they can generate energy. The combustion of unprocessed solid waste releases from 10,000 to 17,000 joules per gram. (Coal releases about 23,000 joules per gram.) Many incinerator technologies, such as the modular and mass-burn incinerators, recover this energy for external use. Both modular and mass-burn incinerators burn essentially unsorted, unprocessed solid waste. The modular incinerator has a capacity of as much as 140 metric tons per day, although two or more parallel units may be installed to achieve larger required capacities. The mass-burn incinerators have capacities of 900 metric tons or more per day. Both types have chambers that combust the solid waste and a boiler that recovers the combustion energy as steam. The steam can be employed for heating buildings, for industrial processes or to generate electricity. Of the 108 incinerators in the U.S., 40 modular and 30 mass-burn incinerators have energy-recovery systems.

Another incinerator-related technology separates the solid waste into noncombustible and combustible components. The noncombustibles are sent to a landfill. All of the combustible fraction called refuse-derived fuel can be burned in special boilers, or a mixture of 90 percent coal and 10 percent refuse-derived fuel can be burned in any utility boiler fitted with the appropriate equipment. The U.S. has 13 refuse-derived-fuel facilities in operation, which have the capacity to process 3.1 million metric tons of waste per year.

Incineration is not a viable alternative for every community, however. Incinerators require much initial capital and usually take from three to five years to construct. The community must have a need for the supply of energy produced by the incinerator and must weigh the impact of the incinerator on the environment.

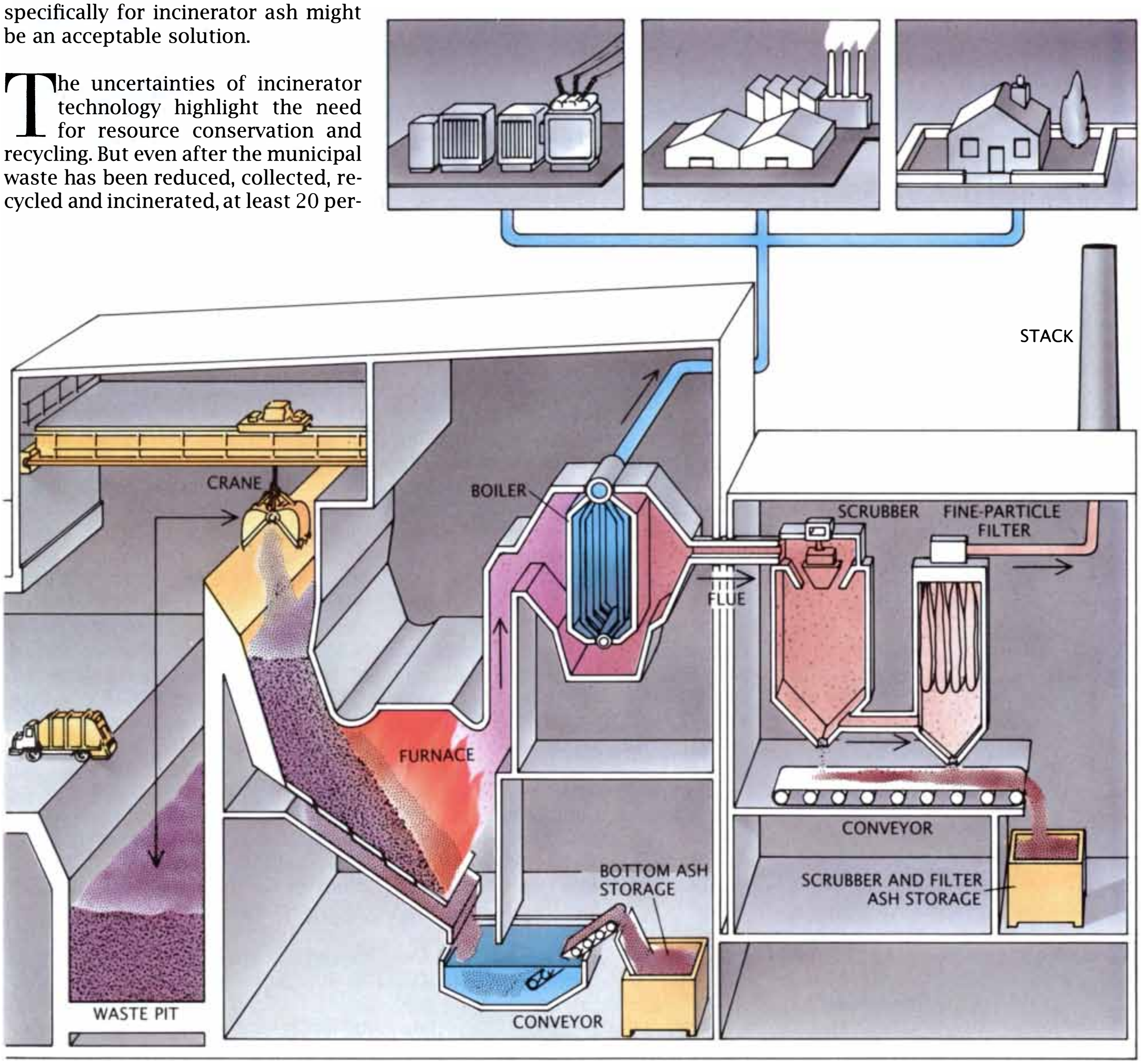
Air pollution persists as the major concern for incinerator technologies. Gases emerging from the stack of an incinerator contain particles and unburned, volatile compounds such as hydrochloric acid, nitrous oxides, dioxins and furans. Much equipment is available that can remove these compounds from stack gases. The effectiveness of pollution-control equipment and the impact of chemicals on the environment and on human health are still widely debated, and much research is still needed.

Land pollution is also an important concern, since the ash produced by incineration is usually disposed of in landfills. Some states demand that incinerator ash be tested for toxic substances. If the ash has high levels of toxins, the Resource Conservation and Recovery Act requires that the waste be handled as hazardous. Some incinerator ash contains hazardous levels of lead and cadmium, but ambiguities in Federal statutory language suggest that municipal solid waste may be exempt from hazardous-materials testing. If incinerator ash is disposed of as hazardous waste, incinerator technology would become expensive indeed. Requiring landfills designed specifically for incinerator ash might be an acceptable solution.

The uncertainties of incinerator technology highlight the need for resource conservation and recycling. But even after the municipal waste has been reduced, collected, recycled and incinerated, at least 20 percent remains to be disposed of in landfills. Landfills are therefore a necessary part of all integrated waste-management systems.

Landfill technology has progressed slowly. Before 1970 landfills were sited in the most convenient locations on the least expensive land. The hydrologic setting and potential environmental impact were not often considered. Typical disposal sites were wetlands, marshes, spent mines, quarries and gravel pits. No systematic operating procedures were implemented to protect the environment except to cover the solid waste with soil to reduce such nuisances as odors, rodents and litter.

Many waste managers failed to recognize that pollutants from the landfill, whether covered or not, can become mobile in the course of normal decomposition. When water from rain or from the waste itself permeates the landfill, the water is initially rendered acidic by biochemical processes. The acidic water percolates through the waste, dissolving elements and com-

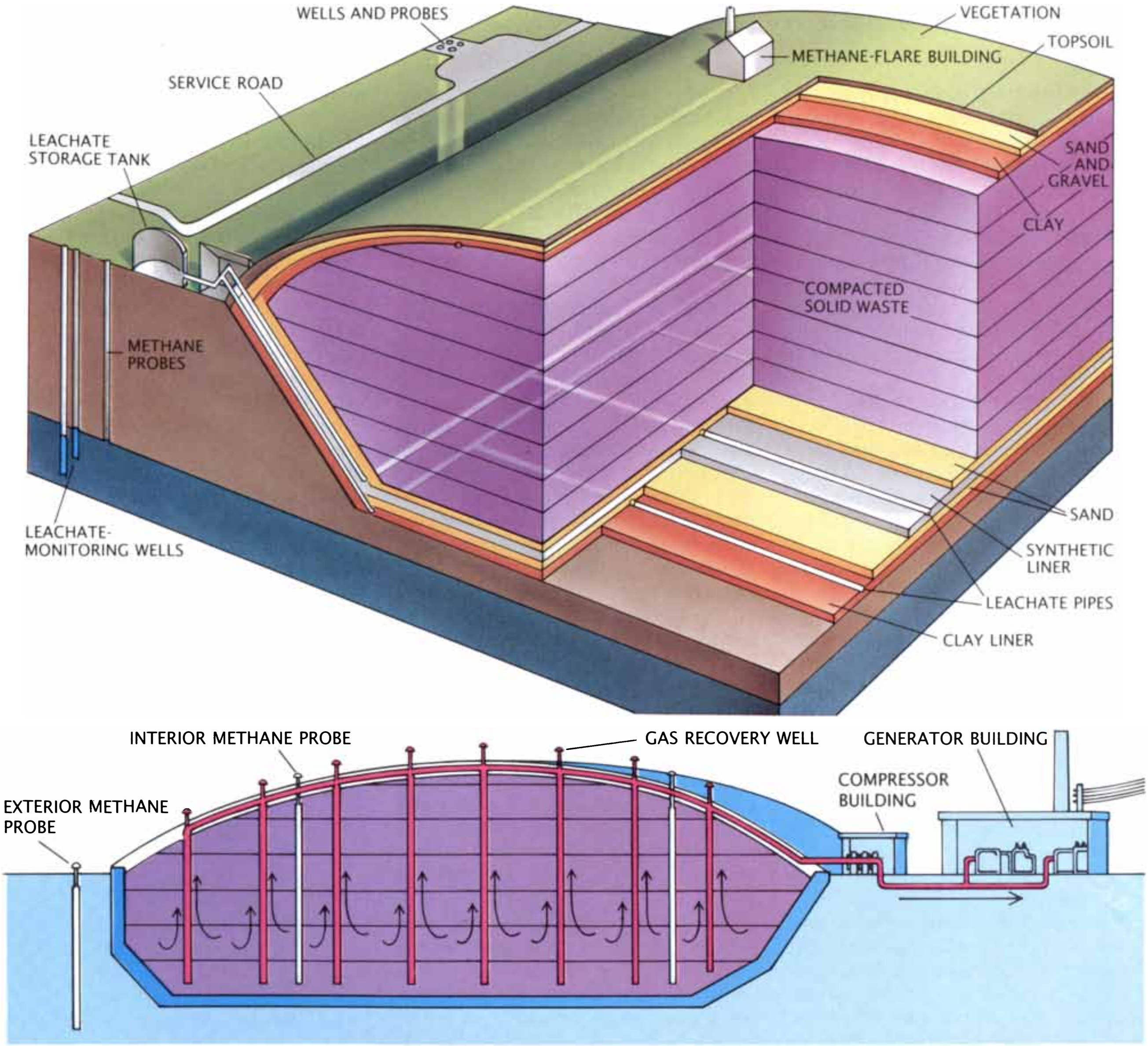


INCINERATORS with systems for pollution control and energy recovery are a viable option for waste management. The mass-burn incinerator diagrammed here reduces 1,000 tons of solid waste into 250 tons of incinerator ash in a single day. Collection trucks deposit solid waste in a pit. A crane transfers the waste to the furnace, where it is burned at a high temperature. The furnace heats a boiler that produces steam for generating electricity, heating buildings and other industrial processes. Ash collects at the bottom of the furnace and is removed by conveyors. Smoke flows through a flue at the top of the furnace and into two pollution-control devices. The scrubber sprays a wet or dry calcium compound into the smoke. The calcium compound reacts with heavy metals and toxic organic compounds and regulates them. The fine-particle filter removes tiny ash particles by passing them through either a porous bag or an electric field that attracts charged particles.

pounds from the waste to form a highly contaminated solution known as leachate. Later in the lifetime of the landfill, alkaline conditions develop that continue to produce leachate. If a landfill's capacity to hold water is exceeded, leachate escapes into the environment in unpredictable quantities, concentrations and directions. Surrounding surface waters, aquifers and entire ecosystems are often contaminated and damaged by leachate.

Although a few sites exist today that can naturally contain leachate, waste managers now engineer barriers that control its flow. After a site has been chosen and a basin has been excavated, the basin is lined with one or more layers of water-retaining material that in effect form a leachate bathtub. The contained leachate is pumped out through a network of pipes, stored in tanks and then directed to treatment facilities.

Two types of liner material are used in landfills: synthetic and clay. Synthetic liners are polymer sheets about 1.5 millimeters thick that physically retain leachate. Clay liners have a high hydraulic conductivity of 10^{-9} meter per second and allow from 5 to 20 percent of the leachate to leak, depending on the design of the landfill. Synthetic liners have a low hydraulic conductivity of 10^{-15} and transmit only minute amounts of leachate. In practice, however, the synthetic liner may have imperfect seams or pinholes, which can greatly increase the leakage of leachate. Compensating for the higher hydraulic conductivity of clay is its capacity for chemical atten-



NEW LANDFILL TECHNOLOGIES (*top*) can protect valuable resources from pollutants. Water from weather and other sources leaches pollutants out of the garbage, forming a solution known as leachate. To protect groundwater from leachate, layers of low-permeability clay and synthetic material line the landfill. The liners contain the leachate, which is pumped out through pipes. Every day layers of waste are dumped, compacted and covered with soil. When the landfill is full, it is covered with clay, sand, gravel, topsoil and vegetation to reduce leachate production and minimize erosion. Another landfill pollutant produced by bacteria decomposing waste is the volatile gas methane. Wells and probes are placed at the perimeter of the landfill to detect leakage of leachate or methane. Methane can be burned off by a flare. An alternative to burning methane is to install a recovery system (*bottom*). The system collects the methane and fuels a turbine to generate electricity.

TOWNHOUSE EXPLODED across the street from a closed landfill in Madison, Wis., on November 19, 1983. Methane produced by the decomposition of solid waste seeped underground into the house and was ignited. Two tenants were burned in the explosion. Since the accident a methane-control system has been installed.

uation. Leachate slowly percolating through a clay liner will undergo chemical reactions that reduce contaminant concentrations. Where clay is abundant and relatively inexpensive, clay liners may be preferred, but synthetic liners may be better in areas where clay liners might leak leachate slowly and continuously into sensitive and potable groundwaters. Clay, synthetic liners or combinations of both are currently required for landfills in many states.

During the operation of the landfill the groundwater must be monitored for leachate leaks, and a method must be found for disposing of leachate. The vast majority of landfill leachate is sent directly to a sewage-treatment plant, but not all plants are capable of handling the highly contaminated water. Many plants depend on bacteria to decompose sewage, and normal operating conditions can be upset by highly concentrated leachate. The plant may also not be able to remove many of the leachate toxins, which may be discharged untreated or accumulate in the plant's sewage sludge. Landfills with leachate-disposal problems may need to apply a combination of biological and chemical processes for on-site leachate treatment before the leachate is shipped to a sewage-treatment plant.

Reducing the volume of water that permeates the landfill is another way to control the leachate problem. Some landfills constructed recently have a multilayered cover of soil or synthetic material that diverts precipitation away from the waste. The cover is sloped to allow the precipitation to drain off the landfill without causing soil erosion. Vegetation grown on top of the landfill helps to minimize erosion and promotes evapotranspiration that reduces water percolating through the landfill.

In addition to the hazards of leachate, landfills produce a colorless and explosive gas called methane that is released as bacteria decompose waste. More specifically, the bacteria generate a gas mixture that is from 50 to 60 percent methane and from 40 to 50 percent carbon dioxide, with traces of other gases.

If methane production is not controlled at a landfill, methane may migrate underground away from the landfill. The methane may reduce oxygen in the soil and thus kill vegetation. Methane may also seep underground into nearby buildings, where at concentrations of from 5 to 15 percent in air it can explode on ignition. Of 29 damage cases that have been associated with the production of methane in landfills, 23 showed that explosive concentrations of methane can exist at distances of up to 1,000 feet from the site in permeable soil. Explosions and fires occurred in 20 of these cases, resulting in five deaths.

Methane can be controlled by monitoring the soil around the landfill, collecting the landfill gases and finally burning away the methane. Methane combustion yields 2,300 joules per gram, and gas-recovery systems have been developed to utilize that energy. Wells are dug into landfills or adjacent soil formations and pipes are laid to collect the landfill gas. The gas can be burned directly in an industrial boiler or can fuel an internal-combustion engine or gas turbine that generates electricity. These systems can generate megawatts of electricity. Several large recovery systems filter out the trace contaminants and carbon dioxide and inject the methane into natural-gas utility pipelines. Some large landfill gas systems recover enough methane to meet the energy needs of 10,000 homes.

The technology to control leachate and gaseous emissions from landfills has not been implemented in most sites currently under operation. Of the 6,000 municipal solid-waste landfills, 15 percent are lined, 5 percent collect leachate and 25 percent monitor groundwater. Methane-collection projects are in place at approximately 100 landfills for the primary purpose of resource recovery and energy production.

As this article was being prepared for publication, however, the EPA proposed minimum national standards that restrict landfills in wetlands and specify landfill-design standards for seismic zones. If the rules are enacted, site operators will be required to cover the landfill every day a site is open, to install groundwater monitoring systems and to inspect municipal solid waste for hazardous wastes. Liners and leachate-collection systems are not mandated but will probably be necessary in many cases to satisfy health standards. The regulations will also require that a landfill site be maintained by the owner for 30 years after the site is closed and be monitored indefinitely.

Waste-management should improve with the development of more reliable and analytical methods for assessing health and environmental risks. As individuals, active promotion and participation in resource-conservation and recycling programs are necessary first steps. As a community, waste-disposal practices that are environmentally safe must be encouraged, and an integrated approach that addresses all aspects of managing municipal solid waste must be adopted. As a nation, the cost, risk and impact of municipal solid wastes will continue to increase until Americans begin to take personal and public responsibility for limiting waste production or until we can no longer afford to support our throwaway society.

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PRESERVE AIRCRAFT SAFETY WITH HOMEGROWN NITROGEN.

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The Geometric Phase

A circuit tracing a closed curve in an abstract space can explain both a curious shift in the wave function of a particle and an apparent rotation of a pendulum's plane of oscillation

by Michael Berry

Take a pencil, lay it on the north pole of a globe and point it in the direction of any of the meridians: the lines of longitude that radiate from the pole. Move the pencil down along the line to the equator and, keeping it perpendicular to the equator, slide it to another line of longitude. Move the pencil back to the north pole along the new meridian, and you will find that although the pencil has been returned to its starting point and at no time was rotated, it no longer points along the original line of longitude.

This simple exercise illustrates how the "parallel transport" of a vector (a quantity that has both length and direction) around a circuit on a curved surface results in an anholonomy: the failure of certain variables describing the system to return to their original values. The anholonomy in the example results from the fact that the pencil was forced to trace out a circuit on the surface of a sphere while remaining parallel to the meridians at all times. It is a purely geometric phenomenon; it does not depend on the energy or mass of the pencil. Moreover, it does not depend on the pencil's initial direction. The extent of the anholonomy depends solely on the area and curvature of the surface enclosed by the circuit.

In 1983 I found that a similar geometric effect exists in the quantum waves that describe matter and its interactions on the smallest scales. In this case the anholonomy appears in a system's wave function (the mathematical description of a system's physical state) after the system has been transported around a cyclic circuit on an abstract surface in "parameter space." I call this anholonomy the geometric phase, because it manifests itself specifically as a shift in the wave function's phase: a quantity that describes where the wave function is in its oscillatory cycle at any given time and place.

It so happens that the geometric phase provides an elegant explanation of various quantum-mechanical phenomena in systems whose environment undergoes a cyclic change: neutrons that pass through a helical magnetic field, polarized light in a coiled optic fiber and charged particles circling an isolated magnetic field. Perhaps more surprising is the fact that the geometric phase can also be generalized to applications in classical physics. Among other things, it offers a new way to describe the behavior of such textbook objects as pendulums.

I discovered the general applicability of the geometric phase in quantum mechanics while studying stationary quantum states, which can be adopted by microscopic systems in unchanging environments. An isolated hydrogen atom provides an example of a stationary quantum state, since the atom's single electron moves in the unchanging electric field of its nucleus. In such a state (which is labeled by a particular set of quantum numbers) measurements of the atom will yield the same result at any time, except for inconsequential shifts in the phase of the wave function describing the system.

Such phase shifts are the result of the dynamical phase inherent in any wave—quantum or classical. Dynamical phase is best understood by considering a familiar example: the traveling wave produced when one jiggles a long extended rope that is held fixed at one end. A series of photographs of the wave would show that those points along the rope that were at the wave's crests in one picture would not be at the crests in another (unless the pictures happened to be synchronized with the wave). In other words, the phase of the wave changes from picture to picture. The rate at which a wave's phase changes in this way is equal to the wave's instantaneous frequency, which for a stationary quantum state is proportional to the state's energy. Because the dynamical phase does not in any way affect the energy or the spatial extent of a quantum system's wave function, it does not influence the system when it is in a stationary state.

The study of stationary states constitutes quantum statics. Statics, however, accounts for only part of both quantum and classical physics. The other part is dynamics, which deals with changing forces and transitions between different stationary states. The area that particularly interested me lies at the border between statics and dynamics; I was studying the effects on a system of very slow changes in its environment. These slow environmental changes, called adiabatic changes, are the subject of a major theorem that was originally conceived outside a formal quantum-mechanical framework by Albert Einstein and Paul Ehrenfest in 1911 and rigorously proved within the framework by Max Born and Vladimir A. Fok in 1927.

According to the quantum adiabatic theorem, a system initially in a stationary state that is labeled by a certain set of quantum numbers will remain in a stationary state that is labeled by the same set of quantum numbers even though its environment may be slowly changing. The power of the theorem lies in the fact that the initial and final environments—and hence the actual form of the corresponding stationary states—can be rather different: the adiabatic condition stipulates only that the environmental change is slow, not that it is

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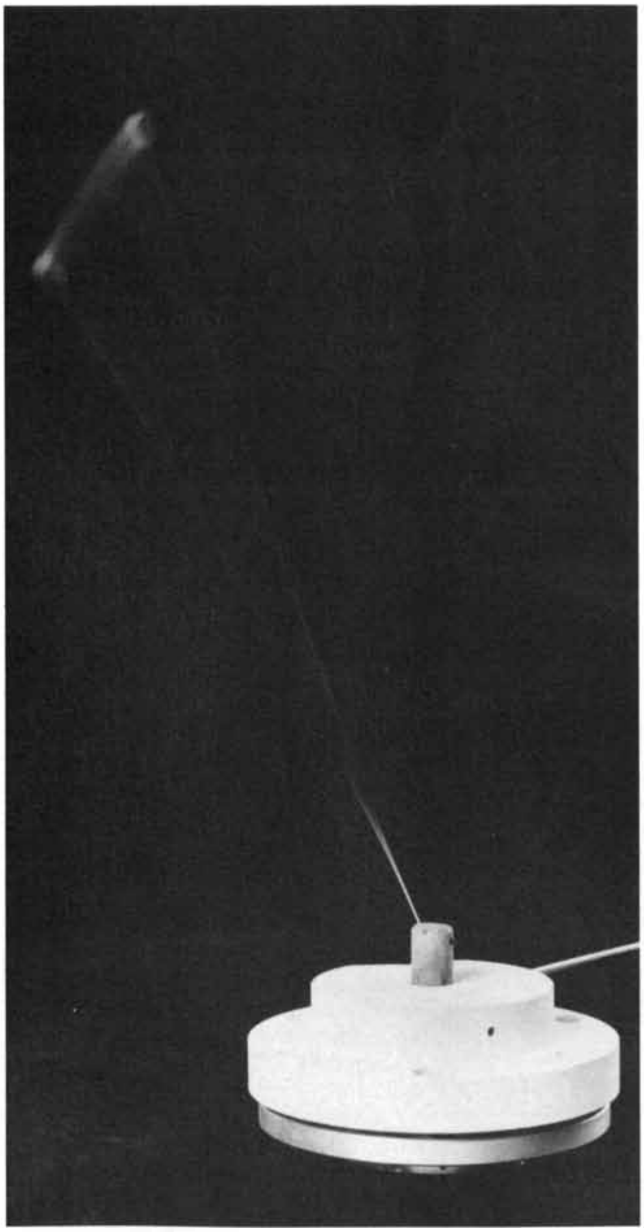
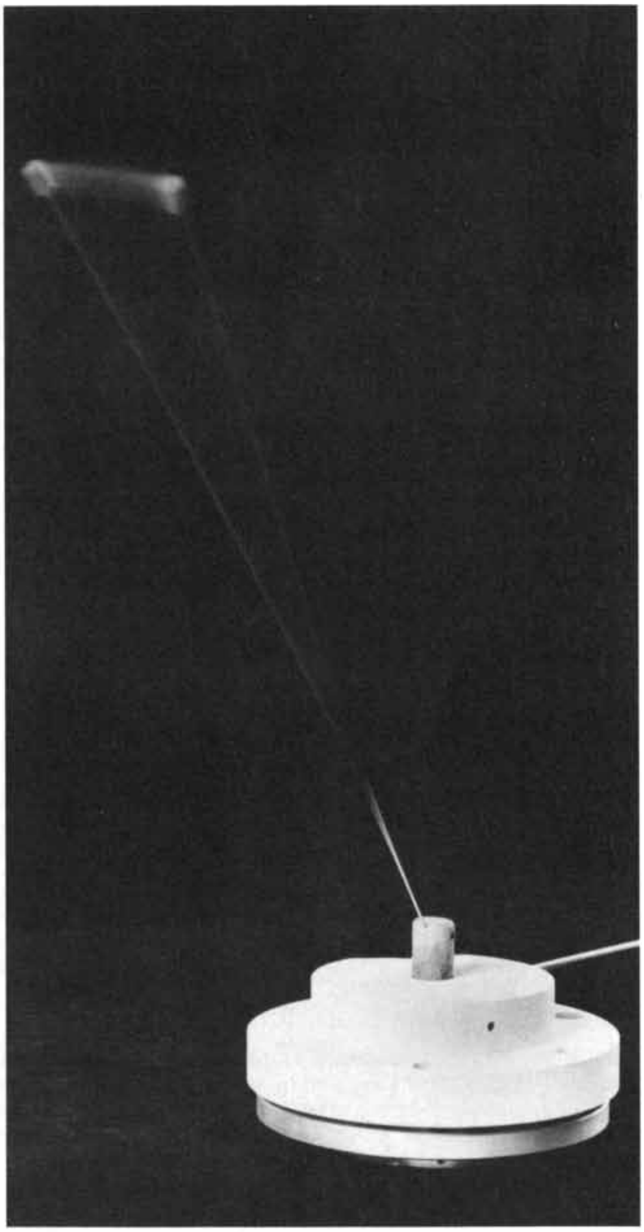
small. (If the change is not slow, the theorem does not apply and the system will make transitions to states labeled by other quantum numbers.)

Perhaps the most useful application of the adiabatic theorem is in approximating the quantum states of a molecule, which is a collection of constantly moving electrons and nuclei. An exact solution of the equation that determines the quantum mechanics of even the simplest molecule (the hydrogen molecule in a charged form that has two protons and one electron) has eluded physicists. Yet because nuclei are several thousand times more massive than electrons, they can be considered to move much more slowly than the electrons. Since the nuclei constitute the electrons' "environment," the electron states can be said to evolve adiabatically as the nuclei move. The continuous motion of the nuclei can therefore be broken down into a sequence of "frozen" configurations, each of which has quantum states given by the electrons' corresponding stationary states.

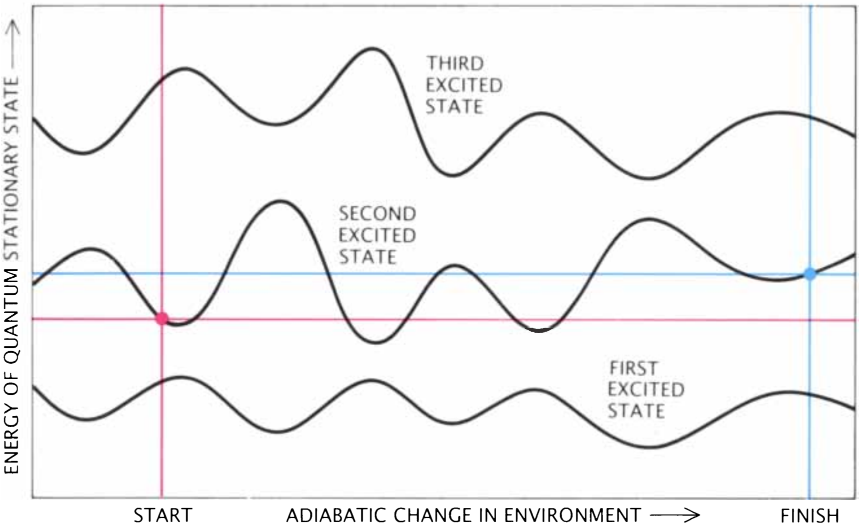
Since a quantum system in a slowly changing environment remains in a stationary state, it may seem as though an adiabatic change is really no change at all. That, at any rate, was the prevalent opinion among physicists for many years, and because of it a curious and subtle effect of an adiabatic change on the phase of a wave function was overlooked.

Consider the phase of the wave function of a quantum system that has undergone a cyclic adiabatic change—one that leaves the environment in the same condition as before the change. Although the initial and final states of the system will be the same, the phases of the initial and final wave functions will be dif-





ANHOLONOMY—the phenomenon underlying the geometric phase—is shown by a device that Moshe Kugler and Shmuel Shtrikman of the Weizmann Institute of Science in Israel have built. An anholonomy is a geometric effect in which variables describing a system do not return to their original values after the system completes a revolution. In the device a wire in a base is set vibrating in a plane (*left*) and the base is turned. After a revolution (*right*) the wire no longer vibrates in the plane.



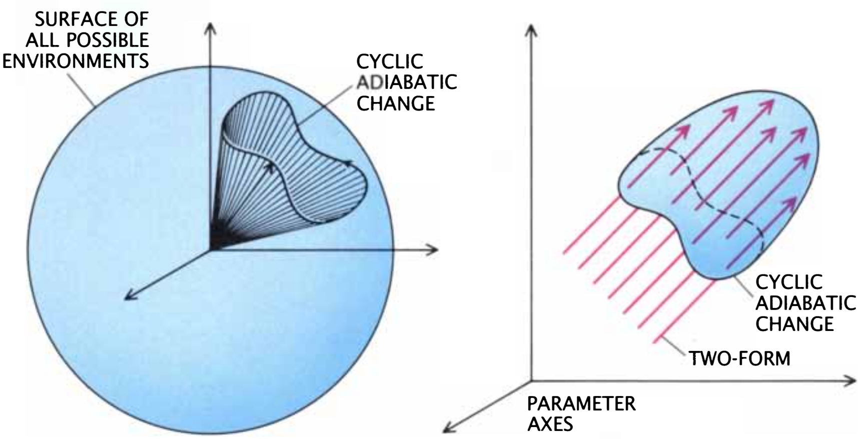
ADIABATIC CHANGES are changes in a system's environment that occur slowly enough for the system to stay continuously in equilibrium with its environment. A system normally adopts a so-called stationary state (which is labeled by a set of quantum numbers) when its environment is static. Yet according to the quantum adiabatic theorem, a system in a stationary state can remain in a stationary state labeled by the same set of quantum numbers even if the environment changes—provided the changes are adiabatic. The theorem applies even if the system's final environment and energy are very different from its initial environment and energy.

ferent owing to the time-dependent dynamical phase of the wave function. This phase difference would exist even if the environment did not change; it simply reflects the time it took the system to complete the cycle.

This much was well known. I was able to show that any cyclic adiabatic change can shift the phase of the wave function in another, rather surprising way and derived a formula for the new phase shift from quantum physics. The formula is best understood by visualizing the slow changes in the environment as a closed circuit in an abstract frame of reference whose axes are parameters: physical variables that describe the system's environment. An analogy to the pencil-and-globe exercise becomes apparent: the phase shift can be seen as the result of an anholonomy that arises whenever the system is made to complete a circuit on a curved surface in the parameter space.

Indeed, as Barry M. Simon of the California Institute of Technology recognized, the mathematics for the parallel transport of a vector around a circuit on a curved surface yields (when properly generalized) the same answer as the formula for the phase component that I obtained from quantum physics. As in the pencil-and-globe example, the phase shift can be calculated from the area and curvature of the surface enclosed by the circuit.

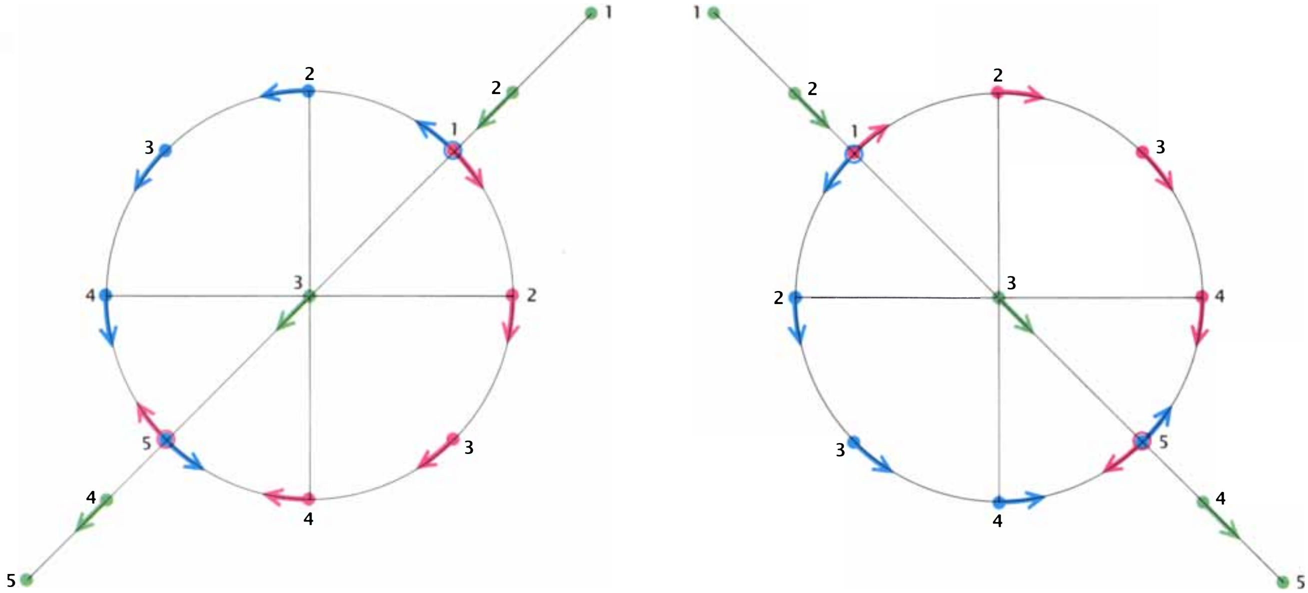
Because such a phase shift depends only on the geometry of the circuit in parameter space, I call it the geometric phase. It is independent of the time it takes the system to complete the circuit (provided that the process occurs slowly enough to constitute an adiabatic change), but it is sensitive to the shape of the circuit and the system's initial quantum state. The geometric phase can therefore be regarded as the best answer the system can offer to the question "What path in parameter space did the system take?" In this sense it is a kind of quantum "memory": it contains information about the past environments of the system.



GEOMETRIC PHASE of a quantum system whose environment has undergone a cyclic adiabatic change can be derived by plotting all possible environments of the system in a frame of reference whose axes are parameters: the physical variables that describe the environment. A cyclic adiabatic change is then represented as a closed curve in the "parameter space." In the simplest case the geometric phase is given in terms of the area of any surface the curve encloses. If the surface is spherical (*left*), the area is equivalent to the solid angle subtended by the curve. The geometric phase can be more readily generalized to parameter spaces with more than three dimensions if it is expressed in terms of a mathematical quantity called a two-form (*right*). A two-form can be thought of as representing the flux, or flow, of a quantity through space. The geometric phase can then be calculated by integrating, or summing, the two-form over any surface that "catches" all the two-form flux through the circuit.

Since I established the theoretical applicability of geometric phase in any cyclic adiabatic change, it has been calculated for a variety of systems cycling through a variety of parameter-space circuits. The phenomenon has also been measured experimentally in quantum spins that have been "turned" slowly. The quantum spin of a particle can be pictured roughly as the spin of a tiny top about an axis. The stationary spin states of the particle are characterized by a quantum number that gives the value of its angular momentum (which is a vector quantity) as measured along a direction determined by the particular symmetry of its environment. Such a symmetry direction is given, for example, by the direction of a magnetic field for particles that are susceptible to magnetic forces. If the symmetry direction is slowly changed, the adiabatic theorem ensures that the spin of the particle turns with the symmetry direction, preserving the particle's angular-momentum component along the symmetry direction and therefore its spin quantum number.

A symmetry direction can be repre-



SUPERPOSITION of two oppositely directed circular motions can result in linear motion. Summing the coordinates of the red and the blue points, which are tracing concentric circles of equal radius, yields the coordinates of a third point (*green*) that slides back and forth along a line. The direction of the line depends on the relative phases of the two circling points. If the two points start their motions in the upper right-hand quadrant of the coordinate system (*left*), the line will be tilted at an angle of 45 degrees. If they start in the upper left-hand quadrant (*right*), however, the angle will be 135 degrees. A similar principle explains how two superposed states of circularly polarized light rotating in opposite senses can result in linearly polarized light. As with the moving points, the relative phases of the states determine the light's direction of polarization.

sented by a vector of unit length and fixed origin. Since a symmetry direction is an arbitrary direction, the tips of all possible symmetry-direction vectors lie on a sphere of unit radius whose center is the origin of the vectors. The surface of this unit sphere represents the parameter space for turned spins, since the symmetry direction determines the environment in which a particle's spin is measured. Any sequence of changes in the symmetry direction can therefore be charted as a curve on the surface of the sphere. A closed curve, of course, would mean that the changes are cyclic. Employing quantum theory, I showed that in tracing such a curve the particle acquires a geometric phase given by the product of its spin-state quantum number and the solid angle enclosed by the curve on the parameter-space sphere.

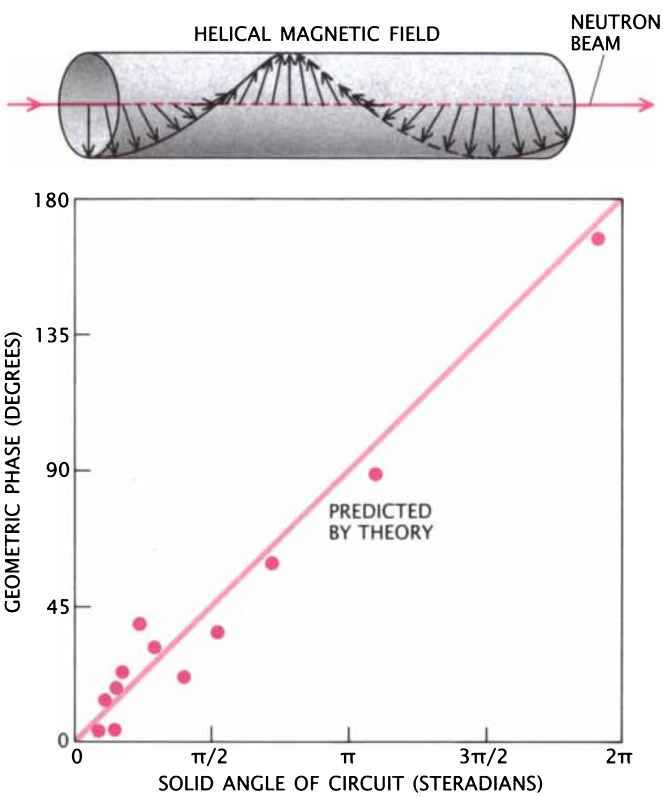
How can one measure the geometric phase of turned microscopic particles? In spite of its fundamental nature, the phase of a quantum wave cannot be detected directly; it becomes measurable only when two or more quantum waves are brought together to produce so-called interference patterns. When two waves are summed, the amplitude of the resulting wave is the sum of the amplitudes of the component waves wherever a crest of one wave coincides with a crest of the other and a trough coincides with a trough. But wherever crests coincide with troughs, the amplitude of the resulting wave is the difference between the amplitudes of the two component waves. Hence the pattern of amplitudes of the resulting wave—the interference pattern—reveals the relative phases of the component waves. (The phase difference of two waves is the fraction of a cycle through which one wave must evolve for its crests and troughs to coincide with those of the other. Fractions of a cycle are generally expressed in angular units, such as degrees or radians, where one complete cycle equals 360 degrees, or 2π radians.)

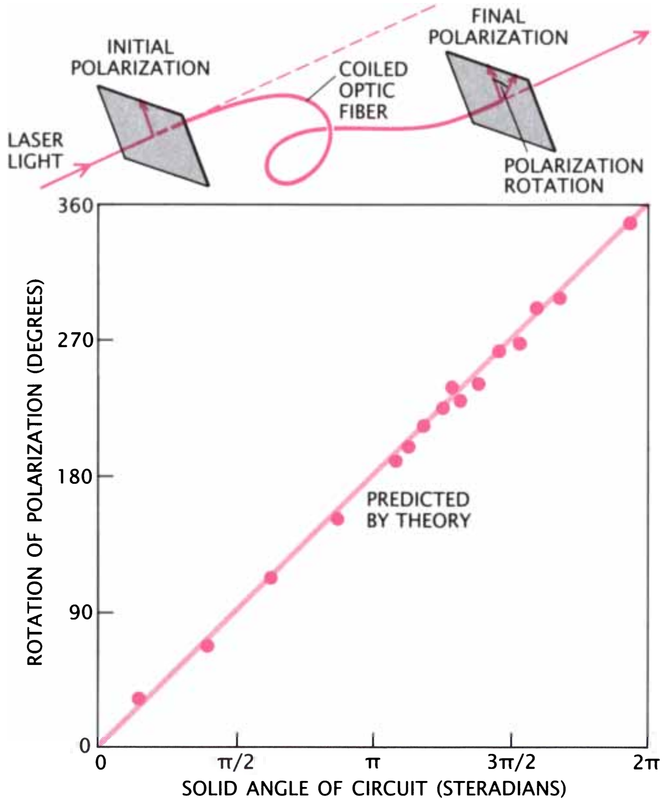
Clearly in order to measure the geometric phase of a turned particle's wave function the particle must first be "added" to a second particle to produce measurable interference patterns. In principle it is possible to do so by splitting a beam of particles that are all in the same spin state, turning the spins of one of the split beams and then recombining the beams. This can sometimes be done in practice, but the experiments have often been difficult to carry out.

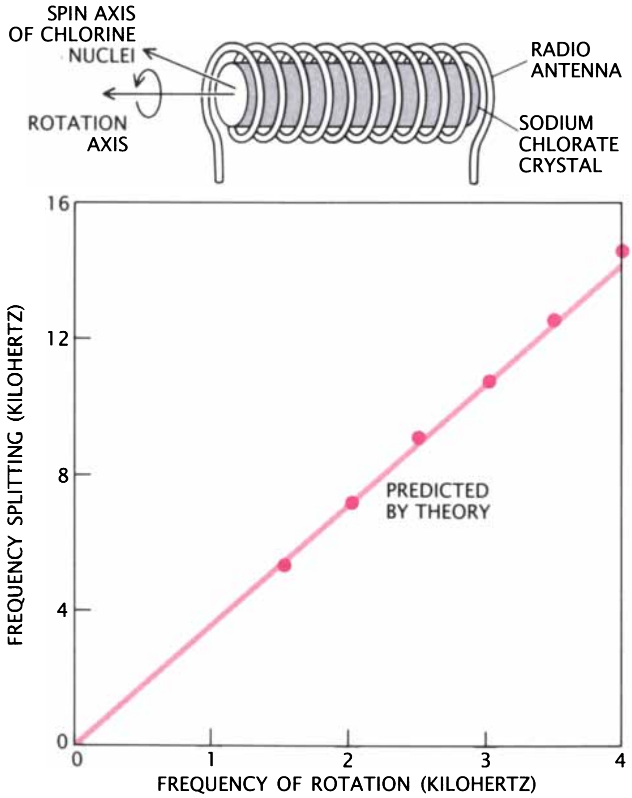
More commonly the initial beam consists of particles in a superposition of different stationary spin states, each labeled by a different spin-state quantum number. The superposed states combine with one another in a way that depends on the relative phases of their respective wave functions. Because the geometric phase of the wave functions depends on their respective spin-state quantum numbers, the phases of the constituent wave functions are shifted differently as a particle's spin is being turned, changing the way the states combine to form the superposed state. Such changes in the form of the superposed state are generally easier to detect than changes in the interference pattern created by combining turned and unturned single-state particle beams.

The solid-angle formula for the geometric phase of turned spins has been confirmed for several different types of particles. T. Bitter of the University of Heidelberg and D. Dubbers of the Laue-Langevin Institute in Grenoble worked with neutrons, whose spin and magnetic-moment directions coincide. The neutron's magnetic moment makes it possible to turn its spin by altering the direction of a magnetic field, since the field lines provide the symmetry direction. In their experiment Bitter and Dubbers changed the symmetry direction cyclically by passing a beam of neutrons through a helical magnetic field produced by a twisted current-carrying coil. The solid angle subtended by the closed curve in the corresponding parameter space could readily be varied by altering the strength of another magnetic field along the beam's axis.

Although a photon also has spin, it does not have a magnetic moment with which its spin can be turned. Raymond Y. Chiao of the University of California at Berkeley, Yong-shi Wu of the University of Utah and Akira Tomita of the AT&T Bell Laboratories nonetheless devised and carried out an experiment in which the spin of photons was turned. They relied on the fact that a photon's spin vector points either along the direction in which it is traveling or in the opposite direction. Hence a photon's spin can be turned merely by changing its direction of travel. By confining a beam of laser light in a coiled optical fiber, Chiao and his colleagues were able to turn the photons' spin; by ensuring that the







THREE EXPERIMENTS in which the spin state of particles is cyclically "turned" confirm the reality of the quantum geometric phase. T. Bitter of the University of Heidelberg and D. Dubbers of the Laue-Langevin Institute in Grenoble took advantage of the fact that a neutron's spin axis coincides with its magnetic moment to turn a beam of neutrons by passing it through a helical magnetic field whose pitch could be varied (*top left*). The geometric phase was measured as a shift in the spin axis of the neutrons. Raymond Y. Chiao of the University of California at Berkeley, Yong-shi Wu of the University of Utah and Akira Tomita of the AT&T Bell Laboratories turned two superposed spin states of photons by shining linearly polarized light through a coiled optic fiber (*top right*). The observed rotation of the light's direction of polarization equals the predicted geometric phase. In an experiment carried out by Robert Tycko of Bell Laboratories the spins of excited chlorine nuclei were turned simply by rotating a crystal of sodium chlorate on an axis that was different from the spin axis of the nuclei (*bottom left*). The nuclei accumulated a geometric phase that was detectable as a frequency shift in the radio signals they emitted.

two ends of the fiber were parallel, the investigators made the process cyclic.

They also took advantage of the fact that linearly polarized light (light whose associated electric field vibrates in a single direction) consists of photons in which the two possible spin states are superposed. The direction of the polarization is given by the relative phases of the two spin states [*see illustration on page 49*]. As a consequence, any change in the relative phases that arises as the two different spin states acquire different geometric phases can be directly observed as a rotation of the light's direction of polarization. (Such a rotation was first observed in 1984 by J. Neil Ross of the Central Electricity Generating Board Laboratory in Leatherhead, England, but he did not attribute it to the geometric phase.)

The rotation that Chiao and his colleagues observed can be explained equally well in classical terms. It can be understood as the result of a parallel transport of the light's electric-field vector along the coiling fiber. For light in a coiled fiber, then, the quantum anholonomy of phase is equivalent to the classical anholonomy of parallel transport of polarization, or, as Chiao and Wu express it: "We would rather think of these effects as topological features... that originate at the quantum level but survive... into the classical level." As several other investigators have pointed out, the solid-angle result in this case can also be derived without resorting to quantum mechanics, from Maxwell's equations of classical electromagnetism.

The work of Robert Tycko of Bell Laboratories provides a final example of turned spins. Tycko excited chlorine nuclei contained in a crystal of sodium chlorate into a superposition of states by exposing them to a pulse of radio waves. Since the spins of the nuclei are aligned with the crystal's axis of symmetry, he was able to turn the spins of the excited nuclei by rotating the crystal about an axis different from its symmetry axis. Consequently the phase difference between the nuclei's component spin states increased according to the solid-angle formula. The effect of repeated rotations was to increase the phase difference continually, which Tycko detected as a splitting in the frequency of a radio-signal response emitted later by the nuclei.

In all the turned-spin experiments I have mentioned, it has been assumed that the environmental parameters governing a system can be determined (at least in principle) to arbitrarily high precision and that the environment remains unaffected by any phase changes it induces in the system. Actually neither supposition is justified. The first one is invalid because the parameters, being physical variables, are themselves subject to the laws of quantum mechanics, which stipulate an inherent uncertainty in their measurement. The second supposition is also invalid because in physics there is no such thing as a unilateral action. For these reasons, what I have referred to until now as the "quantum system" should strictly speaking include the environment: the laboratory apparatus in which the turned-spin experiments were done. Yet because a full quantum-mechanical description of the environment is indescribably complicated, it is usually neglected.

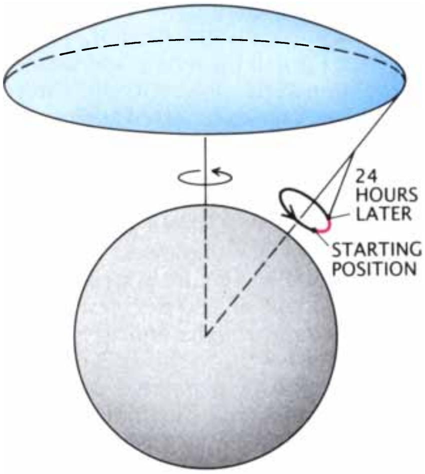
Nevertheless, one can predict a curious effect a quantum system's geometric phase will have on the wave function of its environment. It so happens that the wave function of any state of the "total" system (the product of the wave functions of both the quantum system and its environment) must be a single-valued function: it must have only one unique value—including phase—for any given set of parameters. This is mathematically possible only if, during any circuit of the quantum system in parameter space, the wave function of the environment acquires a compensating phase shift equal to that of the system but of opposite sign.

It might be thought this equal but opposite phase shift is a mathematical artifact arising from the separation of the quantum system and the environment, but in fact it can give rise to observable physical effects. Such effects occur, for example, in molecules in which the electrons constitute the quantum system and the nuclei constitute the environment. In 1979 C. Alden Mead and Donald G. Truhlar of the University of Minnesota (who laid the groundwork for much of the subsequent work on the geometric phase) pointed out that changes in the wave function for the electrons (the system) should affect the wave functions describing the motion of the nuclei (the environment), thereby altering the energies corresponding to vibrations and rotations of the molecule. Such changes are reflected in the energy of the photons emitted or absorbed by a molecule and can be detected by spectroscopy.

An experiment carried out by Guy Delacrétaz and Ludger Wöste of the Swiss Federal Institute of Technology, Edward R. Grant and Josef W. Zwanziger of Cornell University and Robert L. Whetten of the University of California at Los Angeles detected such spectroscopic changes in a molecule composed of three sodium atoms. The sodium nuclei in the molecule undergo a cyclic motion (called pseudorotation) that causes the lowest electron-energy state to acquire a striking geometric phase of 180 degrees: crests have become troughs and vice versa in its wave function. The workers discovered that the geometric phase of the electrons' wave function in turn affects the nuclei's wave function, changing the observed pseudorotation energy levels of the nuclei. The changes were consistent with the predictions of an extended quantum-mechanical analysis of geometric phase.

The geometric phase of a system undergoing a cyclic adiabatic change can be stated most elegantly when it is expressed in terms of a mathematical quantity called a two-form, which represents the flux, or flow, of a quantity through a unit area. The geometric phase is then calculated merely by integrating, or summing, the two-form over any surface spanning the system's circuit in parameter space—any surface that "catches" all the two-form flowing through the circuit. Such a powerful mathematical formulation conjures up the image of the two-form lurking in parameter space, ghostly and hidden until actualized by a quantum system completing a cycle in parameter space. An effect predicted in 1959 by Yakir Aharonov of the University of South Carolina and David Bohm of the University of London (both of whom were then working at the University of Bristol) can be explained precisely in terms of such a geometric-phase two-form.

The Aharonov-Bohm effect is a shift in the phase of a charged particle's wave function produced by transporting the particle around isolated magnetic field lines. The effect was confirmed experimentally in 1960 by Robert G. Chambers of Bristol. In this case the parameter space through which the particle moves is not defined by abstract variables such as symmetry directions; it is the ordinary space through which the particle makes its circuit, described in terms of familiar coordinates (measuring length, width and height). Similarly, the phase two-form is not just a convenient mathematical construct; it is the magnetic field multiplied by the charge of the particle and divided by Planck's con-



ANGULAR SHIFT in the position of the bob of an earth-based pendulum is an example of the geometric phase in classical physics, as described by John H. Hannay of the University of Bristol. One might think that a pendulum bob moving in a circle at one revolution per second would, after 24 hours, return to exactly the same position in space from which it was set in motion. But in fact the bob's position will be shifted in relation to its initial position by an angle (*red*), known as Hannay's angle, equal to the solid angle subtended by the pendulum's axis of revolution (*blue*). Such a pendulum was employed by the French physicist Jean B. L. Foucault in 1851 to demonstrate convincingly the rotation of the earth. Foucault's pendulum, however, swung to and fro rather than in a circle, and the geometric phase manifested itself as a rotation of the bob's plane of oscillation.

stant (6.626×10^{-34} joule-second). Expressed in this way, the phase of the particle passing around the magnetic field depends on the magnetic field flux—a quantity that fits squarely in classical physics.

What does not fit squarely in classical physics, however, is the fact that the charged particle's phase is affected by the magnetic field, in spite of the fact that the particle never crosses a field line. In classical physics charged particles experience forces only when they come in contact with electric or magnetic fields. Yet a charged particle in an Aharonov-Bohm experiment is affected by a magnetic field even though it is kept separate from the field! Physicists say that the field appears to influence the charged particle nonlocally. Unlike the rotation of the plane of polarization in the experiment of Chiao and his colleagues, the Aharonov-Bohm effect cannot be explained in terms of classical physics.

A geometric-phase two-form lends itself to describing quantum-mechanical phenomena that are foreign to our everyday experience, but it can also be generalized to describe even the familiar mechanics of springs and pendulums. John H. Hannay of Bristol has worked out the classical analogue of the quantum-mechanical geometric phase. He began by considering macroscopic systems of oscillating bodies whose configuration at any time is given by one or more angle variables. The environment of the oscillations is made to change slowly, but the process begins and ends at the same set of parameters. After the cycle the oscillations have the same amplitude as they had originally, but the angles have changed.

Hannay realized that the angular shifts can be divided into dynamical and geometric parts, just as the phase shift of a quantum-mechanical system can be. The dynamical part is what would be calculated on the assumption that the angle increases at a rate corresponding to the instantaneous frequency of oscillation. His achievement was to identify the geometric contribution, now called Hannay's angle, and to derive a formula by which it can be calculated as the flux of a two-form through a closed circuit in parameter space. (The analogy with quantum mechanics is not complete, however, because classical motions are often not oscillatory but chaotic. For such systems no angle variables can be defined, and there are no Hannay angles.)

In one of Hannay's examples a bead is imagined as sliding at a constant speed and without friction on a noncircular loop of wire as the loop is slowly rotated once in its own plane. In this case the angle variable is the bead's distance around the loop as measured from a given point on the loop. Hannay's angle gives the position of the bead after the loop's rotation in relation to where the bead would be if the loop had been held stationary. The angle is a purely geometric combination of the perimeter of the loop and the area it encloses; it is large for a long thin loop and vanishes for a circular one.

Another of Hannay's examples gives the classical analogue of the quantum geometric phase for slowly turned spins. Consider a pendulum bob moving in a circle. In this case gravity determines the symmetry direction, namely a vertical line passing through the center of the earth. As the earth rotates, the symmetry direction turns in space (unless the experiment is done at one of the poles), so that after one day the position of the pendulum bob in its circular orbit will be shifted by an angle—Hannay's angle—equal to the solid angle subtended by the symmetry direction.

Such a shift in the position of the pendulum bob is more conspicuous if the bob moves to and fro rather than in a circle. The bob's to-and-fro motion can then be regarded as a superposition of two circular motions in opposite directions (just as linearly polarized light can be regarded as the superposition of two circularly polarized states of light). After a day of swinging, the pendulum's two circular motions will have acquired opposite angle shifts, which manifest themselves as a rotation of the plane in which the bob swings.

What I have just described is the pendulum with which the French physicist Jean B. L. Foucault demonstrated, in 1851, the rotation of the earth. The well-known phenomenon of the rotation of a pendulum's plane of oscillation, which is a popular exhibit in many science museums throughout the world, is thus a special case of Hannay's angle, which in turn is the classical analogue of the quantum geometric phase. It too can be explained as the result of parallel transport, in this case of the pendulum's swing plane by the earth's rotation.

By returning to the parallel transport with which this article began, one can say I have completed a cycle. Yet like the phase of a system undergoing an adiabatic cycle, the end is different from the beginning. The parallel transport that initially illustrated an abstract concept now appears in tangible systems whose behavior is governed by the laws of physics for slow environmental changes. Geometric anholonomy has turned into dynamical anholonomy.

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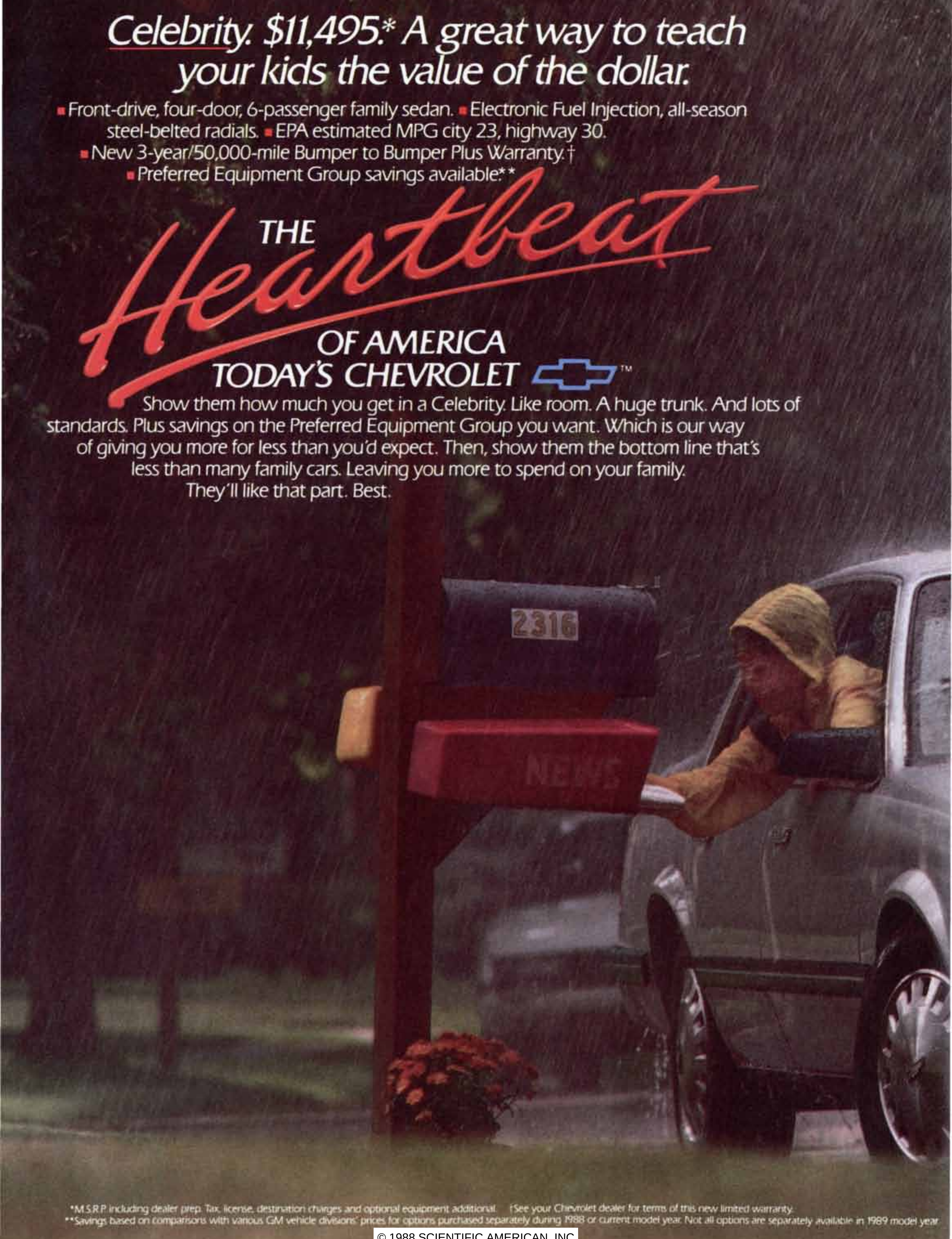
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Plasticity in Brain Development

The final wiring of the brain occurs after birth and is governed by early experience. A protein called MAP2 seems to take part in the molecular events that underlie the brain's ability to change

by Chiye Aoki and Philip Siekevitz

Anyone who has watched an infant reach for a toy will realize that adult capacities of perception and movement are not inborn but instead must develop over the course of time through the exercise of those faculties. The genetic program played out during gestation provides a newborn with intact sensory organs and a well-formed brain, whose 100 billion neurons, or nerve cells, are already linked in pathways that are specialized to perform specific functions. But before the developing brain can attain the full power to process and analyze sensory experience, experience itself must place its own imprint on the finer structure of the brain.

Even though the basic organization of the brain does not change after birth, details of its structure and function remain plastic for some time, particularly in the cerebral cortex, the tissue that forms the brain's convoluted surface. Experience—sights, smells, tastes, sounds, touch and posture—activates and, with time, reinforces specific neural pathways while others fall into disuse. A childhood imbalance in the use of the two eyes, for example, will cause permanent deficits in the visual perception through the underused eye. The developing brain can be likened to a highway system that evolves with use: less traveled roads may be abandoned, popular roads broadened and new ones added where they are needed.

How does experience mold the organization of the brain? We have postulated a sequence of molecular events, triggered by external stimuli, that may contribute to plasticity in one part of the cat brain. It is possible that similar scenarios are followed throughout the developing brain during early experience, not just in cats but in human beings as well. Such molecular events may shape many of the mental features underlying our common humanity. By translating variations in early experience into variations in brain organization, they may also underlie some of our individual differences.

Visual experience is easy to manipulate, and so our study of brain plasticity, like many earlier studies, focused on the visual system. The processing of visual stimuli begins in the retina of the eye, which contains a few hundred million neurons densely packed in a thin sheet. An array of about a million retinal ganglion cells sends the retinal output deeper into the brain. Their elongated processes, called axons, are bundled together to form the optic nerve. Some of the axons in the nerve project to two structures called lateral geniculate nuclei (LGN), one in each hemisphere of the brain. Each retina is connected to the lateral geniculate nucleus on both the opposite (contralateral) and same (ipsilateral) sides of the brain. The LGN neurons in turn send axons to the back of the brain, to a discrete zone called lamina IV, the fourth of six main layers in the primary visual cortex. The neurons in lamina IV form contacts with other layers of the visual cortex.

Patterns of light that fall on the retina are converted into electrochemical signals reaching the retinal ganglion cells, which turn the signals into impulses called action potentials. These impulses propagate along axons and reach the LGN neurons at junctions called synapses. At every synapse, an impulse arriving at an axon terminal triggers the release of chemicals known as neurotransmitters, which cross the synaptic cleft and bind to specific receptors on the cell body or the dendrites—branching receptive processes—of the adjacent cell. Under appropriate conditions the neurotransmitter binding stimulates an LGN neuron to produce its own action potential, which in turn propagates along the axon and reaches neurons in the primary visual cortex. The stimulus is analyzed there and in other areas of the cortex receiving inputs from the primary visual cortex.

How many of these connections are governed by genetics and how many by early experience? A major breakthrough came in the early 1960's with the landmark experiments of David H. Hubel and Torsten N. Wiesel, both then at the Harvard Medical School, who later won a Nobel prize for their work [see "Brain Mechanisms of Vision," by David H. Hubel and Torsten N. Wiesel; SCIENTIFIC AMERICAN, September, 1979]. Hubel and Wiesel chose to use cats in studying the development of the visual system because, like human beings, cats have eyes at the front of the face, so that the visual fields of the two eyes overlap extensively. This overlap gives cats binocular vision in the central 90 degrees of their 180-degree field of view. Hubel and Wiesel studied binocular cells, which respond to stimulation of both eyes, in one part of the visual cortex called area 17. These binocular cells are important for depth perception and constitute about 40 percent of the neurons in area 17 in cats (60 percent in primates). The other neurons are monocular, responding to stimulation of one eye only.

Using electrical probes capable of detecting signals generated by individual neurons, Hubel and Wiesel systematically recorded the number of

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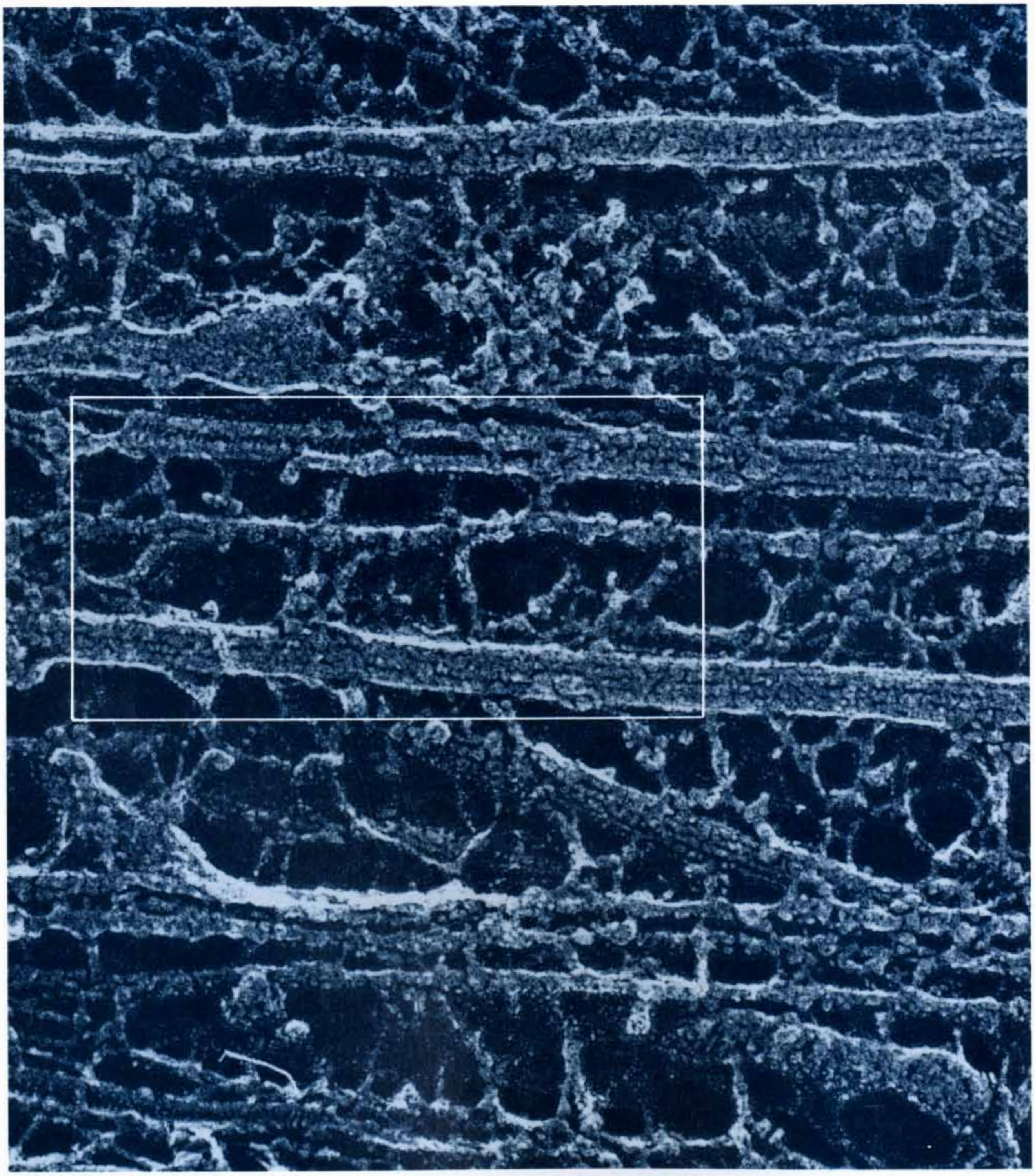
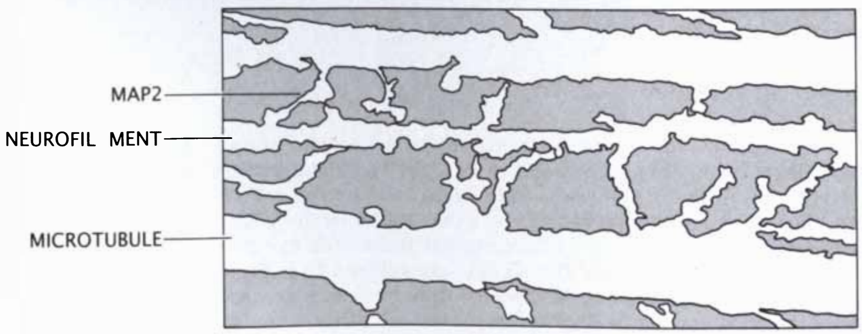


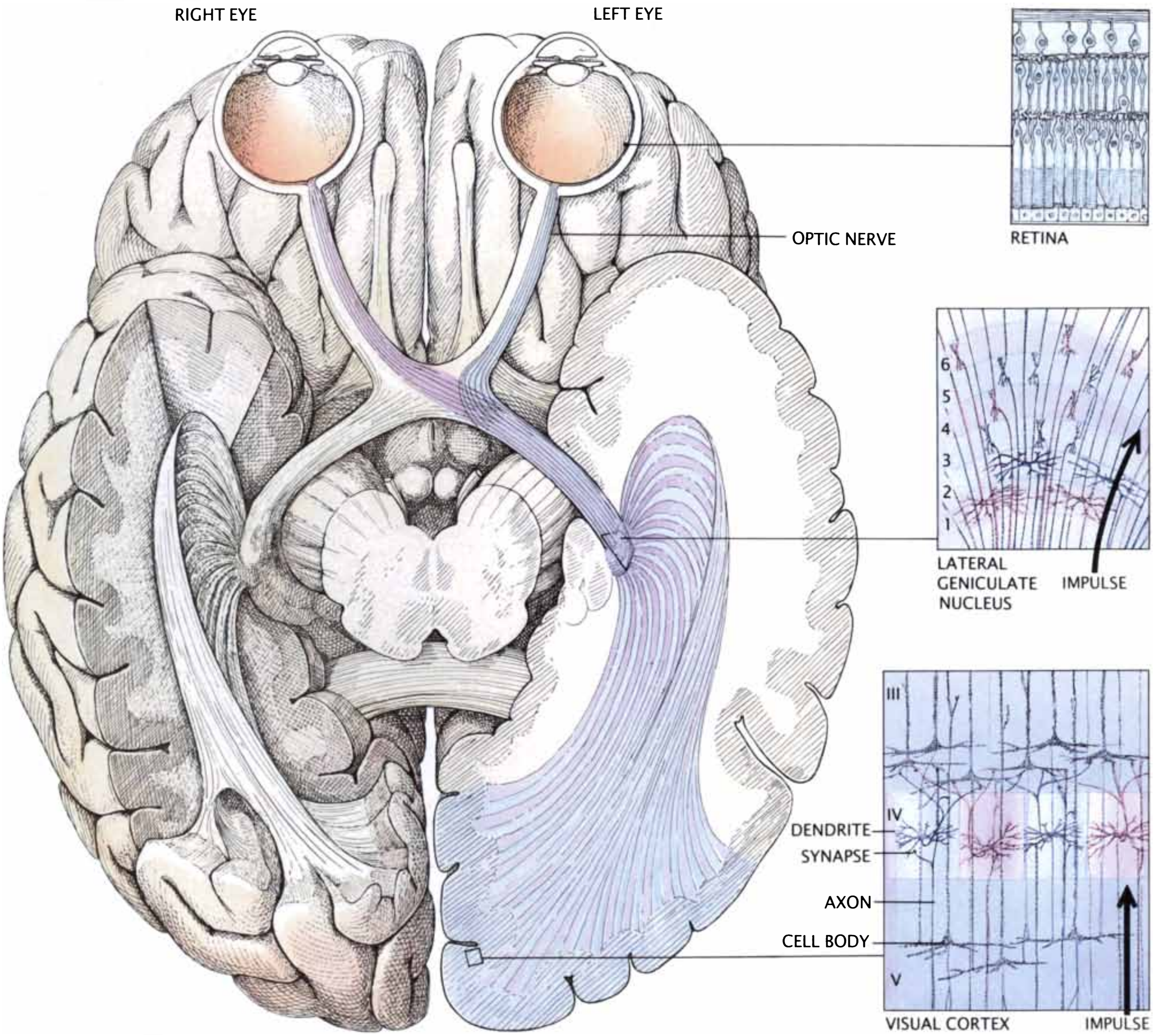


MAP2 MOLECULES form bridges between neurofilaments and microtubules in this electron micrograph of a dendrite, the receptive portion of a nerve cell. Neurofilaments and microtubules are part of an internal skeleton that affects a neuron's growth and structure; by controlling interactions among their component proteins, MAP2 may mediate the formation of new neural pathways. This image of a dendrite in rat spinal cord was made by Nobutaka Hirokawa and his colleagues at the University of Tokyo.

neurons in area 17 that responded to stimulation of the ipsilateral eye only, to the contralateral eye only and to both eyes. They also recorded whether the binocular cells had a preference for one eye over the other. They found that in kittens that had one eye sutured shut during the first several months after birth, the proportion of neurons in area 17 responding to stimulation of the closed eye dropped markedly. As a result the visually responsive neurons in area 17 were nearly all monocular and remained so even after the animal was allowed to use both eyes again. This profound shift in favor of the open eye—a shift in ocular dominance—was permanent, and the animal remained blind in the deprived eye for the rest of its life.

What part of the brain had been affected by the deprivation? Hubel and Wiesel showed that after a period of monocular deprivation, neurons in the retina and the LGN continued to respond normally to light. In other words, the visual pathway from the retina to the LGN was not affected by experience and therefore must be genetically predetermined to a large degree. This result meant that the changes accompanying monocular deprivation must have taken place in the organization of the cortical neurons.

The effect depends crucially on the timing of the deprivation. Hubel and Wiesel later found that monocular deprivation during adulthood did not change the neuronal organization of area 17. Carl R. Olson and Ralph D. Freeman of the University of California at Berkeley systematically studied the effect of an animal's age on the shift in ocular dominance after 10-day periods of monocular deprivation.



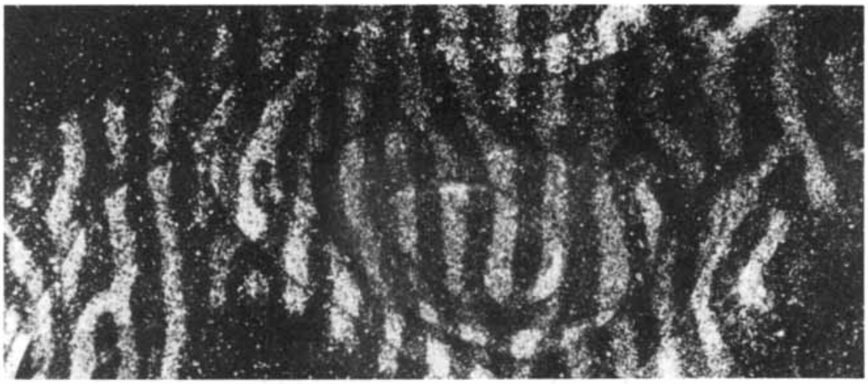
VISUAL PATHWAY is traced schematically in the human brain, seen from below. The path is shown only for signals originating from one side of the visual field. Light falls on the retina and is converted into nerve impulses that travel to the lateral geniculate nucleus (LGN), where signals from each eye are segregated into six layers. The signals are relayed to lamina IV in the primary visual cortex, where they remain segregated into bands corresponding to one eye or the other. Impulses then travel to other layers of visual cortex, where signals arising in both eyes are integrated. The parts of a neuron are labeled in the inset (*bottom*) showing three of the six layers in a small part of the visual cortex. The axon fiber carries a signal away from the cell body to the presynaptic terminal, releasing neurotransmitter chemicals that bind to receptors on the dendrite of the postsynaptic neuron. LGN and cortical cells are actually more densely packed than is shown here.

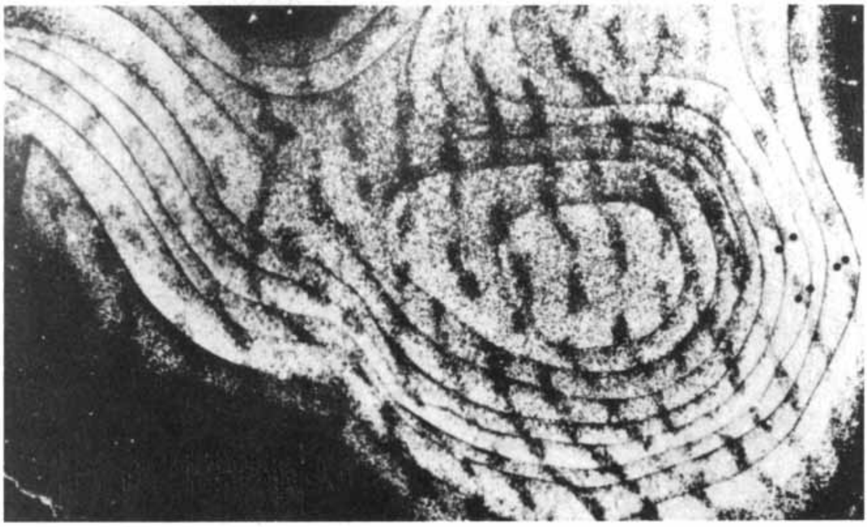
They found that whereas monocular deprivation begun one month after birth causes a dramatic shift, the effect diminishes as the age at which the animal is deprived increases until, at the age of about four or five months, monocular deprivation ceases to have an effect on area 17. Hubel and Wiesel called the interval spanning the second through the fourth month after birth the critical period, because it is only during this period that the visual cortex is plastic enough to change its organization in response to input from the retina.

In an effort to detect the changes in cortical structure that underlie such shifts in ocular dominance, Hubel, Wiesel and Simon D. LeVay employed a technique for tagging neural pathways with radioactive amino acids. The investigators anesthetized monkeys and injected radioactive amino acids into one eye. Cells in the retina incorporated the amino acids into their proteins; the proteins were transported along the axons and passed on to neurons in the LGN, which in turn relayed them to neurons in lamina IV of the visual cortex. Cortical slices from the injected monkey were placed on photographic film, where the radioactivity carried along the visual pathway created ghostly silhouettes of the areas connected to the injected eye.

The radioactive zones of area 17 in lamina IV formed distinct bands that alternated with nonradioactive zones. Each zone turned out to be the target for axons from LGN neurons that receive input from a single eye; adjacent zones receive signals from the opposite eye. In a normal monkey these ocular-dominance columns were equal in width: roughly half a millimeter across. But in a monocularly deprived monkey the columns representing the active eye were markedly expanded, whereas those representing the deprived eye were reduced. LeVay, together with Michael P. Stryker and Carla J. Shatz, got similar results with cats.

Those anatomical findings, together with the electrophysiological evidence, suggest that in monocularly deprived cats synaptic contacts between axons from the LGN and neurons in lamina IV develop in favor of the functionally active visual pathway. The phenomenon resembles the development of muscles that are exercised and the atrophy of muscles that are idle. The peculiarity here, however, is that the activity-dependent development occurs within a narrow window of time—the critical period.





OCULAR-DOMINANCE COLUMNS appear as bright and dark stripes in these autoradiographs of lamina IV in a monkey's visual cortex. Each column is defined by axon terminals from LGN neurons that receive signals from one eye only. The bright columns resulted when a radioactive label was injected into one eye and was carried along the visual pathway; columns corresponding to the other eye are dark. In a normally raised animal (*top*) columns that received signals from one eye are as wide as those that received signals from the other eye. In an animal that was deprived of the use of one eye (*bottom*) the bands representing the active (injected) eye are expanded, nearly obliterating the narrow bands representing the deprived eye.

In the 20 years since Hubel and Wiesel carried out their initial experiments, plasticity of the visual cortex has been studied intensively, both electrophysiologically and neuroanatomically. In 1979 we became interested in a new question: What molecular mechanisms translate visual experience during the critical period into neural architectures?

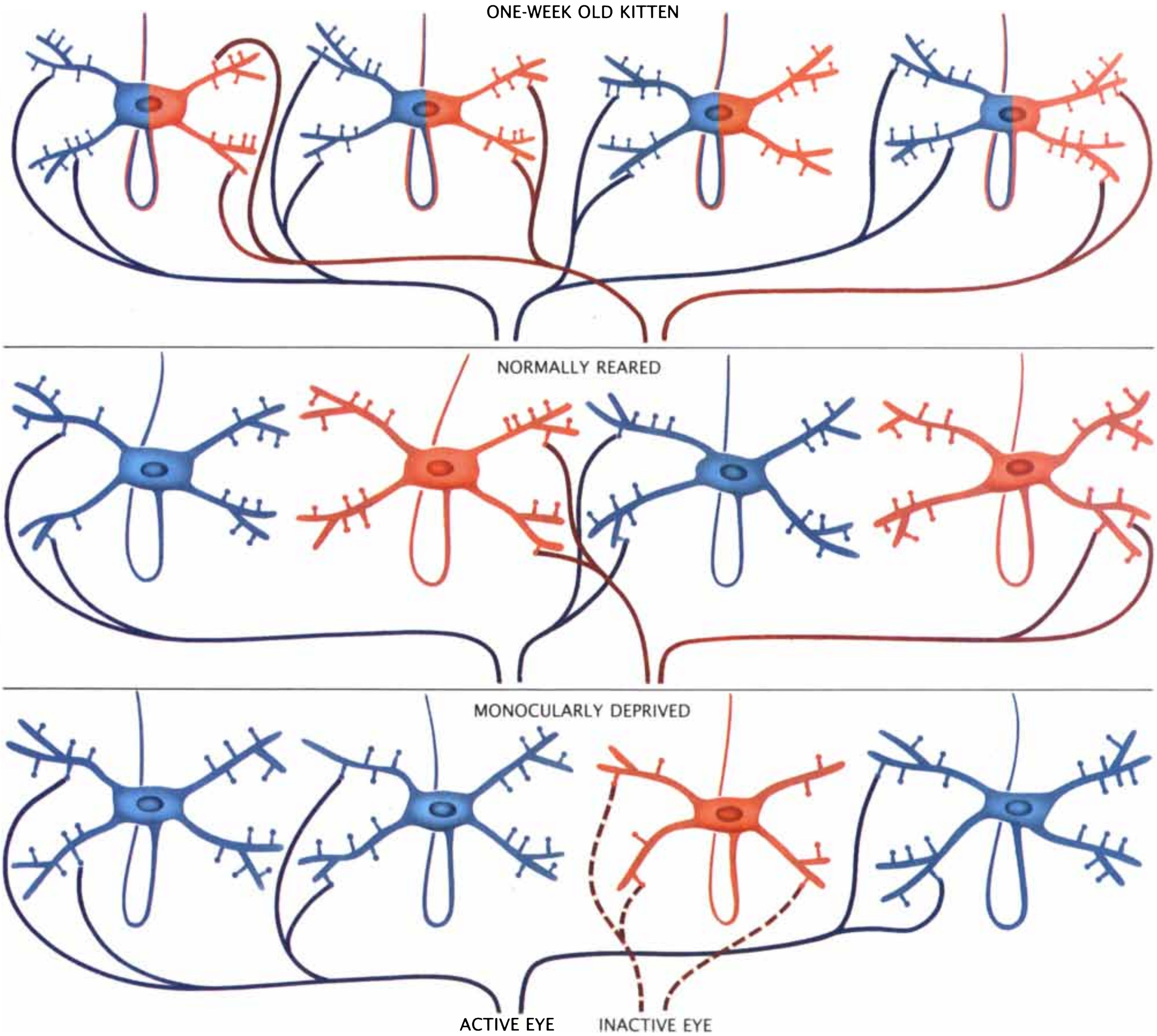
We began by looking for biochemical changes that mark the beginning and end of the critical period. To do so we needed a strategy for picking the biochemical processes that play a specific role in cortical plasticity from among those that accompany general growth and maintenance. Here we found another advantage to studying the cat's visual system: it is possible to delay the onset of the critical period by rearing kittens in total darkness, thereby allowing all other developmentally related changes to occur. The critical period for ocular dominance can then be studied in isolation. This strategy, called dark-rearing, was first explored by Max S. Cynader, then at Dalhousie University in Nova Scotia. It enabled Cynader to initiate shifts in ocular dominance in cats that were as much as two years old, even though normally the critical period ends at the age of about four or five months.

Cynader found that as soon as dark-reared kittens are brought into the light, the experience-dependent changes in cortical connections begin. What is more, George D. Mower and his colleagues at the Boston Children's Hospital found that in dark-reared kittens exposed to just a few hours of light the cortical changes activated by the light continue even if the kittens are then returned to darkness. This result suggested that a biochemical event important in plasticity lies dormant until it is triggered by light.

We initiated the search for this light-triggered biochemical event by studying the effects of a small molecule called cyclic adenosine monophosphate (cyclic AMP). Cyclic AMP is a standard "second messenger" in cells: it relays messages received at the cell surface to specific sites within the cell. There were several reasons for our choice. Analogues of cyclic AMP have been found in vitro to stimulate the development of neuronal precursor cells into neurons. More pertinent, Takuji Kasamatsu and his colleagues, then at the California Institute of Technology, had found evidence leading them to propose that norepinephrine, a common neurotransmitter, may play a role in cortical plasticity by activating the synthesis of cyclic AMP. Kasamatsu's proposal led us to examine the role of cyclic AMP in greater detail.

Cyclic AMP might conceivably have an effect through a series of well-documented biochemical events. Norepinephrine binding to a receptor on the cell surface acts as a "first messenger," which together with a protein called G-protein activates the enzyme adenylate cyclase, which in turn synthesizes cyclic AMP. Cyclic AMP then acts as an intracellular second messenger by activating another enzyme, cyclic AMP-dependent protein kinase, which phosphorylates (adds phosphate groups to) particular proteins in the cell. For many of these proteins the effect of phosphorylation is not known, but it is thought the addition of negatively charged phosphate groups to specific sites on a protein molecule may change the protein's three-dimensional folding pattern and thereby alter its biological activity.

We decided to search the visual system of cats for proteins that are phosphorylated by the cyclic AMP-dependent protein kinase. To identify phosphorylated proteins, we homogenized cells from the visual cortexes of devel-



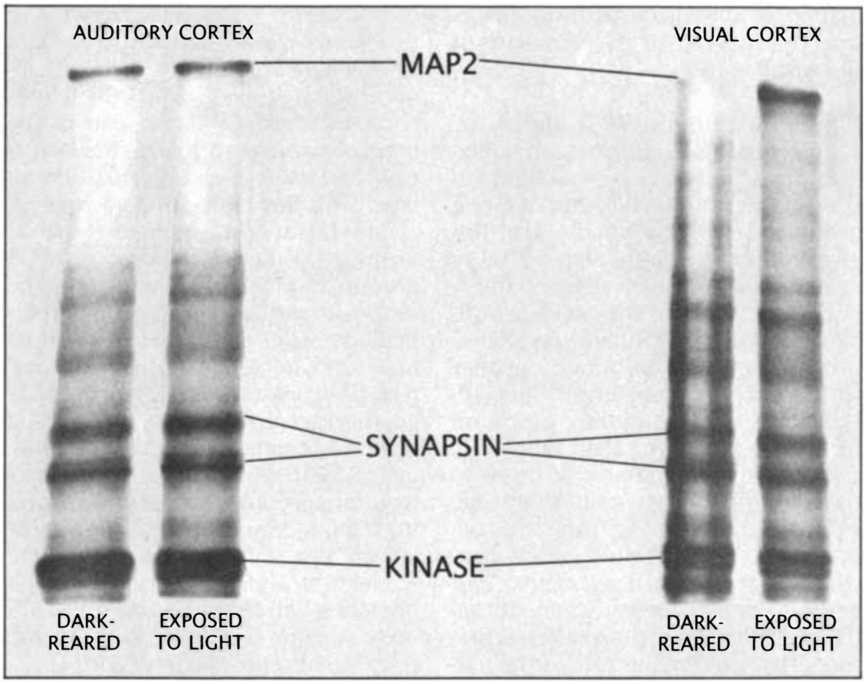
REORGANIZATION of neuronal connections during development leads to ocular-dominance shifts. The drawings depict lamina IV cells being contacted by axons from LGN neurons. The colors distinguish the paths of signals originating in different eyes. Many neurons in a one-week-old kitten (*top*) receive signals from both eyes. In normal development (*middle*) the LGN axons segregate into columns that serve only one eye or the other. If one eye is deprived (*bottom*), however, most of the cells form contacts with LGN axons carrying signals from the active eye and come to respond only to that eye.

oping cats and incubated the preparation with radioactive adenosine triphosphate (ATP), which served as a source of phosphate groups. Any proteins that were phosphorylated during the incubation would carry a radioactive phosphate group. When the proteins were separated by gel electrophoresis, the radioactive label made it possible to detect phosphorylated proteins on X-ray film.

We looked for proteins that became more phosphorylated when cyclic AMP was added to the homogenized cells than when it was not. Several proteins did appear to be phosphorylated by the protein kinases that are activated by cyclic AMP. One of them was synapsin, which is found in high concentrations at synapses. We ruled it out as an intermediary in cortical plasticity, however, because we found that the phosphorylation of synapsin was the same for dark- and light-reared cats. A second candidate was the cyclic AMP-dependent protein kinase itself. We found that this enzyme is present in equal amounts at birth and in adulthood and is not affected by dark-rearing. Its phosphorylation also does not change during development.

Our search focused on a third phosphorylated protein, an unusually large molecule weighing around 300,000 daltons. We identified it as microtubule-associated protein 2, or MAP2, by means of antibodies specific for the protein, which were given to us by Lester I. Binder of the University of Virginia and Andrew Matus of the Friedrich Miescher Laboratory in Basel. The concentration of this protein is the same in cortexes of both dark- and light-reared animals. But we found that the phosphorylation of MAP2 is different before and after the critical period. In tissue taken from the visual cortex of normally raised cats whose critical period was over, MAP2 was easy to phosphorylate in vitro, which indicated that many sites on the protein were not phosphorylated in the living animals. In contrast, in the visual cortex of dark-reared cats (in which the onset of the critical period had been delayed) MAP2 could barely be phosphorylated, indicating it had been fully phosphorylated in vivo.

Could the apparent difference in phosphorylation be related to the difference in plasticity before and after the critical period? To test that possibility we examined tissue taken from kittens whose critical period had been delayed by dark-rearing and then triggered by exposure to a few hours of light. We found MAP2 could be easily phosphorylated in vitro, like MAP2 from normally reared cats. Thus the protein seemed to remain fully phosphorylated throughout the dark-rearing but became dephosphorylated as soon as light began to stimulate the visual pathway.



BIOCHEMICAL DIFFERENCE is evident in MAP2 from the visual cortex of a cat that had been dark-reared for 52 days and a littermate that had been dark-reared and then was exposed to light. The dark bands in these autoradiographs indicate proteins that took up radioactive phosphate groups during phosphorylation and then were separated according to molecular weight by gel electrophoresis. Proteins from cortical cells were incubated with cyclic AMP and cyclic AMP-dependent protein kinase, together with the radioactive label. Two proteins—synapsin and the kinase—were phosphorylated to the same degree in both cats, but MAP2 clearly was not. In the visual cortex of the dark-reared cat, MAP2 was probably already fully phosphorylated, and so it did not take up the radioactive label, whereas in the cat that was exposed to light, MAP2 was dephosphorylated and so became strongly labeled. Exposure to light had no effect on MAP2 phosphorylation in the auditory cortex of the animals.

In order to establish a role for MAP2 phosphorylation in cortical plasticity, however, we still had to rule out the possibility that we were observing only some aspect of an unrelated adaptation to darkness. To do so, we studied adult cats that had been reared normally and then put in the dark. We knew that this procedure had no effect on cortical plasticity, because the critical period of these animals had long since ended. The phosphorylation of MAP2 in these cats was not significantly different from that in adult cats living in normal lighting. Nor did it change when the cats were brought out to the light again.

We also had to rule out the possibility that the phosphorylation of MAP2 was caused by a general effect of dark-rearing on development, such as retarded growth of the entire brain. We therefore examined the phosphorylation of the protein in dark-reared cats' auditory cortex, the part of the brain that processes sound. We reasoned that because dark-reared cats were not deprived of sound stimuli, the timing of the critical period for the auditory cortex would remain unaffected, so that any general effect of dark-rearing on MAP2 phosphorylation would show up. We found that phosphorylation of MAP2 in the auditory cortex was in no way influenced by dark-rearing or subsequent exposure to light.

Might the phosphorylation be associated with changes in visual stimulation per se and not with plasticity? To rule out that last suspicion, we studied MAP2 in the LGN. Hubel and Wiesel had shown that cells in the LGN do not exhibit plasticity after birth and continue to respond normally to light after a period of monocular deprivation. We found no change in MAP2 phosphorylation in the LGN before and after the critical period. This final result supported our conjecture that the phosphorylation of MAP2 in the visual cortex is not caused simply by stimulation of the visual pathway but is directly involved in the plasticity of the visual cortex.

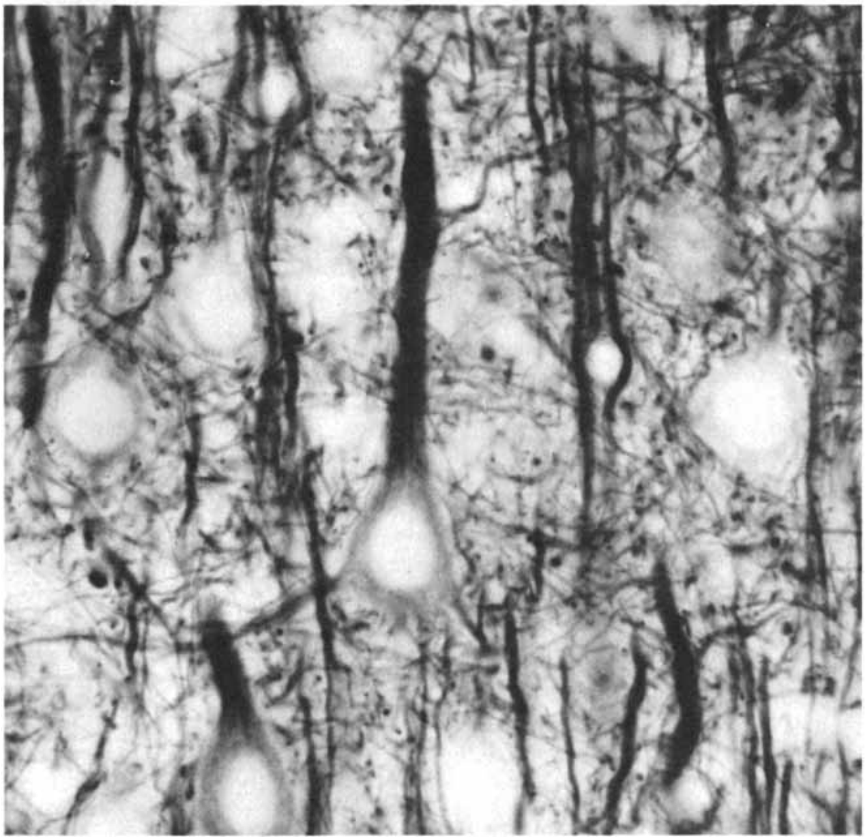
The MAP2 molecule is one of the cytoskeletal proteins, so called because they are thought to serve as structural elements in a cell, giving it form just as the skeleton gives form to the body. Many of these proteins are also involved in the transport of molecules and organelles within cells. The microtubule-associated proteins, or MAPs, are found together with a major component of the cytoskeleton, the microtubules, which are formed by a protein called tubulin.

MAP2 itself is found only in neurons, where it is associated not only with microtubules but also with actin (which forms another cytoskeletal component, the microfilaments) and neurofilament protein (which forms the neurofilaments, cytoskeletal structures that are unique to neurons). In fact, MAP2 has been detected in every kind of neuron that has been examined, which suggests it may play a role in plasticity not just in the visual cortex during the critical period but in regions throughout the brain and throughout life. (Interestingly, an abnormal tangling of cytoskeletal proteins, including MAP2, is seen in the brain of patients with Alzheimer's disease, and its degree seems to be correlated with the degree of dementia.)

How might MAP2 influence cortical plasticity? First of all, as a cytoskeletal protein it must help to dictate the shape of neurons, which is under particularly strict control. Most neurons have a characteristic branching pattern of axons and dendrites. There is good evidence to suspect that MAP2 is involved in determining the morphology of the dendrites in particular. Electron microscopy, for example, shows that microtubules (which are associated with MAP2) are oriented along the lengths of dendrites and dendritic branches, and Matus has used an antibody staining technique to show that MAP2 is concentrated in dendrites.

What is more, Richard Bernhardt, working with Matus, observed that MAP2 accumulates in newly formed dendrites before tubulin, the major component of microtubules, appears at the site. Matus and Bernhardt have suggested that MAP2 initiates and controls the assembly within dendrites of structures consisting of MAPs, tubulin, neurofilament protein and actin. In this way MAP2 may dictate the details of dendritic shape, as well as the intracellular traffic of molecules between dendrites and the cell body.

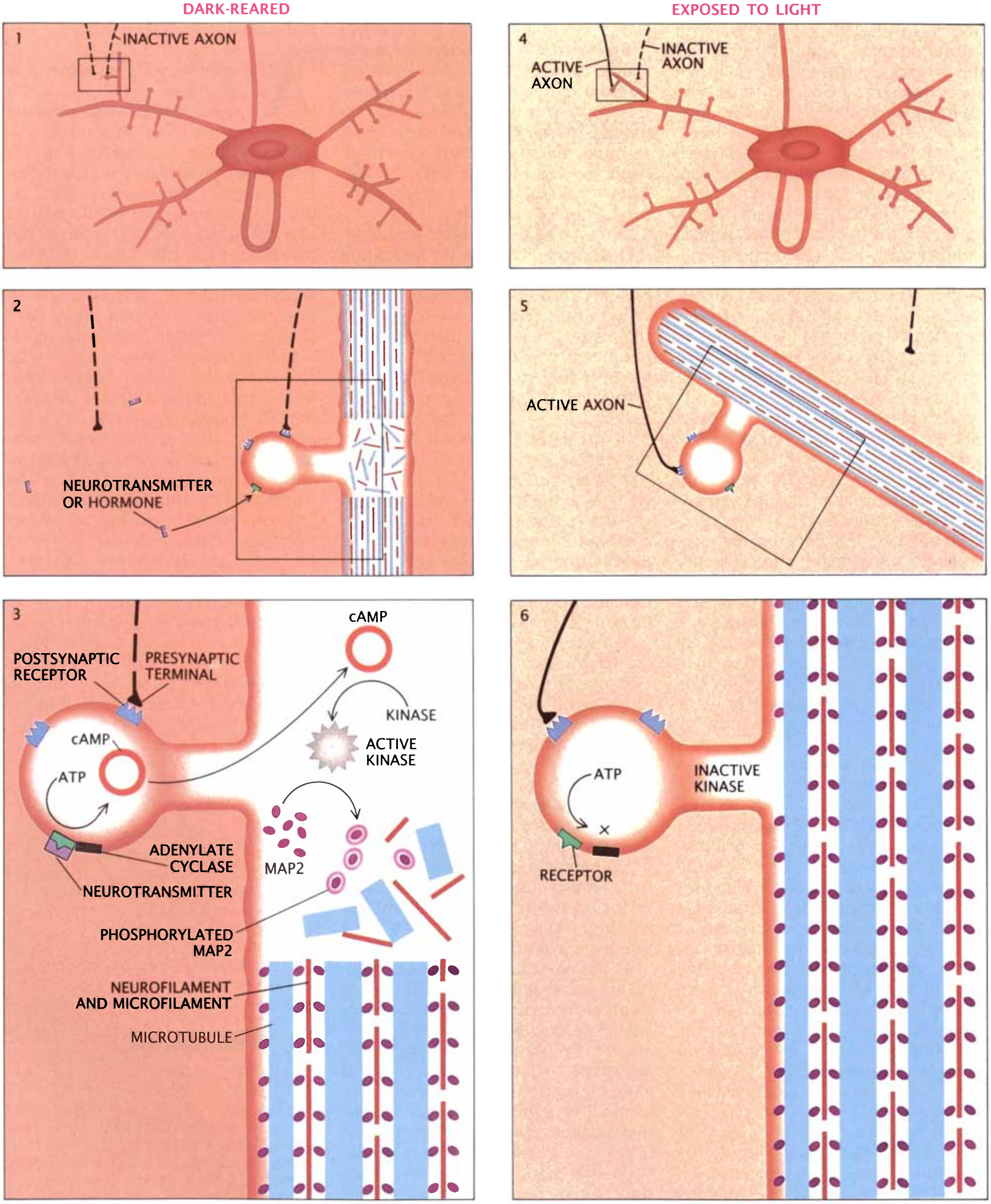
Dendritic shape can influence neuronal function in several ways. For example, the more branched and extended the dendrites of a neuron are, the more signals it can receive and integrate from other neurons. In addition dendritic branching can affect the efficacy with which a neuron relays a signal. When the dendrites of a neuron receive excitatory or inhibitory inputs from other neurons, the dendrites initiate their own signal, which is conducted toward the cell body. If a strong enough signal reaches the cell body, the cell generates an action potential of its own. The shape and size of a dendrite determine how fast and how far the signal can spread and thereby influence the cell's ability to respond to incoming signals. For instance, a signal generated in a large dendrite close to the cell body has a better chance of triggering an action potential than a signal generated at a small dendrite far from the cell body.



DISTRIBUTION OF MAP2 in pyramidal cells (a common type of neuron) from the rat visual cortex is shown by the dark areas in this section, which was stained by a color indicator that was coupled to an antibody binding specifically to MAP2. Strong staining indicates MAP2 is concentrated in the dendrites radiating from the cell bodies, which also contain MAP2 except in their unstained nuclei. The presence of MAP2 in dendrites suggests that the protein may regulate the shape of dendrites.

Just how might MAP2 affect cytoskeletal structure, as Matus and Bernhardt suggest it does? One clue may lie in the observation that tubulin requires the presence of dephosphorylated MAP2 in order to polymerize and become assembled into microtubules. Indeed, as a general rule dephosphorylated MAP2 promotes stable interactions of the cytoskeletal proteins tubulin, actin and neurofilament protein, whereas phosphorylated MAP2 weakens them. Thus when MAP2 inside a neuron is dephosphorylated, dendrites may be static, whereas when the MAP2 is phosphorylated, dendrites may become dynamic, readied for changes in shape and length.

In our earlier studies we postulated that MAP2 from dark-reared kittens is phosphorylated in vivo, and that when light triggers the onset of experience-dependent synaptic changes, MAP2 becomes dephosphorylated. We suspect that as long as MAP2 remains fully phosphorylated—the state it is in when the kittens are kept in darkness—the cytoskeletal architecture of cortical neurons remains indeterminate. The cortex is therefore fully primed to change its organization in response to neuronal activity evoked



MAP2'S ROLE in rearranging dendrites is shown schematically here. (The drawings are not to scale.) A cortical cell (*1*) in a dark-reared kitten is contacted by an inactive axon. A neurotransmitter or hormone that exists during dark-rearing binds to receptors on the dendritic spine and destabilizes cytoskeletal proteins (*2*) by way of a cascade of molecular events (*3*). The binding of the neurotransmitter or hormone to a receptor activates adenylate cyclase, an enzyme that converts adenosine triphosphate (ATP) into cyclic AMP. Cyclic AMP activates another enzyme, a kinase that phosphorylates MAP2. Phosphorylated MAP2 prevents the formation of microtubules and also inhibits the interaction of microtubules with microfilaments and neurofilaments. When the kitten is exposed to light, the plastic nature of the dendrite enables it to move to an active axon (*4*). The dendrite proteins may stabilize (*5*) when unknown events that occur with visual stimulation cause MAP2 to become dephosphorylated and form cross bridges between the cytoskeletal proteins (*6*). The process may be reversible.

by exposure to light. The subsequent decline in plasticity during the critical period may be caused in part by the progressive dephosphorylation of MAP2, which makes the neuronal cytoskeleton increasingly rigid. The process stabilizes the shape of neurons, thereby limiting the degree to which neuronal interconnections in the visual cortex can be reorganized.

The notion that details of neuronal architecture remain undetermined until the critical period ends is supported by studies of the visual cortex in dark-reared monkeys and rodents. Neurons there show a conspicuous paucity of dendritic spines, the short, protruding processes normally found on the surface of dendrites. These spines are the major sites for synaptic contact between neurons. Hence the lack of spines could profoundly affect neuronal connectivity. It may be that MAP2 acts on microtubules to control the formation and alteration of spines as well as dendrites.

Through its influence on the cytoskeleton, MAP2 might also influence cortical plasticity by controlling the transport and anchoring of molecules necessary for synaptic transmission and growth. Such molecules may include receptors for hormones, neurotransmitters and growth-promoting factors, as well as membrane proteins that modulate neuron excitability.

We have identified one molecule, MAP2, whose biochemical characteristics in the visual cortex change with the onset of the critical period. It is the first such protein to be identified, but it will undoubtedly not be the last. There may be other proteins that our methods simply were not able to detect. For example, the biological activity of many proteins may be altered at the start of the critical period by means other than phosphorylation. And although the evidence for MAP2's role is strong, we cannot be certain yet whether MAP2 dephosphorylation actually causes the change in plasticity or instead is merely an effect of the change. We think, however, that molecular changes must precede the structural changes in the dendrites.

Even though the precise function of MAP2 phosphorylation remains uncertain, the observation has generated new questions. In particular, how might the stimulation of the visual pathway by light change the state of MAP2's phosphorylation in the visual cortex? Does the change result from a change in the intracellular concentration of cyclic AMP (which activates the protein kinase that phosphorylates MAP2)? We thought perhaps exposure to light can affect the level of cyclic AMP by changing the density of receptors for norepinephrine, the neurotransmitter for which Kasamatsu proposed a role in cortical plasticity. (Bear in mind that the binding of norepinephrine to a receptor activates adenylate cyclase, which catalyzes the production of cyclic AMP.)

To test this hypothesis, we identified the receptor sites by incubating sections of the visual cortex with a radioactive probe that binds specifically to the receptors. We found that the distinctive layered distribution of norepinephrine receptors did not differ in any obvious way in the brain of normal cats, dark-reared cats and dark-reared cats that had been exposed to light. This result indicated that changes in MAP2 phosphorylation were not correlated with any crude changes in the location and density of these receptors. Our technique, however, would not have detected any redistribution of receptors among different cell types within a given layer. Detailed microscopic analyses need to be done to answer this question.

Another possibility is that a different transmitter- or hormone-receptor system is altered by exposing the visual system to light. An interesting recent finding by Mark F. Bear of Brown University and Wolfe Singer of the Max Planck Institute for Brain Research in Frankfurt indicates that cortical plasticity is maintained not by norepinephrine alone, as Kasamatsu had thought, but by the synergistic action of norepinephrine and a second neurotransmitter, acetylcholine, which is abundant in the visual pathway. Still another transmitter, glutamate, has also been hypothesized to play a role.

We are now examining the possibility that visual input triggers the release of other molecules known to activate adenylate cyclase and thereby stimulate the synthesis of cyclic AMP. We are also trying to determine whether visual input affects the level of cyclic AMP by modifying the activity of cyclic AMP phosphodiesterase, an enzyme that degrades cyclic AMP. A third possibility is that visual input affects MAP2 directly. For example, it may be that during dark-rearing MAP2 is situated near cyclic AMP-dependent protein kinases, so that it is maintained in a phosphorylated state. When light first stimulates the visual system, MAP2 may somehow become translocated to a site distant from the kinases. A fourth possibility is that an enzyme called protein phosphatase, which dephosphorylates proteins, may become activated by visual stimulation.

A full understanding of MAP2's role in the critical period requires a more detailed understanding of the protein itself. Richard B. Vallee and William E. Theurkauf of the Worcester Foundation for Experimental Biology in Shrewsbury, Mass., report that the MAP2 molecule has 22 sites at which phosphorylation can take place, of which 13 depend on the amount of cyclic AMP. Perhaps the biological function of MAP2 is subtly altered depending on how many sites are phosphorylated, or in what combination. Indeed, intracellular cyclic AMP-dependent protein kinases continue to phosphorylate MAP2 throughout adulthood, suggesting that the phosphorylation and dephosphorylation of MAP2 plays other critically important roles besides endowing the cortex with developmental plasticity.

We are only beginning to understand how molecular events influence the structure of neurons and how these structural changes are translated into changes in brain function. As we try to answer such questions, we hope to get closer to understanding how the external world comes to be mirrored in the microscopic structure of the brain. Ultimately the answer will lead to a profound appreciation of how each individual person, in spite of being formed by inexorable genetic processes, is also the unique product of experience.

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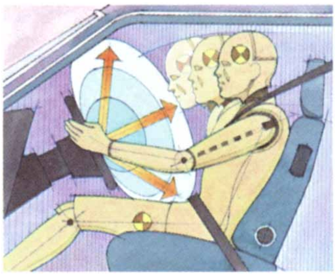

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Patterned Ground

A common physical phenomenon shapes these uncommon manifestations of natural geometry

by William B. Krantz, Kevin J. Gleason and Nelson Caine

Order in nature would appear to be the exception, not the rule. The regularity of the solar system, the complex organization of living things and the lattice of a crystal are all transient patterns in a grand dissolution into chaos. The prevailing theme of the universe is one of increasing entropy. All the more wondrous, then, are the examples of order in nature. One particularly fascinating example is a geophysical curiosity known as patterned ground.

The term "patterned ground" refers to natural regularities defined by stones, ground cover or topography that assume forms such as circles, stripes and polygons. In this article we shall restrict our attention to patterns occurring in water-laden soil that undergoes repeated freeze-thaw cycles. Such patterns are found throughout the world, at sea level in polar and subpolar regions and at higher elevations in more temperate climate zones.

Some of the patterns stretch over square kilometers and others cover areas less than a square meter. Some include boulders as large as a man, whereas others arise from localized variations in vegetation. There are active patterns that are still being formed and inactive relicts that were shaped during the past ice age.

Patterned ground has been the subject of scientific inquiry for more than a century: one of the earliest chroniclers, the Swedish geologist Fredrik V. Svenonius, published his observations in 1880. In 1907 another Swede, Otto Nordenskjöld, proposed a mechanism for its formation that, some 80 years later, we have developed into a predictive, validated model. Nordenskjöld suggested that patterned ground results from free convection.

Free convection is the familiar phenomenon that gives rise to billowing thunderheads and makes the air above a hot asphalt pavement dance. It can occur when a fluid is heated from below. The warmer fluid near the heat source expands and becomes less dense; then gravity drives the denser fluid down, allowing the less dense fluid to rise. If heat is supplied continuously, an overturning circulation can be established.

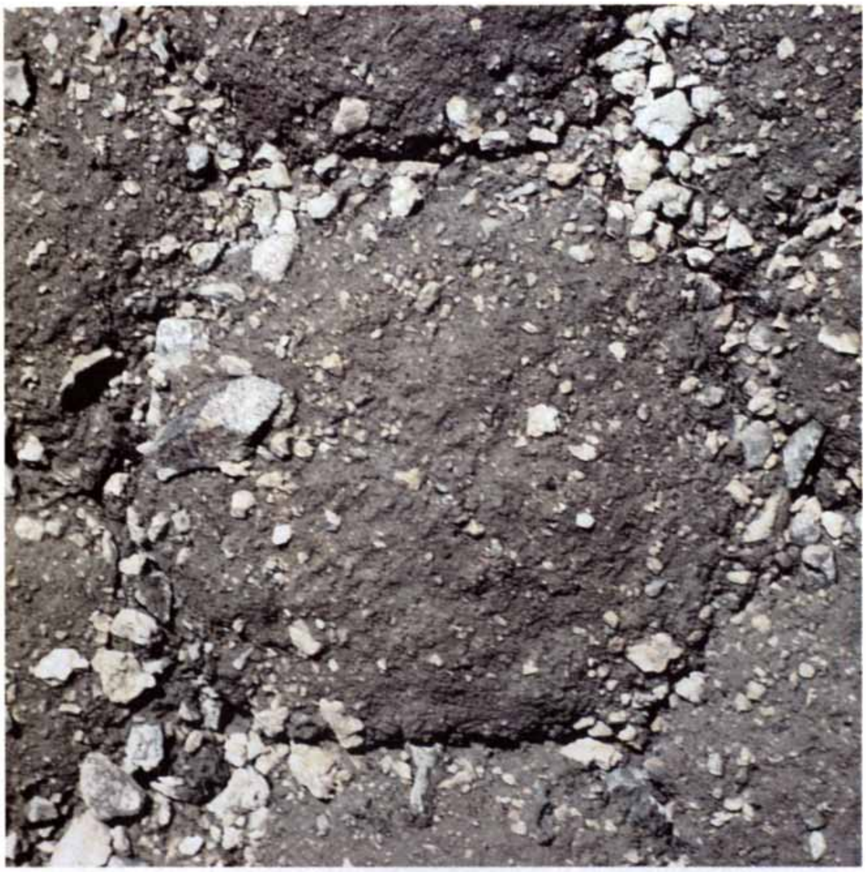
As the fluid circulates, it divides into distinct closed orbits, or "cells," which can assume highly ordered patterns. Struck by the geometric regularity of the patterns, Nordenskjöld proposed that free convection of water through porous soil might be responsible for some forms of patterned ground.

But Nordenskjöld was at a loss to explain how convection cells could reproduce geometric patterns on the ground surface. Indeed, today's theorists are still struggling with the question. The model we have developed over the past decade provides a plausible explanation for the regularity of some forms of patterned ground. In order to envision our mechanism one

WILLIAM B. KRANTZ, KEVIN J. GLEASON and NELSON CAINE approach the subject of patterned ground from somewhat different perspectives. Krantz, professor of chemical engineering at the University of Colorado at Boulder, became interested in it 10 years ago while studying underground coal gasification; he is currently working as both a Guggenheim and a Fulbright fellow at the University of Oxford. Gleason completed a master's thesis on patterned ground in 1984 under the joint supervision of Krantz and Caine and is now working toward a Ph.D. at Boulder. Caine, professor of geography at the university and research associate at the Institute of Arctic and Alpine Research, studies patterned ground as part of his larger research on periglacial features.

CIRCLES OF STONE measuring about three meters across decorate the Brog-

gerhalvoya peninsula in western Spitsbergen, Norway. The surface layer of water-laden soil freezes every winter and thaws in the spring. The authors think free convection in the thawing ground dictates the geometry of the circles.



STONE POLYGONS can exhibit nearly perfect hexagonal geometry (top). *On level ground the polygons form a continuous mesh* (bottom). *These patterns arose from daily rather than seasonal freeze-thaw cycles and have diameters ranging from five to 20 centimeters (about eight inches). The authors photographed the hexagon near Beartooth Butte in Montana; they took the bottom photograph in the San Juan Mountains of southwestern Colorado.*

must first review how free convection takes place in the ground.

Free convection can occur when frozen ground thaws. During thawing, water near the ground surface warms up while water near the thaw front (the boundary between thawed and frozen ground) stays cool. In most fluids this would mean that the denser fluid is on the bottom, and free convection would not occur. Water, however, is densest not at its freezing point but at four degrees Celsius—four degrees above its freezing point.

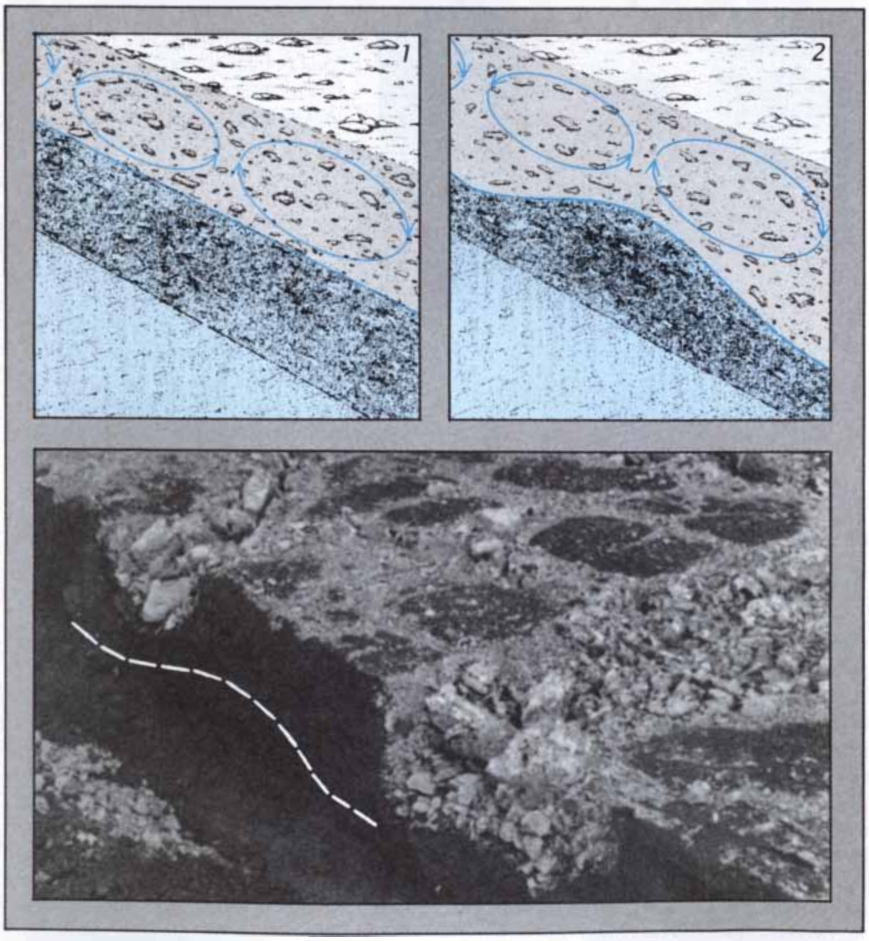
Hence free convection is possible whenever ice is covered with warmer water. This is exactly the situation in thawing ground. The denser water sinks to the thaw front, cools to zero degrees and rises again, thereby establishing continuously circulating cells.

It was the picture of free-convection cells circulating over the thaw front that suggested our mechanism. We reasoned that convection could sculpt the frozen ground under the thawed layer. During thawing, the descending plume of warm water would melt the underlying ice and the ascending cold water would retard melting. Thus the thaw front would become corrugated in a manner that reflects the shape of the convection cell. We know now that significant corrugation can occur even in the course of a single thaw.

Once the convection cell's geometry has been impressed in the thaw front, other geophysical processes may take part in reproducing that geometry on the ground surface. For example, stones can get pushed into the troughs of the corrugated thaw front through the action of "upfreezing"—the upward migration of the thaw front during freezing. Then the stones are pulled to the surface by a phenomenon familiar to many farmers: frost heaving, which causes fields to "grow" stones. During a frost, stones move upward and soil "fines" fill in under them so that they cannot settle to their former position when the ground thaws.

Cryostatic pressure has also been implicated in the transferring of the thaw-front geometry. This pressure is generated during freezing, when the descending "freeze front" approaches the corrugated thaw front, trapping water in the thaw-front troughs. The pressure could crack the ground surface or heave the soil in a pattern that reflects the underlying corrugations. Stones that become trapped in the cracks or collect around the uplifted soil could enhance the pattern; cracking and uplifting could also produce variations in ground cover (such as

RELICT STRIPES in the Colorado Rocky Mountains have probably been dormant for thousands of years. The age of the relicts can be inferred from lichen growth, carbon dating and pollen analysis. The authors have shown that the stripes, which occur on sloping ground, can result when gravity elongates the free-convection cells circulating in the underlying soil.



FREE CONVECTION establishes the geometry of patterned ground. Convection cells of circulating water (arrows) *may be generated as frozen ground thaws* (1)*; the cell shape is determined by the geological character of a region. The flow of water corrugates the frozen "thaw front"* (broken blue line) *in a way that reflects the cell shape* (2). *Other geophysical processes, such as frost "heaving," transfer the corrugated pattern to the ground surface. The trench cut through a stone polygon* (bottom) *reveals that the pattern extends well below the surface.*

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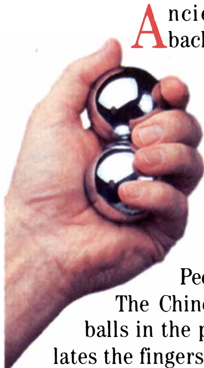

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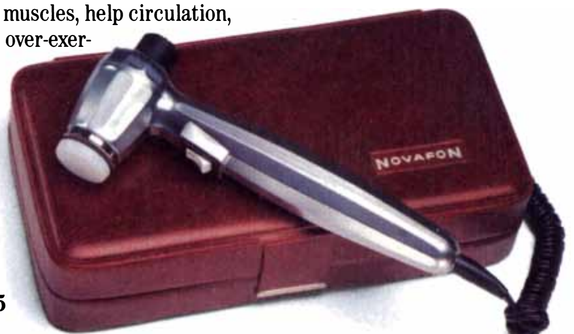

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UNDERWATER PATTERNS occur only where the water is shallow enough to freeze into the lake bed. Both lakes pictured here are in the Amphitheater Mountains of Alaska. The top photograph shows pits of stones near the shoreline; the aerial photograph of stone polygons reveals that patterns are confined to the shallow perimeter of the lake.

vegetation or lichen growth) by altering drainage and exposure.

The degree to which these and other mechanisms are involved in transferring the pattern of a corrugated thaw front to the ground surface is an active area of geomorphic investigation. Meanwhile we have done mathematical analyses based on the free-convection model that predict several forms of patterned ground. They demonstrate that stripes, circles and a variety of polygonal shapes could arise from simple free convection.

Our analyses have been most successful in describing polygonal and striped forms of patterned ground. They show quantitatively why the hexagonal geometry is preferred in nearly horizontal, laterally uniform ground where cells can be generated in a continuous network. The hexagons are interspersed with other polygonal forms where inhomogeneities (such as variations in soil properties) and barriers (such as protruding bedrock) occur in the ground.

The free-convection model also explains the formation of the less common stone pits, which are in a way the inverse of stone polygons. Whereas stone polygons result from a thaw-front pattern of interconnected polygonal troughs, stone pits reflect a network of polygonal peaks. The free-convection cells that give rise to stone polygons circulate up through the cell center and down along the cell borders, but stone pits reflect a circulation down through the center and up along the borders. We can predict the direction of circulation based on the properties of the soil.

Furthermore, our model's predictions are consistent with the observation that striped patterns appear on sloping ground. On such terrain, subsurface drainage would encourage the formation of longitudinal-roll and helical-coil convection cells, which give rise to stripes. The submerged patterns one observes in lakes also fit our model. They form only in shallow bodies of water, where freezing extends into the lake bed.

We have used our model to predict the ratio of pattern width to the depth of a thawed layer and have validated our predictions in the field. Depending on pattern geometry, the width ranges between three and five times the depth. The convection cells that generate underwater polygons circulate into the lake itself and so, as one would expect, the ratio of pattern width to thawed-layer depth is greater than that observed for nonsubmerged polygons. Similarly, seasonal freeze-

PATTERNS OF TOPOGRAPHY such as a field of earth hummocks in Iceland (top) *are perhaps the commonest examples of patterned ground in Arctic and sub-Arctic regions. The formation of topographical patterns is not well understood, but the regularity of hummocks and the fact that they elongate into stripes on sloped terrain* (bottom) *suggest that convection may play a role in it.*

SUBMERGED POLYGONS near Crazy Notch in south-central Alaska are 1.5 meters wide. The pattern results when water flows up through the center of a polygonal free-convection cell. The cells that form submerged patterns circulate in the lake bed and into the lake itself.

thaw cycles give rise to patterns larger than those produced by daily cycles.

There are several areas in which we still need to explore the applicability of our model. For example, we are just beginning to examine its application to patterns defined by ordered topography, which have been somewhat neglected by theorists. We are also investigating the model's ability to account for stone circles such as those pictured at the beginning of this article. Another convection model, which entails circulation of the soil itself rather than circulation of the water through the soil, has been applied to circles by Bernard Hallet of the University of Washington. Its implications are not unlike those of our own model.

So far these analyses of patterned ground fall short of a step-by-step description of its formation. Yet our efforts are spurred incessantly by the diverse rewards such research promises. Relict patterns may divulge clues to prehistoric climates. Active patterns could serve as monitors of mankind's impact on polar regions. Already studies of frozen ground on the earth have helped to illuminate the history of climatic conditions on Mars, where space-probe images reveal furrowed rings, polygonal fractures and ground-ice patterns.

Even if a complete theory of patterned-ground formation is established, the subject is not likely to lose its fascination. The wonder of patterned ground is not so much how it happens but that it happens at all. The same can be said of the more familiar regularity of snowflakes. An element of mystery will always attend phenomena that unite the precision of geometry with the vagaries of chance.

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STONE PITS, less common than polygons, form when water circulates down through the center of a polygonal free-convection cell. These pits in Norway are about a meter across.

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Fertilization in Mammals

The events that immediately precede and follow the fusion of sperm and egg must occur in a precise sequence. Surprisingly, a single molecule seems to have a crucial role at many points along the way

by Paul M. Wassarman

It has been more than a century since Hermann Fol, a Swiss zoologist, peered into his microscope and became the first person to see a sperm penetrate an egg, fertilize it and form the first cell of a new embryo. In that century many of the steps constituting the fertilization pathway—the events that occur in a compulsory order from the initial contact of sperm and egg to their fusion—have come into focus, as have the events immediately following fertilization.

Like Fol, who observed fertilization of a starfish egg, early investigators concentrated on studying marine invertebrates. The main reason was that the eggs of such organisms (in contrast to mammalian eggs) are fertilized outside the female (in seawater) under conditions that can be readily mimicked in the laboratory [see "The Program of Fertilization," by David Epel; SCIENTIFIC AMERICAN, November, 1977]. Since the late 1950's, culture systems that support the fertilization and early development of mammalian eggs in vitro have been developed and perfected, making it possible to study sperm-egg interactions of mammals in some detail.

The investigations have clarified not only the basic events of mammalian fertilization but also the molecular mechanisms underlying those events.

PAUL M. WASSARMAN is chairman of the department of cell and developmental biology at the Roche Institute of Molecular Biology in Nutley, N.J. After earning his Ph.D. in biochemistry from Brandeis University in 1968, he spent two years as a Helen Hay Whitney Foundation fellow at the Medical Research Council's Laboratory of Molecular Biology in Cambridge, England. He then joined the faculty of Purdue University before moving in 1972 to the Harvard Medical School, where he started his research on mammalian development. Wassarman left Harvard in 1985 to accept his current position.

Recently my colleagues and I identified and characterized the specific molecule in the outer coat of the mouse egg that serves as the receptor for sperm. We also found that this receptor molecule plays other critical roles in the fertilization pathway and in the events immediately following fertilization. Studies of the receptor molecule, other molecules involved in the fertilization pathway of mice and analogous molecules in other mammals may facilitate future biochemical studies of human reproduction. Such studies could lead to novel methods for both contraception and the treatment of infertility in human beings.

Although we have concentrated on mice (since human eggs are not available in the quantity needed for biochemical studies), their fertilization pathway is quite similar to that of human beings and other mammals. The basic process begins when many sperm first attach loosely and then bind tenaciously to receptors on the surface of the egg's thick outer coat, the zona pellucida. Each sperm, which has a large number of egg-binding proteins on its surface, binds to many sperm receptors on the egg. More specifically, a site on each of the egg-binding proteins fits a complementary site on a sperm receptor, much as a key fits a lock.

Generally the binding of sperm to an egg is species-specific—that is, the sperm receptors on the egg recognize only sperm of the same species and screen out all others. The ability of male and female gametes, or sex cells, of the same species to recognize one another is a ubiquitous feature of the fertilization process in all organisms, plant or animal. For good reason. Laboratory studies have shown that, with a few notable exceptions (such as the mule embryos resulting from the union of a horse and a donkey), embryos produced by interspecies fertilization cannot develop normally.

The binding of sperm to the zona pellucida is followed by what is called the acrosome reaction in the bound sperm. The acrosome is an organelle rich in digestive enzymes that lies in the anterior region of the sperm head, just under the plasma membrane encasing the head. During the reaction the front two-thirds or so of the plasma membrane fuses with the outer membrane of the acrosome. The fusion results in the formation of small vesicles that consist of the sperm's plasma membrane and the outer acrosomal membrane. These hybrid vesicles are eventually sloughed off, exposing the zona pellucida to the inner acrosomal membrane and the acrosomal enzymes. Abetted by the enzymes, which digest the zona pellucida, the acrosome-reacted sperm then bore through the outer coat.

One of the multitude of advancing sperm reaches the perivitelline space, a narrow region between the zona pellucida and the egg's plasma membrane, and fuses with the membrane, fertilizing the egg: the genetic material of the male parent mingles with that of the female parent, initiating development of the resulting embryo. The fusion also triggers a series of reactions that within seconds alters the plasma membrane and within minutes, in what is called the zona reaction, alters the zona pellucida as well. Both the plasma membrane and the outer coat are thereby made refractory to other sperm. These changes are crucial in order to prevent a lethal condition known as polyspermy: the fusion of more than one sperm with a single egg.

Interestingly, the zona pellucida has at times been viewed by investigators as a nuisance, a barrier to sperm and hence an impediment to fertilization, and it has often been stripped away in experiments with mammalian eggs. Now it is clear the coat serves as a sophisticated biological security system that screens incoming sperm, selects only those compatible with fertilization and development, prepares sperm for fusion with the egg and later protects the resulting embryo from polyspermy.

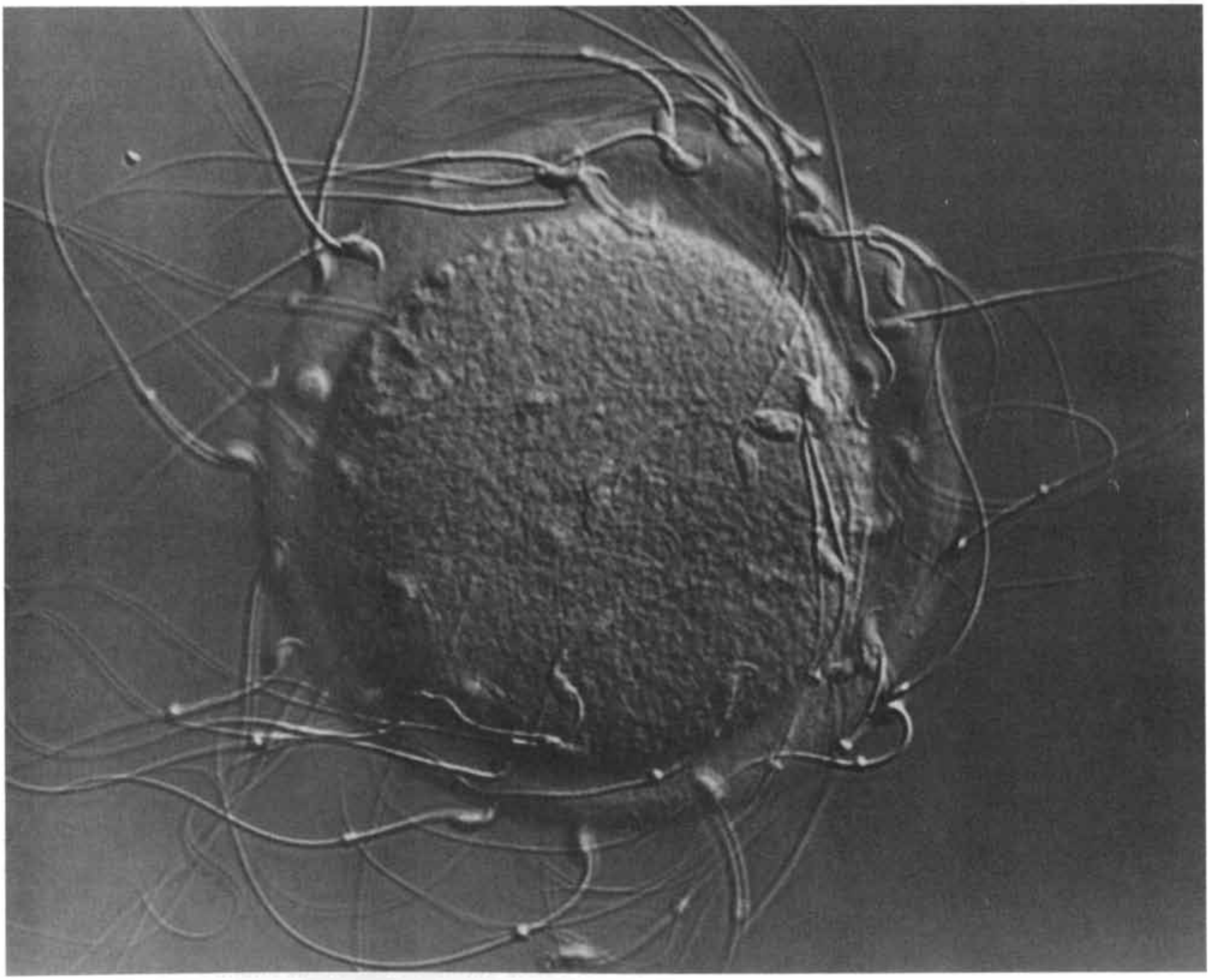
When my colleagues and I began to study mammalian fertilization about a decade ago, some of the major unanswered questions were: What is the nature of the putative sperm receptor in the zona pellucida, what initiates the acrosome reaction following sperm binding and what biochemical changes occur after fertilization to render the zona pellucida refractory to sperm? It turns out that a single glycoprotein—a polypeptide, or string of amino acids, to which groups of sugars are attached—constitutes a part of the answer to all three questions.

We came to the zona pellucida indirectly. In the course of an investigation of mouse development we were attempting to identify genes that are switched on and off only during the growth of oocytes, the precursors of eggs. Genes governing production of zona pellucida proteins were promising candidates for our study, but we needed to isolate such proteins before we could hope to identify their corresponding genes.

Jeffrey D. Bleil, then a graduate student in my laboratory at the Harvard Medical School, and I discovered that the zona pellucida of the mouse is constructed from three different glycoproteins. We named them ZP1, ZP2 and ZP3. We knew little about their chemical structure but were able to distinguish among them by gel electrophoresis, a standard technique that separates molecules according to their molecular weight. As ZP1, ZP2 and ZP3, which respectively weigh 200,000, 120,000 and 83,000 daltons, are synthesized and secreted by growing oocytes, they join to form a porous coat that grows to be about seven microns (thousandths of a millimeter) thick. (The coat of human eggs is almost twice as thick and that of certain other mammalian eggs can be four or five times as thick.)

We were somewhat surprised by the simplicity of the composition of the mouse egg's zona pellucida. After all, most mammalian cells are enveloped by an extracellular matrix that is significantly more complex, incorporating many different proteins. Yet subsequently our findings were supported by reports that the zonae pellucidae of all mammals under study, including human beings, also consist of just a few glycoproteins.

The simplicity pointed us in another



MANY SPERM can bind to and penetrate the zona pellucida, or outer coat, of an unfertilized mouse egg, but only one sperm will eventually fuse with the thin plasma membrane surrounding the egg proper (*inner sphere*), fertilizing the egg and giving rise to a new embryo. Recent studies of mice have begun to elucidate the molecular mechanisms underlying the fertilization pathway in mammals. The sperm and the egg are enlarged about 1,000 diameters in this micrograph made by the author.

direction. Presumably one of the three zona pellucida glycoproteins in the mouse was the sperm receptor, and we could identify it. First, however, we had to demonstrate that the zona pellucida did in fact contain sperm receptors.

We turned to what is called a competition assay. We isolated zonae pellucidae from unfertilized eggs and dissolved the material in a mildly acidic solution so that all the glycoproteins from each coat, not just those at the outer surface, would be free to interact with sperm. We then neutralized the zona pellucida solution and added it to mouse sperm in a laboratory dish, after which we removed the sperm and incubated them with unfertilized mouse eggs under conditions known to support both in vitro fertilization and development.

We assumed that if the zona pellucida solution contained sperm receptors, those receptors and the egg-binding proteins on the sperm would find each other and bind, forming complexes. The formation of the complexes would then prevent the egg-binding proteins from interacting with the zonae pellucidae of unfertilized eggs in the last step of the assay, and hence the treated sperm would fail to bind to and fertilize the eggs. In other words, the solubilized, free receptors would compete successfully with sperm receptors on eggs. On the other hand, if the solution contained no receptors, sperm would not be affected by treatment with the zona pellucida solution and would bind to and fertilize eggs normally.

We found the treated sperm could not bind to or fertilize eggs, demonstrating that the zona pellucida of the mouse egg does indeed contain sperm receptors. On the other hand, solubilized zona pellucida preparations taken not from unfertilized eggs but from one-cell embryos did not interfere with either binding or fertilization, indicating that the coats of the embryos lacked competent sperm receptors. This latter finding was consistent with the fact that sperm cannot bind to and penetrate the coat of a fertilized egg (a one-cell embryo). It also suggested that at least part of the reason the zona pellucida becomes refractory to sperm after fertilization is that fertilization leads to a modification of the egg's sperm receptors—a modification that destroys the receptors' binding capability.

Satisfied that the zona pellucida contains sperm receptors, we sought to learn which of the three zona pellucida glycoproteins serves as the receptor and what changes in the receptor render it unable to recognize sperm. Quite soon we were able to answer the first question. We purified ZP1, ZP2 and ZP3 from both unfertilized eggs and one-cell embryos and tested each of them in the competition assay. The assay showed that binding of sperm to eggs was inhibited only when sperm were treated with ZP3 purified from egg zonae pellucidae. Neither ZP1 nor ZP2 from either eggs or embryos had any effect, nor did ZP3 from embryos. Moreover, purified egg ZP3 was just as effective as egg zona pellucida preparations at inhibiting binding, indicating that ZP3 had been responsible for inhibiting binding in the original competition assays. ZP3 appeared to be the sperm receptor.

When we compared ZP3 from unfertilized eggs with embryo ZP3 by gel electrophoresis, we found that the two molecules—one an active receptor and the other inactive—were indistinguishable. Clearly some subtle chemical change accounted for the receptor's inactivation after fertilization. We would have to learn more about the composition of the receptor before we could begin to understand how the inactivation was accomplished.

That would take some time. Meanwhile we continued several other pursuits. These included gathering additional evidence that egg ZP3 was the sperm receptor. We also wanted to determine whether ZP3 played a role in the acrosome reaction. In one study to evaluate ZP3's role as a receptor we took advantage of discoveries made in our own laboratory at Harvard as well as by Bayard T. Storey and his colleagues at the University of Pennsylvania: only sperm with an intact acrosome can bind to the egg's outer coat and only acrosome-reacted sperm can accomplish the next step, penetration of the coat.

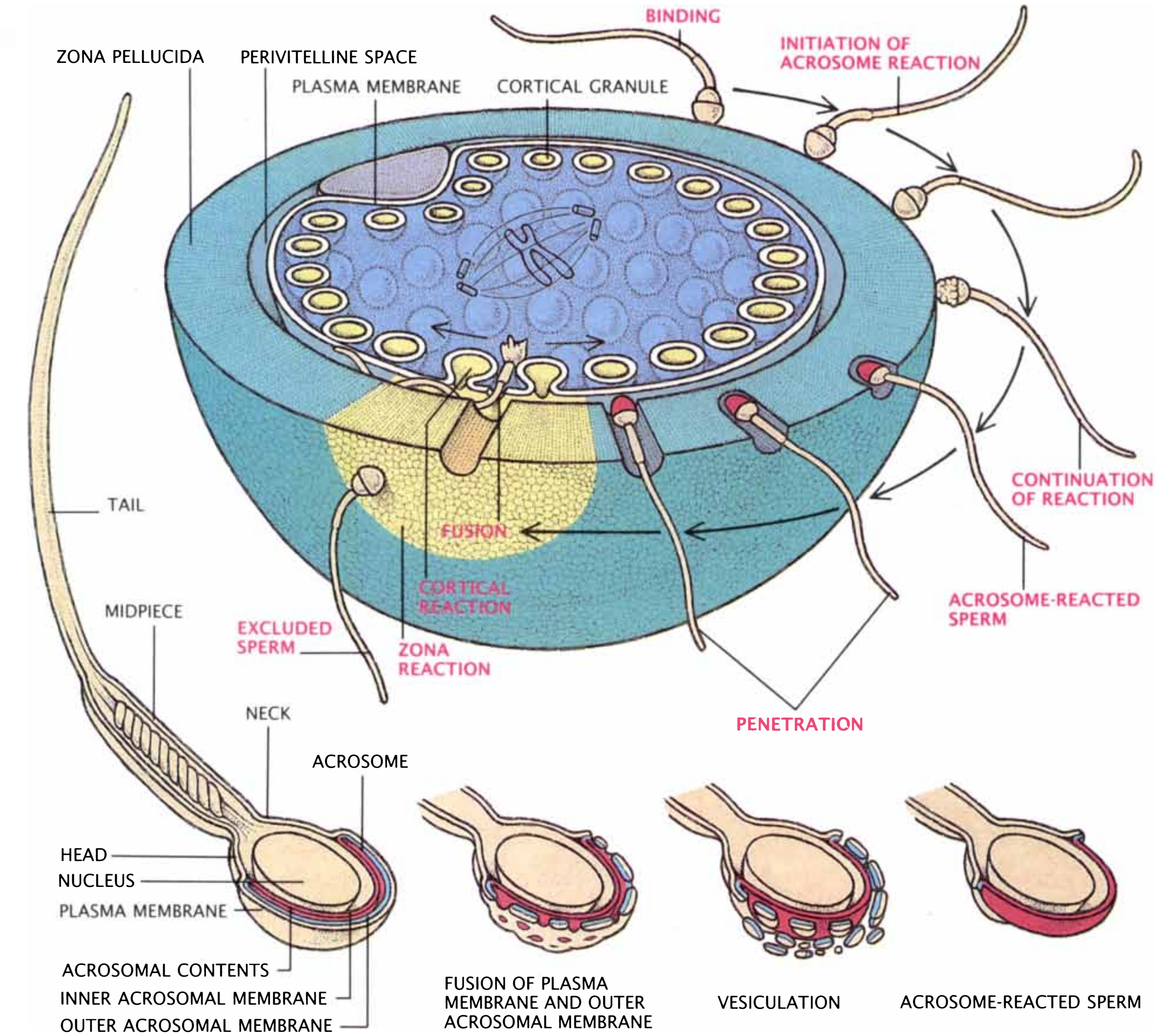
The discoveries allowed us to assume that if ZP3 was a sperm receptor, it would recognize only acrosome-intact, and not acrosome-reacted, sperm when mixed with sperm in a laboratory dish. It would also recognize only the sperm head, where binding to the zona pellucida takes place; it would not recognize the sperm's midpiece or tail.

We evaluated the ability of ZP3 to discriminate between acrosome-intact and acrosome-reacted sperm and between different regions of the sperm by means of autoradiography. We labeled purified ZP3 with a radioactive isotope and then recorded the molecule's radioactive emissions on film. The resulting autoradiographs indicated that the labeled ZP3 behaved as expected, binding only to acrosome-intact sperm and only to the sperm head. These experiments also enabled us to estimate that each acrosome-intact sperm could bind some 10,000 to 50,000 ZP3 molecules. In view of the fact that mammalian sperm are highly motile, this suggested that tens of thousands of receptors in the intact zona pellucida are necessary to bind each sperm cell firmly to the surface of the zona pellucida.

Bleil and I also collaborated in elucidating the mechanism by which the acrosome reaction is induced. It was entirely possible that a zona pellucida glycoprotein other than ZP3, that is, ZP1 or ZP2, might induce the reaction after the initial binding of sperm to ZP3 takes place. We therefore combined acrosome-intact sperm with each of the zona pellucida glycoproteins from mouse eggs and observed the effect on sperm. Only ZP3 purified from egg zonae pellucidae proved able to induce the acrosome reaction in vitro, indicating that it is the natural inducer. ZP1 and ZP2 from either eggs or embryos did not induce the reaction, nor did ZP3 from embryos. Apparently ZP3 loses its ability to induce the acrosome reaction after the egg is fertilized, just as it loses the ability to bind sperm. Exactly how binding of sperm to ZP3 induces the acrosome reaction is still not clear. Some evidence supports the possibility that binding renders the sperm's plasma membrane more permeable to calcium ions, and that such a change might facilitate fusion of the plasma and acrosomal membranes.

The discovery that ZP3 has two important functions—sperm binding and induction of the acrosome reaction—came as a pleasant surprise. The situation is quite different in sea urchins and other marine invertebrates, which divide the functions between two distinct molecules. The eggs of these organisms have two outer coats: a thick, jellylike outer layer and a much thinner inner layer, the vitelline envelope. A carbohydrate molecule in the jelly coat induces the acrosome reaction, whereas a glycoprotein in the vitelline envelope is responsible for species-specific binding.

Knowing that ZP3 could bind to sperm and induce the acrosome reaction did not explain how it did so. That became another major pursuit, although my colleagues and I also wanted to learn more about the distri-



FERTILIZATION PATHWAY includes a succession of steps. After a sperm cell binds to the zona pellucida, what is called the acrosome reaction takes place (*see detail at bottom*). The outer membrane (*light blue*) of the acrosome, an enzyme-rich organelle in the anterior of the sperm head, fuses at many points with the plasma membrane surrounding the sperm head. Then those fused membranes form vesicles, which are eventually sloughed off from the head, exposing the acrosomal enzymes (*red*). The enzymes digest a path through the zona pellucida, enabling the sperm to advance. Eventually the sperm meets and fuses with the egg's plasma membrane, fertilizing the egg. Completion of the pathway triggers the cortical and zona reactions. First enzyme-rich cortical granules in the egg's cytoplasm release their contents (*yellow*) into the zona pellucida, starting at the point of fusion and progressing right and left. Next, in the zona reaction, the enzymes modify the zona pellucida, transforming it into an impenetrable barrier to sperm as a guard against polyspermy (multiple fertilization).

bution of ZP3 in the zona pellucida. In particular we wanted to determine whether the surface of the coat displayed enough ZP3 molecules to make possible the tens of thousands of interactions we thought were necessary to hold each sperm in place.

Jeffrey M. Greve, then a postdoctoral fellow in my laboratory at Harvard, and I established that the zona pellucida consists of long, interconnected filaments, each about seven nanometers (millionths of a millimeter) wide. Later, at the Roche Institute of Molecular Biology in Nutley, N.J., Greve and I determined that the fundamental building block of the filaments is a unit composed of one ZP2 and one ZP3 molecule, and that this unit is repeated as often as hundreds of times in every filament. The zona pellucida filaments are connected to one another by ZP1, which consists of two identical polypeptide chains joined by intermolecular disulfide bonds. This filamentous architecture places tens of millions of ZP3 molecules at the surface of the zona pellucida, more than enough to tenaciously bind an army of sperm cells.

Investigation into the molecular interactions that enable ZP3 to bind to sperm and initiate the acrosome reaction began with a preliminary analysis of the molecule's chemical makeup. These studies were carried out in my laboratory at Harvard by Greve and two of my graduate students, Richard J. Roller and George S. Salzmann. The work could not immediately distinguish between features that are important to receptor function and those that are not, but it gave us a firm basis for further studies.

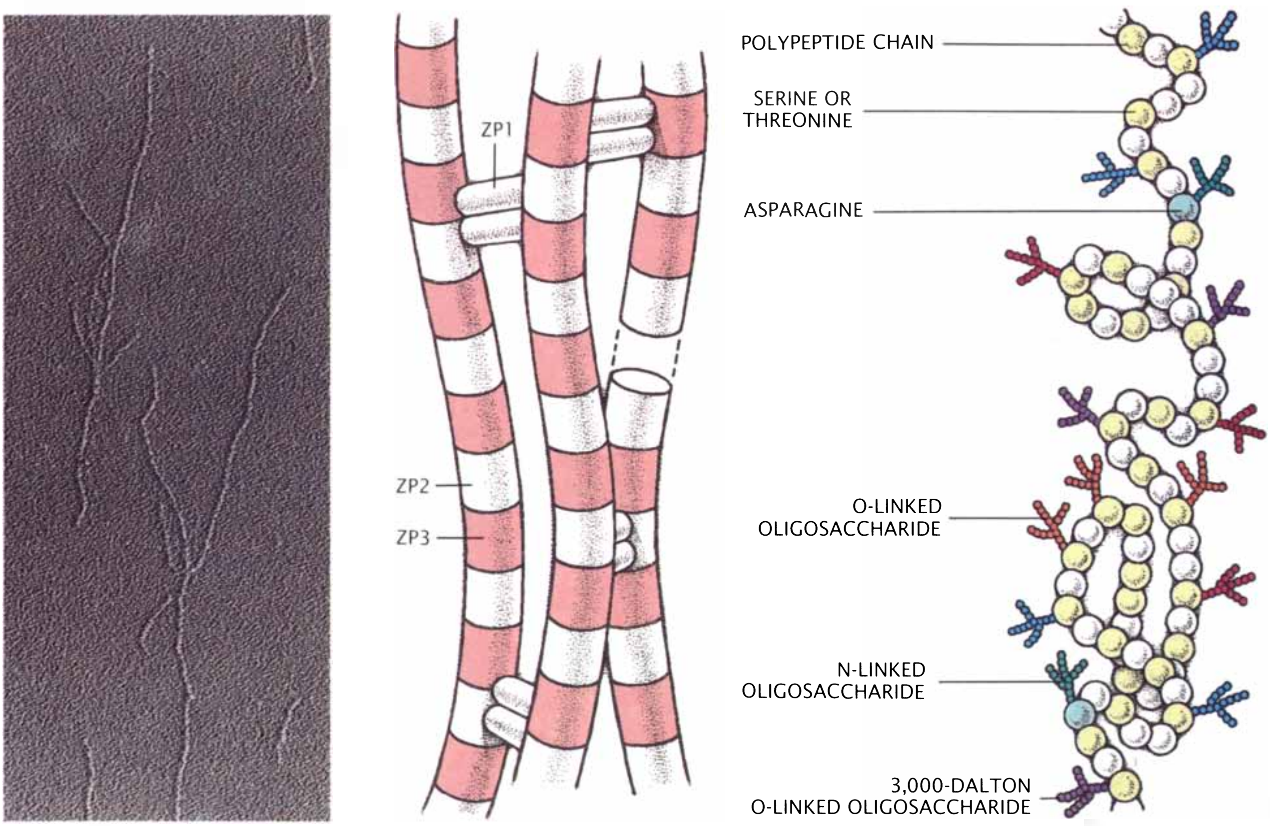
We learned that ZP3's polypeptide chain consists of some 400 amino acids. Extending from the polypeptide are many branches of oligosaccharides, short chains of simple sugars. Three or four are N-linked oligosaccharides, meaning that they are linked to a nitrogen atom on the amino acid asparagine. An undetermined but relatively large number are O-linked oligosaccharides, linked to an oxygen atom on one of two amino acids: serine or threonine. The oligosaccharides appear to come in many varieties, and not every ZP3 molecule has the same sequence of sugar chains.

Shortly after Harvey M. Florman joined my laboratory at Harvard as a postdoctoral fellow, we set out to determine whether the polypeptide chain or the oligosaccharides, or both, are responsible for ZP3's sperm-receptor activity. In many examples of receptor interactions the three-dimensional structure of the receptor, which is often a protein, is critical to its ability to bind a complementary protein. We did not know the conformation of ZP3 but we did know how to alter it, and in so doing could determine whether the shape of ZP3 was important for its ability to interact with the egg-binding protein on mouse sperm.

We found that exposing ZP3 to agents that unfolded its polypeptide backbone did not influence sperm binding, implying that ZP3's conformation is not an important factor in this instance. To confirm this, we cut up ZP3 molecules into small glycopeptides with pronase, an enzyme quite indiscriminate in its choice of cleavage sites. We then returned to our competition assay, mixing sperm with the entire collection of glycopeptides and exposing the treated sperm to unfertilized eggs. The small glycopeptides were as effective as intact ZP3 in preventing binding of sperm to eggs, a result that virtually eliminated the possibility that a specific conformation is required for ZP3's sperm-receptor activity.

The fact that ZP3's conformation was not important for sperm binding indicated that the polypeptide chain probably did not provide the binding site. To confirm this, we exposed ZP3 to trifluoromethanesulfonic acid, a reagent that removes both N- and O-linked oligosaccharides from the polypeptide, and then tested the denuded chain for sperm-receptor activity in the competition assay. As expected, exposure of sperm to the protein alone had no effect on the binding of sperm to eggs: the polypeptide itself had no detectable sperm-receptor activity.

In similar tests we removed just the N-linked oligosaccharides from ZP3 by means of the enzyme endoglycosidase F, leaving the O-linked sugar chains in place. This modified form of ZP3 did retain sperm-receptor activity. The finding strongly implicated O-linked oligosaccharides as the part of ZP3 that was most important in the binding of mouse sperm to zonae pellucidae. When we removed just the O-linked oligosaccharides with a mild alkali, on the other hand, the altered molecule showed no sperm-receptor



MOLECULE KNOWN AS ZP3 is a major component of the filaments (*left*) that associate to form the zona pellucida. ZP3 is a glycoprotein: a polypeptide to which sugar groups are attached. It combines with another glycoprotein, ZP2, to form the basic building block of the filaments, which are drawn highly schematically at the center; a third glycoprotein, ZP1, links the filaments. ZP3, shown in detail at the right, is the receptor molecule that binds sperm; it also induces the acrosome reaction. The actual binding elements are a subset of the sugar chains radiating from ZP3's polypeptide backbone; they are the O-linked oligosaccharides (those attached to the amino acids serine and threonine) with a molecular weight of about 3,900 daltons. The same sugar chains appear to collaborate with the polypeptide in ZP3 to induce the acrosome reaction.

activity. Moreover, exposure of sperm to minute concentrations of just the O-linked sugar chains—released from ZP3—prevented both the binding of sperm to eggs and fertilization. Collectively these results demonstrated that O-linked oligosaccharides are indeed the sperm-binding elements of the ZP3 molecule.

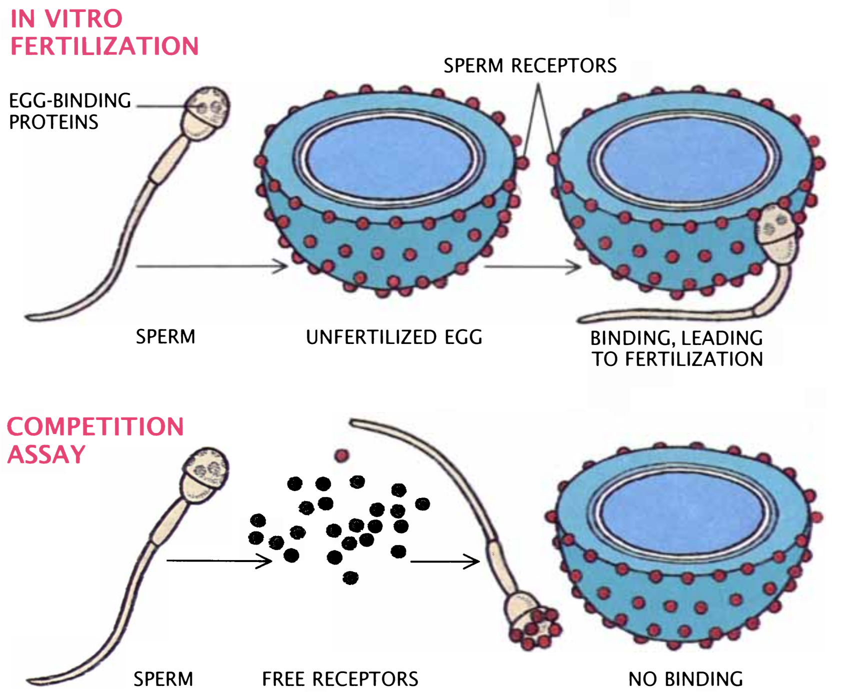
Not all ZP3's O-linked oligosaccharides exhibit sperm receptor activity, however. Studies in which we separated the sugar chains on the basis of size and mixed them with sperm, as well as studies in which we mixed sperm with the full complement of O-linked sugar chains released from ZP3 and then looked to see which oligosaccharides bound to the sperm, have all shown that fewer than 10 percent of the O-linked oligosaccharides on ZP3 can bind to sperm. The ones that bind are those with a molecular weight of about 3,900 daltons.

The finding that O-linked sugars are involved in sperm-egg recognition in mice adds to a growing body of data indicating that sugars are important in gamete recognition, as well as in other types of cell-to-cell interactions, not only in vertebrates but also in invertebrates and plants. For instance, sugars are crucial to the species-specific binding of sperm to the eggs of marine invertebrates and to the induction of the acrosome reaction. There is also evidence that sugars play a fundamental role in the gamete interactions of the marine invertebrate *Ciona intestinalis* and the brown alga *Fucus serratus.*

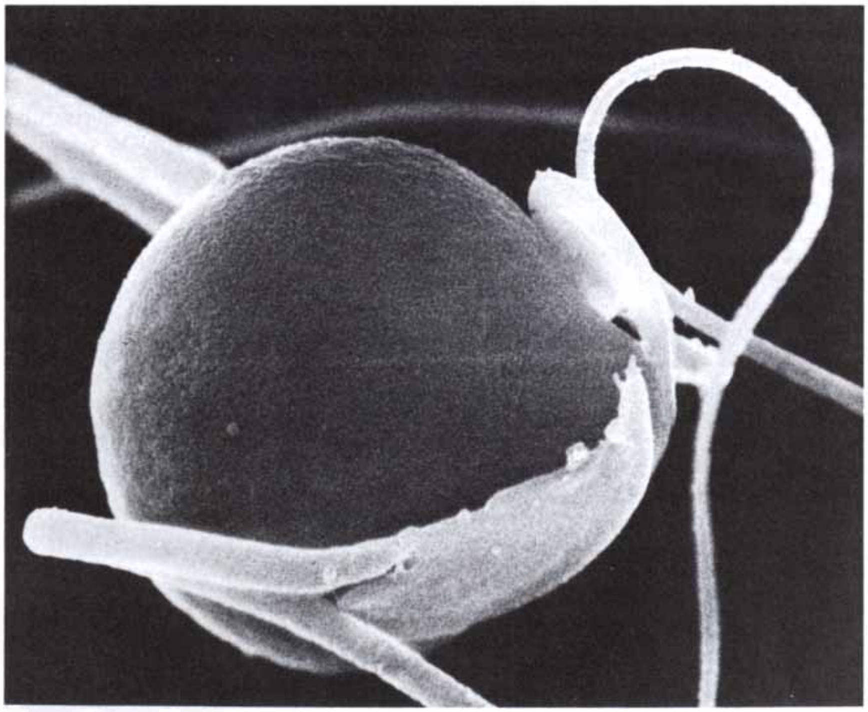
Since we knew that binding of ZP3 to the sperm head induces the acrosome reaction, we went on to examine the role of the ZP3 polypeptide chain and its oligosaccharides in that process. Florman and I began by enzymatically degrading ZP3 into glycopeptides ranging in molecular weight from about 1,500 to 70,000 daltons and adding glycopeptides of various sizes to sperm in vitro.

Glycopeptides that were larger than about 40,000 daltons induced the acrosome reaction but smaller ones did not (although in our earlier experiments small glycopeptides were able to bind to mouse sperm). O-linked oligosaccharides released from purified egg ZP3 also failed to trigger the acrosome reaction.

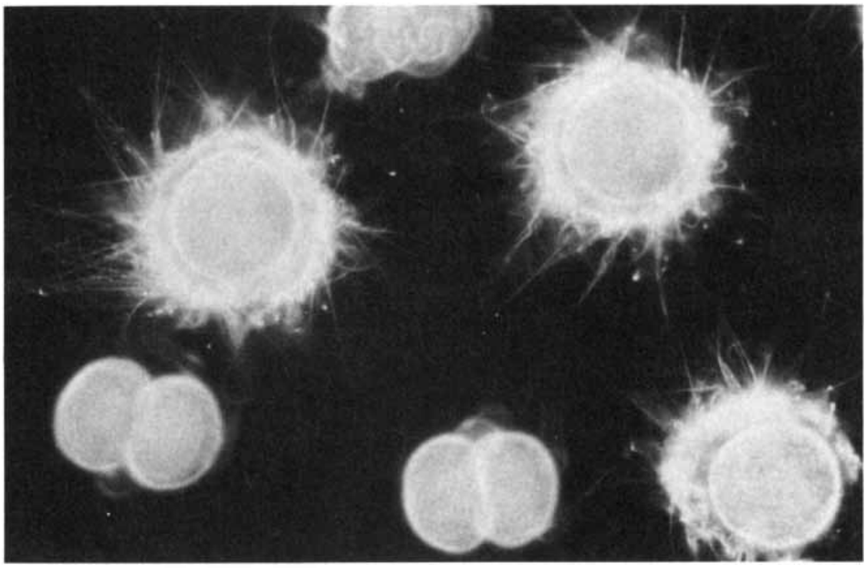
These observations and others suggest that whereas only O-linked oligosaccharides on ZP3 are needed to bind sperm to eggs, relatively long stretches of the molecule's polypeptide chain are needed to induce the acrosome



COMPETITION ASSAY helped to demonstrate that ZP3 in the zona pellucida is the sperm receptor in mice. When sperm are exposed to unfertilized eggs in a laboratory dish (*top*), egg-binding proteins on the sperm bind to sperm receptors on the eggs, and fertilization ensues. In the competition assay (*bottom*) the sperm are first incubated with putative sperm receptors. If receptors are present, the sperm bind to them; because the egg-binding proteins are now blocked, the sperm can no longer bind to and fertilize eggs. If no receptors are present, the sperm are not affected and fertilize eggs normally. In the competition assay ZP3 isolated from unfertilized eggs—but not ZP1 or ZP2—prevented sperm from interacting with mouse eggs.



SPERM bind tightly to a glass bead that is coated with ZP3 from a mouse egg. This finding, combined with the finding that neither ZP1, ZP2 nor other glycoproteins elicit such binding, provides more evidence that ZP3 is the sperm receptor in mice. The scanning electron micrograph was made by David M. Phillips of the Population Council with material prepared by Monica H. Vazquez of the author's laboratory.



EFFECT OF ZONA REACTION becomes dramatically clear in this dark-field photomicrograph made by the author. Sperm bind to unfertilized eggs (*starbursts*) but not to two-cell embryos. ZP3 may well be involved in the zona reaction. Cortical enzymes released into the zona pellucida apparently alter the ZP3 molecule in such a way that the former receptor now shuts out sperm instead of drawing them in.

reaction. Whether the polypeptide chain itself interacts directly with bound sperm is not yet clear; it may instead merely serve as a backbone enabling some required number of properly spaced O-linked oligosaccharides on the ZP3 molecule to interact with sperm.

Having gained some insight into how ZP3 binds to sperm and causes the acrosome reaction, we returned to the question of why ZP3 loses those abilities once eggs are fertilized. Not all the changes that take place in the zona pellucida after fertilization are understood, but the changes are known to be a consequence of the so-called cortical reaction, which immediately follows the fusion of sperm and egg and immediately precedes the zona reaction. In mice the cortical reaction involves the fusion of the egg's plasma membrane with the membrane surrounding each of 4,000 or so enzyme-rich organelles, called cortical granules, lying just under the plasma membrane. The reaction causes the granules to release their enzymes into the perivitelline space, from which they seep into the zona pellucida.

Might those enzymes alter the zona pellucida's constituent glycoproteins? Some evidence from work with hamster gametes suggests that the molecule of most interest to us, ZP3, is indeed altered by cortical-granule enzymes. Ryuzo Yanagimachi and his colleagues at the University of Hawaii at Manoa found that hamster sperm failed to bind to the zona pellucida of eggs exposed to cortical-granule enzymes. It is likely that much the same thing occurs in mice, that ZP3 is rendered inactive as a sperm receptor by a cortical-granule enzyme. In view of the primary role of ZP3's O-linked oligosaccharides in sperm binding, the possibility exists that a cortical-granule enzyme acts specifically on those oligosaccharides to render them unrecognizable to sperm. In support of this idea, my colleagues and I have recently found that removal or modification of certain sugars at the end of the 3,900-dalton O-linked oligosaccharides—something cortical-granule enzymes could probably do—destroys their receptor activity.

Although many questions about the molecular basis of mammalian fertilization have been answered recently, others will keep biologists busy in the future. Tools are becoming available with which to address the unanswered questions. For example, within the past year the gene encoding ZP3 has been cloned by Ross A. Kinloch, a postdoctoral fellow in my laboratory at Roche, as well as by Jurrien Dean and his colleagues at the National Institutes of Health. The availability of such clones enhances the likelihood that the DNA sequences and the cellular factors regulating production of the sperm receptor during oogenesis can soon be identified. In addition the entire sequence of amino acids in the ZP3 polypeptide chain has been determined, both in my laboratory and in Dean's. This information should facilitate identification of the specific regions of ZP3 involved in sperm-receptor activity, induction of the acrosome reaction and the assembly of zona pellucida filaments.

We and other investigators are attempting to isolate the cortical-granule enzymes that apparently catalyze the zona reaction; we are also attempting to isolate the egg-binding protein on sperm that recognizes ZP3's O-linked oligosaccharides, and to determine the sugar sequence of the 3,900-dalton O-linked oligosaccharides on ZP3 that are recognized by sperm. Finally, we hope to extend our studies to human fertilization, analyzing it in as much molecular detail as we have analyzed mouse fertilization. Molecular studies of human fertilization could lead to new methods of contraception that interfere with the binding of sperm receptors to egg-binding proteins. They could also lead to new therapies for forms of infertility in which molecular abnormalities in the sperm or egg are a factor.

Studies of fertilization in mice and other animals should also yield even broader knowledge. The interactions that take place between sperm and egg constitute only a fraction of the interactions occurring between cells in the course of animal development, albeit a most crucial fraction, given that sperm-egg interactions initiate development. The ongoing research into these early interactions will undoubtedly lead one day to important new insights into cellular interactions in general and in turn to life-enriching applications in medicine and other fields.

FURTHER READING

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Soft-X-Ray Lasers

A quarter of a century after the appearance of the optical laser, experimental X-ray lasers have begun to produce beams with wavelengths 100 times shorter than those of visible light

by Dennis L. Matthews and Mordecai D. Rosen

In the almost 30 years since their invention, lasers have become commonplace in our society. These devices, which produce highly concentrated light of a single wavelength, are the critical components of such diverse systems as inertial-guidance platforms in jetliners, precision scalpels for surgeons, bar-code readers at supermarkets, compact-disc players and laser printers.

The development of the laser has been marked by a progression toward successively shorter wavelengths. The first lasers, built in the middle 1950's, were strictly speaking masers, which generated not visible light but electromagnetic radiation of a much longer wavelength: microwaves. A typical maser might emit a microwave beam with a wavelength of five centimeters, somewhat shorter than ultrahigh-frequency television signals. By 1960 the laser itself came into existence. An optical laser typically emits a beam of visible light with a wavelength of about 500 nanometers (one nanometer is a billionth of a meter), a reduction in wavelength by a factor of 100,000 from the maser.

DENNIS L. MATTHEWS and MORDECAI D. ROSEN helped to pioneer the development of soft-X-ray lasers. Matthews received a Ph.D. in experimental physics from the University of Texas at Austin in 1974. Since then he has been employed at the Lawrence Livermore National Laboratory (LLNL) and is currently a group leader for Soft-X-Ray Laser Development and Application. Rosen received his Ph.D. in plasma physics from Princeton University in 1976. He then joined the LLNL as a target designer in the inertial confinement (laser fusion) program. He is at present associate division leader for laser target design and is coholder of the patent for the soft-X-ray laser. The LLNL soft-X-ray team was awarded the U.S. Department of Energy Award for Research Excellence for the demonstration of the world's first soft-X-ray laser.

One of the elusive dreams of laser physicists has been the development of an X-ray laser. Like microwaves, X rays differ from visible photons only in their wavelength. X rays occupy the region of the electromagnetic spectrum between roughly 10 nanometers and .01 nanometer. The longer wavelengths are referred to as "soft" because photons at such wavelengths are unable to penetrate air or living tissue. Shorter wavelengths, such as those of about .03 nanometer used by dentists, are referred to as "hard" because of their penetrating ability.

After 25 years of waiting, the X-ray laser has at last entered the scientific scene, although those now in operation are still laboratory prototypes. They produce soft X rays down to about five nanometers, or 100 times as short as optical wavelengths; eventually investigators may be able to coax X rays as short as two nanometers from such devices.

Such short-wavelength lasers may have a multitude of applications. Chief among them might be the creation of holograms of microscopic biological structures too small to be investigated with visible light. Such holograms would allow biologists to visualize for the first time the three-dimensional structure of key proteins and the hierarchical twistings that transform DNA from its basic double helix into the compact structure of chromosomes.

X-ray lasers retain the usual characteristics of their optical counterparts: a very tight beam, spatial and temporal coherence (meaning that the X rays travel in phase with one another) and extreme brightness, or intensity. Present X-ray lasers are, for example, nearly 100 million times brighter than the next most powerful X-ray source in the world: the electron synchrotron.

In principle the only difference between an optical laser and an X-ray laser is that the latter produces photons of much shorter wavelength. This single difference, however, makes it extremely difficult to construct such a device, and in fact the first successful X-ray laser was built only in 1984 at the Lawrence Livermore National Laboratory (LLNL). The complications are a direct result of quantum mechanics, which states that the wavelength of a photon is inversely proportional to its energy: the shorter the wavelength of a photon, the higher its energy. Higher energies make it much harder to achieve the fundamental ingredient of any laser: a population inversion in the lasing material.

To understand how a population inversion is brought about, consider the common helium-neon lasers of supermarket bar-code readers. In these lasers a high-voltage electric current excites, or pumps, an electron in an atom of the helium-neon gas from its ground state to a higher energy level. After a characteristic time the electron decays spontaneously to a lower orbit. In the process it emits a photon whose energy corresponds to the energy difference between the two orbits [*see illustration on page 88*].

Some photons emitted in this way will encounter other excited atoms and stimulate the decay of their excited electrons to the lower energy level. During this stimulated decay each atom will emit a photon; assuming all the transitions take place between the same two energy levels, all the photons will have the same energy and consequently the same wavelength. Quantum mechanics also shows that they will be emitted in the same direction and in phase with the incoming photons. The process is repeated as the photons are reflected back and forth between mirrors until an avalanche of photons is created, all at the same wavelength, all traveling in the same direction and all in phase. Hence the acronym "laser": light amplification by stimulated emission of radiation.

Lasing cannot be achieved, however, unless a majority of atoms have more electrons in the excited state than in the ground state; this configuration is known as a population inversion. A population inversion is difficult to arrange because (according to one of the basic results of statistical mechanics) in the usual state of thermal equilibrium more electrons occupy lower energy levels than occupy higher energy levels. Electrons in high energy levels tend to decay quickly to achieve this equilibrium. If there are more atoms with electrons in the ground state than there are atoms with electrons in the excited states, more photons are absorbed than are emitted and lasing does not take place. For a robust inversion one must therefore pump the electrons into the excited states at a rate faster than the rate at which they fall down.

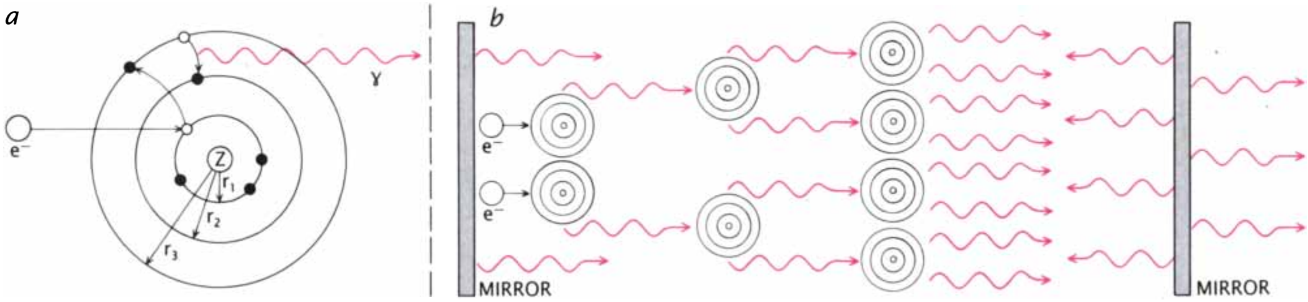
The energy of the emitted photon is equal to the energy lost by the electron when it falls from a high energy level to a lower one. Therefore if soft-X-ray photons are 100 times more energetic than optical photons, then at least 100 times as much energy must be pumped into an X-ray laser to excite the electrons to the desired levels. The energy-level differences in helium-neon and other materials employed in optical lasers are generally too small for high-energy photons to be emitted in electron transitions. At the LLNL we have chosen to solve the problem by going to elements of high atomic number, that is, elements containing large numbers of protons. Then the electrical attraction due to the increased number of protons in the nucleus strongly binds the innermost electrons to the nucleus. Much energy is needed to excite these electrons; conversely, high-energy photons are emitted when the electrons decay.

Going to high atomic numbers is not in itself sufficient. The neutral uranium atom, for example, although it has the highest atomic number of any naturally occurring element, would not be a suitable lasing material for an X-ray laser. Many of uranium's 92 electrons are not tightly bound to the nucleus, because the attractive, positive charge of the proton-rich nucleus is effectively screened, or canceled, by the negative charge of the innermost electrons. Indeed, the effective atomic number, or charge, of the uranium nucleus is close to zero. Consequently one generally needs to begin by ionizing the lasing substance—stripping it of its outer electrons. This decreases the amount of screening, increases the effective electric charge of the nucleus (designated by Z) and thus allows the remaining electrons to be more tightly bound.

To make an atom with an effective charge of about zero into a "high-charge ion" with an effective charge Z in this way, it is necessary to strip away a number of outer electrons equal to about Z. Now, the transition energies in the simplest atomic model, as well as the energy required to strip an outer electron, are proportional to Z^2. The demand that the emitted photons be about 100 times as energetic as optical photons then requires, in the LLNL scheme, elements with a Z about 10 times as large as those of the elements employed in optical lasers. This in turn means that to strip the outer electrons one must supply an X-ray laser with about 1,000 times the energy needed for an optical laser: 100 times the energy for each electron, multiplied by a factor of 10 for the number of outer electrons that are to be stripped.

Moreover, it turns out that the rate at which electrons spontaneously decay to lower energy levels is propor-

NOVA LASER at the Lawrence Livermore National Laboratory is the world's most powerful optical laser. It can deliver 100,000 joules of energy in less than one-billionth of a second, a 10^{14}-watt pulse. Two of Nova's 10 beams serve as the energy source for X-ray lasers, which require about 1,000 times the pump energy of optical lasers, delivered about 10,000 times as fast.



ALL LASERS operate by stimulated emission, illustrated by the Bohr atom. Pump energy (here high-energy electrons) from an external source excites electrons in the atom from a lower-energy orbit (r_1) to a higher-energy orbit (r_3). The electron decays spontaneously to an intermediate orbit (r_2) and emits a photon (*wavy line*) whose energy equals the energy difference between the two orbits. The photon strikes an atom (*right*) whose electrons are already excited and stimulates one electron to jump to the lower-energy state, emitting a second photon that travels in the same direction as the first and in phase with it. The process is repeated until the resulting cascade of photons passes through the mirror as a coherent laser beam.

tional to Z^4. Therefore to achieve a robust population inversion in soft-X-ray lasers one not only must supply 1,000 times as much energy as for an optical laser but also must supply it roughly 10,000 times as fast. To do this, high-power optical lasers are employed as pumps. At the LLNL the pumps are two beams of the 10-beam Nova, the world's most powerful laser [see "Progress in Laser Fusion," by R. Stephen Craxton, Robert L. McCrory and John M. Soures; SCIENTIFIC AMERICAN, August, 1986], which is capable of delivering up to 10^{14} watts in a pulse of less than a nanosecond.

These lasers were originally developed for the LLNL's ongoing laser-fusion program, whose ultimate goal is to provide a virtually limitless energy source through nuclear fusion. Although the LLNL is widely known for its hard-X-ray laser program, in which the pump energy is supplied by nuclear explosives and which has potential applications in the Strategic Defense Initiative (the "Star Wars" program), soft-X-ray lasers have no direct military applications. These lasers, and the scientific tools that result from their development, may one day have a place in the design and diagnosis of both laser fusion and hard-X-ray lasers, but the work we shall discuss here is entirely unclassified.

In the X-ray lasers now operating at the LLNL, the Nova beam strikes a thin foil of, say, selenium, yttrium or molybdenum. These elements (whose choice was first suggested by Peter L. Hagelstein, now at the Massachusetts Institute of Technology) are normally solids, but their atoms can be ionized in the way we described above. In fact, when the Nova beam strikes the foils, it vaporizes them completely and creates a plasma in which, for example, selenium atoms (with 34 electrons) are stripped of their outer 24 electrons. The electrons freed by the intense Nova beam are of high energy—1,000 electron volts (1 keV) or, equivalently, a temperature of 10 million degrees Kelvin. They travel through the plasma and, colliding with the selenium ions of the plasma, excite one of the remaining inner 10 electrons to the desired energy levels. Such an excitation scheme, referred to as collisional excitation, was proposed more than two decades ago by Raymond C. Elton of the Naval Research Laboratory and Michel A. Duguay of the AT&T Bell Laboratories.

In more detail, the inner electrons in the selenium ions are in a ground state, which is conventionally labeled $1s^2 2s^2 2p^6$, or $2p$ for short [*see illustration on opposite page*]. (The letters *s* and *p* refer to atomic orbitals whose orbital angular momentum quantum numbers are 0 and 1 respectively. The numbers preceding them refer to the energy levels given by the principal quantum number *n;* the superscripts refer to the number of electrons in each level.) Collisions with the energetic free electrons excite $2p$ electrons in some of the ions to the energy level 1.5 keV higher, labeled $1s^2 2s^2 2p^5 3s$ ($3s$), or to the still higher level labeled $1s^2 2s^2 2p^5 3p$ ($3p$). (In a plasma of average energy 1 keV there are many electrons with an energy greater than 1.5 keV capable of such excitation.)

Normally one would expect the $3s$ level to be filled with electrons before the $3p$ level because it is at a lower energy. Electrons in the $3s$ state, however, decay very rapidly back to the $2p$ ground state. Such a decay process is quantum-mechanically forbidden to electrons in the $3p$ state, which therefore remain at that level for a long time. Typically 96 percent of the ions will have electrons in the $2p$ state, 3 percent will have electrons in the $3p$ state and 1 percent will have electrons in the $3s$ state. Thus a population inversion is created between the $3p$ and $3s$ states. Transitions are allowed between these two states, and when the electrons in the $3p$ level finally decay spontaneously to the $3s$ level, a 20-nanometer soft-X-ray photon is emitted. It is these photons that initiate the lasing action by stimulating other similarly excited ions to emit photons at this wavelength.

Once photons of the required wavelength are produced, they must be amplified. Amplification of the beam in an optical laser is achieved by reflecting the photons back and forth between two mirrors. Only photons that are traveling along the laser axis are reflected and become part of the amplification process; photons that are not reflected quickly pass out of the beam (a fact that also explains why a laser beam is so tightly collimated). Mirrors that are nearly 100 percent reflective in the X-ray spectrum, however, do not exist. Workers have therefore been forced to develop other techniques for achieving X-ray amplification.

At the LLNL the selenium foil is actually a layer about 75 nanometers thick, several millimeters wide and several centimeters long, which is deposited on a vinyl substrate to give it rigidity. Special lenses focus the Nova beam to a line of about the same length but .1 millimeter wide. When such a line-focused light pulse from Nova strikes the selenium target, the thin selenium foil is heated throughout, explodes and forms a cylindrically shaped plasma about .1 millimeter in diameter and several hundred times that in length. The cylindrical shape provides a preferred axis for X-ray amplification: photons traveling radially pass out of the plasma, whereas photons traveling along the axis stimulate the emission of other X rays. Since there are no mirrors, the amplification takes place on only a single pass.

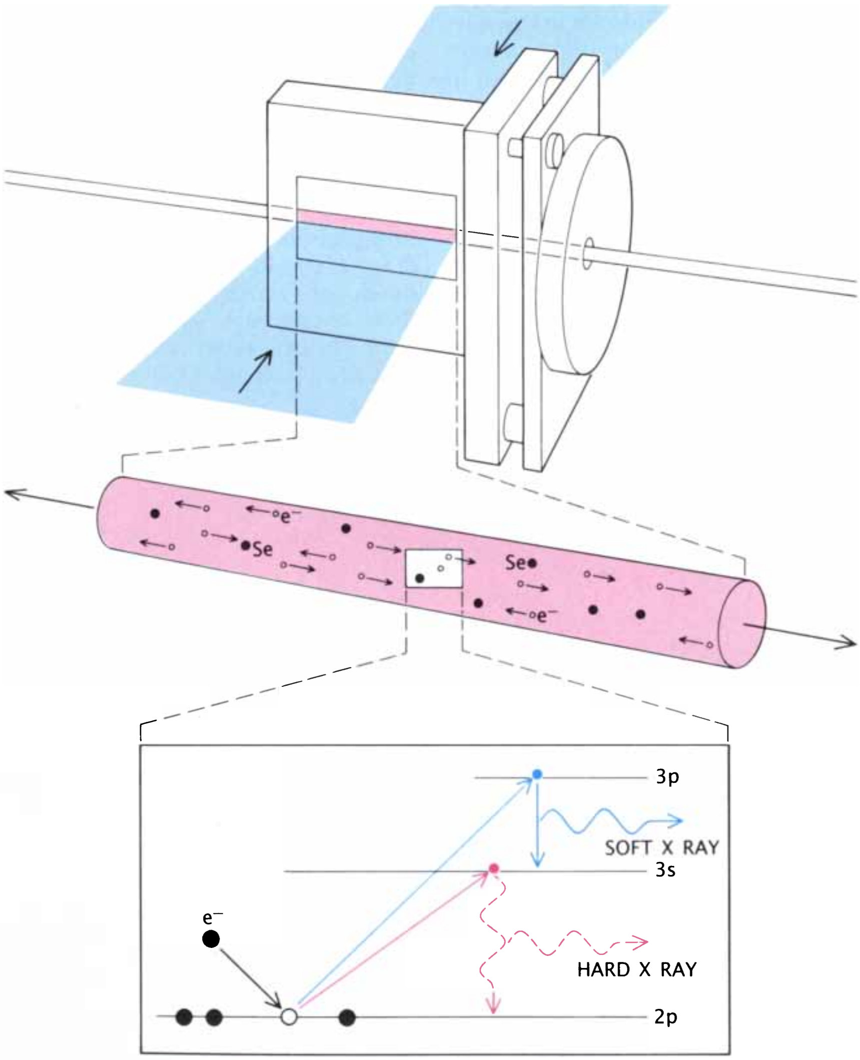
Proving that lasing even occurs in such a device is not a trivial task and, as we mentioned above, the first experiments were successfully carried out only in 1984 at the LLNL Three important observations showed that lasing took place. First, we found in the emitted X-ray beam certain spectral lines that were brighter than other lines, which indicated that the appropriate atomic transitions were taking place. Second, we found lines whose emission was much stronger along the beam axis than in other directions. Third and most important, we measured the variation of the X-ray intensity with the length of the target. If lasing is taking place, the number of photons that enter the avalanche should grow exponentially with the length of the target and consequently so should the intensity of the beam. This behavior was observed [*see illustration on page 91*].

Since these initial experiments numerous ions have been found that result in X-ray lasing at wavelengths from 30 nanometers down to 10. The intensity of the selenium laser, which emits 20-nanometer X rays, increases by a factor of 100,000 when its length is increased from one centimeter to four centimeters; the laser has an output of from five to 10 megawatts in a pulse lasting .1 nanosecond.

Although this is an impressive power output, the collisional-excitation scheme employed in the selenium laser is too inefficient to generate much shorter wavelengths. For instance, a target of silver, whose atomic number is 47 (as opposed to the 34 of selenium), results in an X-ray beam of about 10 nanometers. To produce a four-nanometer beam one would need to go to a still higher Z, but the present excitation scheme would require an optical pump roughly 100 times more powerful than Nova, which is the world's most powerful laser.

The design of the kind of lasers described above would not have been possible without the help of two advanced computer-simulation codes: LASNEX, which was developed by George B. Zimmerman and his coworkers at the LLNL in the 1970's and 1980's for the laser-fusion program, and XRASER, developed by Hagelstein during the same period. LASNEX models the essential physics of the pump laser and its interaction with the foil target. The designer provides as input data the shape, size and composition of the proposed target and the specifications of the Nova beam. LASNEX then calculates how the target will explode and how the density, temperature and pressure of the resulting plasma will develop as a function of time.

XRASER takes these quantities as input parameters, along with detailed atomic-physics data, and calculates the electron populations of the various energy levels in the selenium plasma, the transition rates and ultimately the gain, or amplification, of the X-ray laser. If one has chosen beam and target specifications properly, XRASER will predict a gain that grows exponentially with the length of the target—the signal that the stimulated emission of photons is taking place. If one has chosen specifications poorly, this too will be reflected in XRASER's output. Over the past 10 years the codes have been considerably refined and extended by constant testing of their predictions through experiment and incorporation of the hard lessons



OPTICAL PULSE from Nova begins the process of X-ray lasing. The Nova beam strikes a rectangular target of selenium. The selenium is vaporized, creating a cylindrical plasma consisting of free electrons and the selenium ions from which the electrons were detached. In a process called collisional excitation, a free electron collides with a selenium ion and excites one of the still-bound electrons from the ground state 2*p* to either of the higher-energy states 3*s* and 3*p*. Electrons from the 3*s* state rapidly decay to the ground state; transitions from 3*p* to ground are forbidden. The result is that ions with an electron in the 3*p* state outnumber those with an electron in the 3*s* state, a situation known as population inversion. Electrons decaying from the 3*p* to the 3*s* state emit X-ray photons that stimulate ions in the 3*p* state to emit other photons in the same phase, and these constitute the laser beam.

learned. Currently XRASER and LASNEX serve, with increasing confidence, as design and diagnostic tools whose predictions match in detail many (but not all) of the features of the selenium-laser data.

M. Stephen Maxon, Richard A. London and their co-workers at the LLNL have recently applied LASNEX and XRASER to design lasers with gain at wavelengths as short as five nanometers; Brian MacGowan and his co-workers subsequently demonstrated the feasibility of the design. The targets were ytterbium foils that had 42 electrons stripped off and one of the 28 inner electrons excited from the 3*d* state to a 4*d* state; the mechanism is analogous to the one employed in the selenium laser, except that the population inversion is created between the 4*d* and 4*p* states. (The letter *d* refers to a state with an angular momentum quantum number equal to 2.) The codes also predict good gain at wavelengths ranging from 4.48 and 4.16 nanometers in tantalum, tungsten and rhenium targets, and we shall soon be testing these predictions.

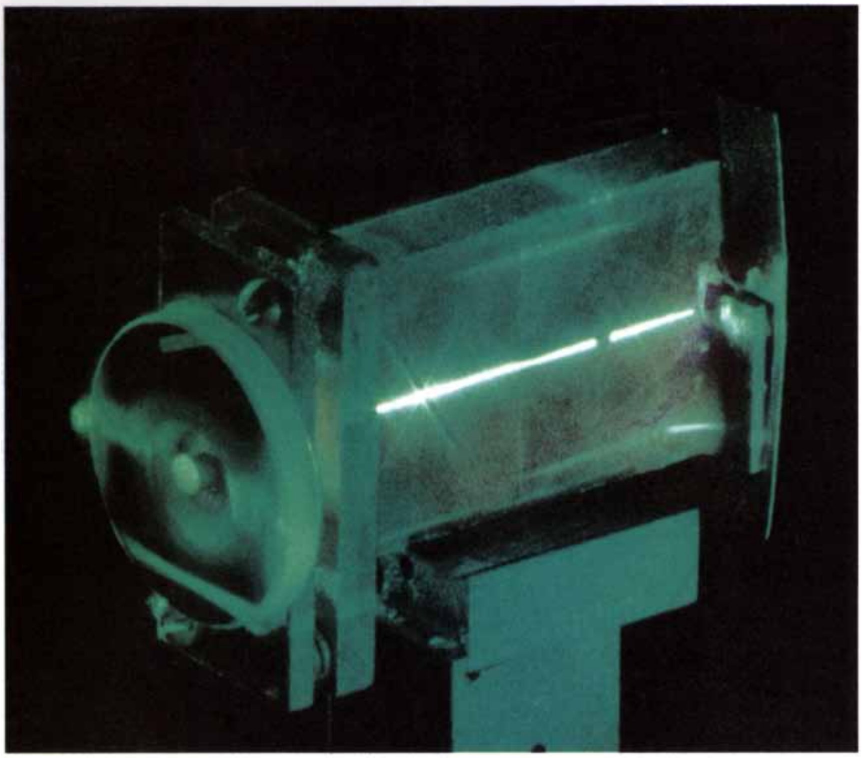
The X-ray lasers described above are, as we have pointed out, single-pass devices. Mirrors capable of reflecting X rays would allow multipass amplification and hence significantly increased laser output. The first X-ray mirrors were invented in the 1970's by Eberhard A. Spiller of the IBM Corporation's Thomas J. Watson Research Center in Yorktown Heights, N.Y.; since then the technology has matured to the point where they have been successfully tested in experiments at the LLNL, Princeton University and the University of Paris.

The X-ray mirrors now being constructed by Natale M. Ceglio, Troy W. Barbee, Jr., and their co-workers at the LLNL are laminations: layers of material transparent to X rays are sandwiched between layers of material that reflect X rays with the highest efficiency possible—which is only about 1.3 percent of the incident electric field of the laser beam. If the reflective layers are spaced half a wavelength apart, X rays reflected by two successive layers interfere constructively, increasing the effective reflectivity. (The reflection process is technically known as Bragg scattering.) X-ray mirrors so far developed can have up to several hundred layers, each about 100 atoms thick; the best reflectivity obtained to date is an intensity of 60 percent at a wavelength of 120 nanometers with a mirror of 30 layers.

Even with mirrors it is a hard task to achieve multipass amplification. If the mirrors are closer than about one centimeter to the end of the target, radiation from the vaporizing selenium damages or destroys them. Moreover, the plasma is expanding and diluting on a time scale only slightly longer than the time required for the X rays to traverse the length of the plasma. Consequently after a small number of passes the plasma will have dissipated and the laser will fail to show further amplification. Yet in experiments at the LLNL we have demonstrated that two passes indeed generate an ouput 30 times as large as a single pass, indicating that the mirror survived and that double-pass amplification is taking place.

In a still more audacious experiment we attempted a triple-pass amplification, which employed not only an X-ray mirror but also an X-ray beam splitter (a partially transmitting mirror). It succeeded, but by the third pass the plasma was already so dilute that amplification had dropped off substantially.

One possible solution to the dissipation problem is to go to solid targets that would not vaporize completely when struck by the pumping beam. Rather, one would employ a long-pulse optical pump laser, the target would vaporize gradually and the plasma would be replenished; such a scheme might solve the dilution problem. We are currently investigating such an approach.

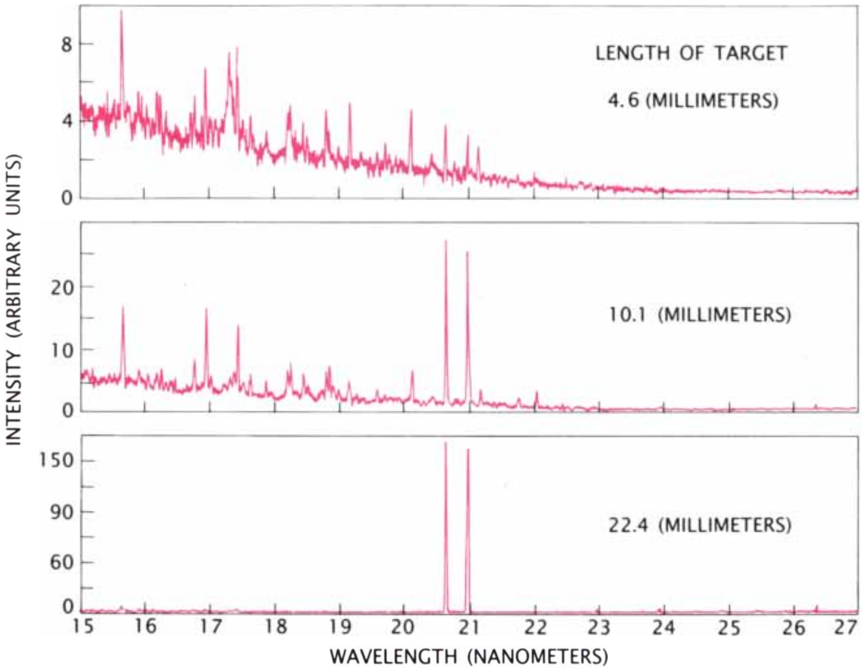


NO MIRRORS are employed in most prototype X-ray lasers because mirrors capable of reflecting X rays have only recently become available. (The round mirror on one end is for alignment purposes only.) The plasma cylinder (*bright line*) created when the selenium target explodes under the impact of the Nova pulse is several hundred times longer than it is wide. Only photons moving along the long axis become part of the laser beam. Selenium emits X rays with a wavelength of about 20 nanometers.

The soft-X-ray lasers now in operation at the LLNL have shown great promise but are still in a primitive state. Once X-ray lasers become reliable, efficient and economical, they will have several important applications. First and foremost, their short wavelengths, coherence and extreme brightness should allow the exploration of living structures much smaller than one can see with optical methods.

In particular, diagnostic tools for obtaining high-resolution images of living specimens at the subchromosome level are not yet available. Electron microscopy, for instance, typically requires one to slice a dehydrated specimen and treat it with a metallic fixative, in this way killing it. Scanning tunneling microscopes or scanning X-ray microscopes call for long exposure times, during which any motion of live objects blurs the images.

Soft-X-ray lasers provide a solution.



TARGET LENGTH determines laser amplification. The number of photons participating in lasing action grows exponentially with target length, and so the beam intensity grows exponentially as well. This behavior is observed in the spectral lines of a selenium target. In the top graph the 21-nanometer emission line has a relative intensity of nearly three for a target length of 4.6 millimeters. In the middle graph, where the target length has been increased by a factor of 2.2, the line intensity has gone up by a factor of almost nine. When the target length is doubled to 22.4 millimeters, as in the bottom graph, the emission lines totally dominate the spectrum.

The short wavelengths of X rays—ideally at 4.4 nanometers to maximize contrast between water and the biological structure—will allow high-resolution imaging; their extreme brightness and coherence will make possible very short exposure times that can "freeze" even a moving object. The specimen would, of course, be destroyed by the X-ray beam, but by that time the exposure would already have been made. By means of such a technique investigators should be able to produce high-resolution in vitro holograms of living structures.

Recently a group at the LLNL led by James E. Trebes has used our 20-nanometer selenium laser to create the first X-ray holograms of inanimate test objects: a carbon fiber 8,000 nanometers in diameter and a gold fiber 10,000 nanometers in diameter. The success of the experiments is a significant first step toward demonstrating the promise of soft X rays for the investigation of living structures. Nevertheless, considerable design work will be needed to achieve full coherent power at the desired four-nanometer wavelength.

The short wavelengths and high intensities of X-ray lasers also provide a diagnostic tool for the investigation of plasmas, such as those produced when the Nova laser vaporizes a selenium target, and hence for the further development of X-ray lasers themselves. Until now optical lasers have been relied on to probe the plasma, but they are able to give information only on plasma densities lower than .001 gram per cubic centimeter, because an optical beam is severely refracted by higher densities. Soft X rays will enable workers to monitor densities four orders of magnitude higher than the densities now accessible.

X-ray lasers may be able not only to probe plasmas but also to produce them. We estimate that an X-ray beam striking a solid target will generate plasmas of much higher density and temperature than those now formed even by the Nova laser when its beam strikes the selenium target. Such an accomplishment would allow investigators to learn much more about the behavior of a plasma at temperatures and densities that resemble those in the interior of the sun.

Although such applications lie some years in the future, progress in the field of X-ray lasers has been great. Even 10 years ago the construction of such a device would have been considered impossible. Now research has arrived at the point where pulsed X-ray lasers are operating routinely, high-reflectivity X-ray mirrors have been manufactured and the first X-ray holograms have been made.

Over the past 10 years progress toward achieving shorter wavelengths has also been remarkable and there appear to be no magic barriers to the wavelengths that can be achieved. Indeed, new schemes are currently being devised that could achieve 2.8 nanometers and, eventually, even shorter wavelengths.

It might seem that this kind of progress will be forever confined to the laboratory and that devices requiring the million-gigawatt Nova as a pump can never be made small and practical. Although it is true that the high-Z scheme employed at the LLNL requires high pump power, work on a variety of approaches to short-wavelength lasers is proceeding at the LLNL (where the leaders are David Eder and Christopher J. Keane), at Princeton (Szymon Suckewer and Charles Skinner), at the Rutherford Appleton Laboratory in England (Michael Key and Geoff Pert), at the University of Paris (Pierre Jaeglé) and at many other national laboratories, universities and industrial laboratories worldwide.

Some of the new approaches, in contrast to the one described in this article, do not require high-Z atoms and high-power pumps such as the Nova. They focus instead on more efficient excitation mechanisms that have smaller power requirements. Eventually these new methods may succeed in bringing down the power requirements far enough so that true tabletop X-ray lasers become a reality.

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Snakes, Blood Circulation and Gravity

When a snake climbs or rears up, its cardiovascular system must resist strong pressure gradients. These effects of gravity explain why the circulatory system of a tree snake differs from that of a sea snake

by Harvey B. Lillywhite

Gravity is a pervasive force in the world, and both animals and plants have adapted to it in a variety of ways. Trees, for example, can grow to extraordinary heights (as much as 364 feet) and still circulate vital fluids to their upper branches. At the other extreme, consider animals that live at the bottom of the sea. How do they function at depths of more than 19,000 feet, where the weight of the water column exceeds 8,800 pounds per square inch? It is not surprising that these and other adaptations to gravity have inspired the curiosity of scientists for centuries.

In terrestrial environments gravity places special demands on the cardiovascular system of animals, and its effects can be particularly pronounced in larger species that adopt vertical orientations. Because the design of an animal's cardiovascular system reflects its lifestyle and the extent to which it is affected by gravity, certain animals have proved to be valuable models for studies of circulatory regulation. The giraffe is one such animal. Because its head is so far above its heart, unusually large pressures are needed to send blood to its brain. Of all the vertebrates, however, snakes perhaps excel in the extent and variability of adaptations involving gravity and the cardiovascular system.

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Snakes are remarkably well-adapted animals. During their evolutionary history, which exceeds 100 million years, they have successfully diversified to fill a great variety of ecological niches. Today there are approximately 16 families and 2,700 species of snakes in the world. They exhibit a broad range of body sizes, occupy many different environments and display wide variation in behavior. Some snakes are totally aquatic, others are terrestrial and a large number live in trees.

Such diversity is possible in part because snakes have wonderfully effective cardiovascular systems that enable them to circulate blood against the force of gravity. A corn snake, for example, may crawl straight up the trunk of a tree in search of eggs in an unprotected nest; a tree boa may hang with its head down while pursuing prey in a tree. Both animals are exhibiting behaviors that would not be possible without a cardiovascular system adapted to maintain adequate blood circulation when the body deviates from a horizontal orientation.

In order to understand why gravity places such demands on the circulatory systems of animals, it helps to think of blood vessels as cylindrical tubes. If a sealed cylinder filled with water is turned to stand on one end, the weight of the water in it creates a vertical pressure gradient, which is lowest at the top of the tube and greatest at the bottom; at the center of the column it remains essentially unchanged. If instead of a rigid cylinder a thin balloon is filled with water and held vertically, it will bulge at the bottom and perhaps be broken by the pressure of the water inside. The pressure thus created is called gravitational pressure. It increases with depth and is present in any continuous fluid column regardless of whether the fluid is in motion or not. If the fluid is set in motion by a pump, as in the circulatory system, overall pressure is increased: the pressure created by the pump, or heart, is added to that imposed by gravity.

Gravitational pressure can severely affect larger animals that are not physiologically adapted to withstand its force. Increased pressure in the lowermost vessels of an animal's circulatory system tends to cause blood pooling: it distends the walls of the vessels and may cause plasma to leak from the capillaries. As blood pools in the lower body, central blood pressure falls and circulation to critical organs, such as the brain, eventually fails. If all but the smaller snakes were highly susceptible to blood pooling, they would be restricted to aquatic or horizontal habits. But this clearly is not the case.

A little more than 10 years ago I became curious about the ability of snakes to maintain adequate blood circulation while they are in a vertical position. Why, I wondered, did a long snake not faint while climbing a tree? I had the chance to address this question while I was a visiting lecturer at Monash University in Australia. There I collaborated with Roger S. Seymour, who is now at the University of Adelaide. Together we began a comparative analysis of the effects of gravity on the blood pressures of snakes. We studied sea snakes, which when surrounded by water are virtually immune to the effects of gravity; terrestrial nonclimbing snakes, which live on the ground and are usually horizontal, and arboreal snakes, which often assume a vertical posture as they climb up and down trees.

Sea snakes (close relatives of cobras and coral snakes) occupy tropical regions of the Pacific Ocean and are particularly abundant in coral reefs surrounding Australia, where they can be captured with a hand-held net. In the ocean they are supported by salt water, whose density is nearly equal to that of blood. Buoyed by the weight of the water, snakes can adjust their lung volume so as to be effectively weightless, much like objects floating in outer space. In theory blood circulation in these aquatic snakes is affected very little by gravity. The reason is that vertical pressure gradients within the blood vessels are counteracted by similar gradients in the pressure of the surrounding water; hence there is no tendency for gravity to expand the vessel wall, and the distribution of blood remains about the same regardless of orientation.

Sea snakes are descended from terrestrial ancestors. We therefore wondered whether they retain a physiological capacity to withstand gravitational pressure when they are removed from the supportive medium in which they normally live. Captured snakes were brought into the laboratory, chilled with chipped ice and anesthetized briefly. One or more catheters—small, flexible tubes filled with saline—were then inserted into their blood vessels to measure changes in pressure. Before mobility was restored the snakes were put in long plastic tubes attached to a central pivot.

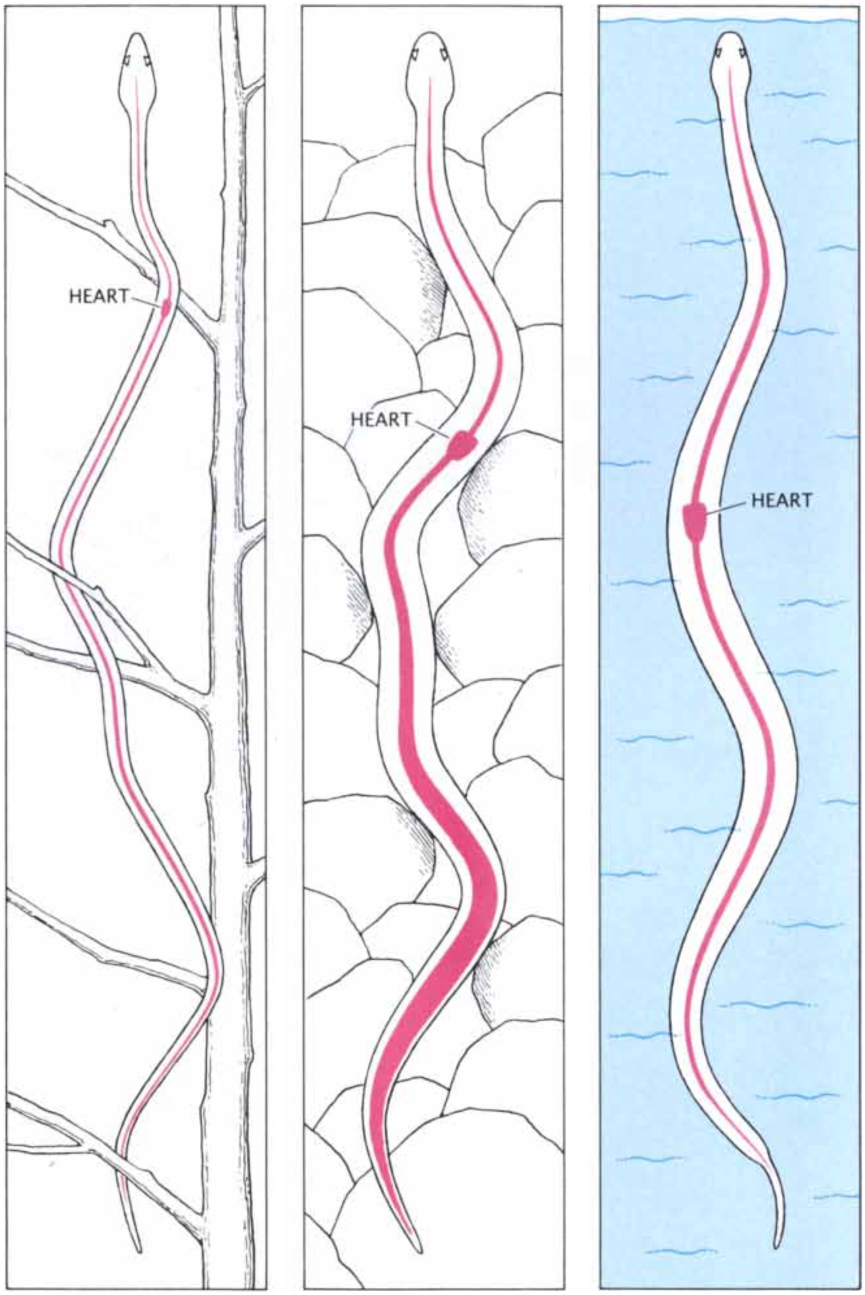
By rotating the tubes from a horizontal position to various angles with the head tilted up, we were able to measure the effects of gravity on an animal's cardiovascular system. Using an electronic pressure transducer connected to a catheter inserted into the snake's dorsal aorta, we recorded blood pressures at the midpoint of the snake's body. Recalling the analogy to a closed tube, we expected that a snake not adapted to gravity would lose pressure at its midpoint and be unable to compensate for the fall of pressure at the head. We monitored the heart rate of each snake to see if the heart would compensate for failing blood pressure by beating faster.

The results were interesting. As the angle of tilt increased, pressure at the snake's midpoint decreased, a sign that blood was pooling at the snake's lower end. The heart beat faster but could not compensate for the drop in pressure, which at the level of the brain fell to zero or even became negative. Presumably the anterior blood vessels had collapsed and could no longer accommodate adequate blood flow while in that orientation.

When the same experiment was re-

CORN SNAKE *Elaphe guttata* of North America has the long, narrow body typical of many arboreal and semiarboreal snakes. Without a skinny body and a circulatory system specifically adapted to cope with pressure changes due to gravity, a snake of this length could not maintain adequate blood circulation while in a vertical posture.

peated with terrestrial snakes, the results were quite different. I experimented with the tiger snake *Notechis scutatus,* considered by many taxonomists to be a member of the same family (the Elapidae) in which sea snakes are classified. Tiger snakes are endemic to Australia, where they inhabit a broad range of habitats including floodplains and rain forest. When these snakes were tilted head up, blood pressure actually increased at the body's midpoint. As a result cranial pressure decreased only slightly and there were no signs of circulatory failure. Clearly terrestrial snakes have evolved a variety of physiological mechanisms by which they are able to regulate blood pressure.



EFFECTS OF VERTICAL ORIENTATION on the circulatory system (*red*) of a generalized climbing snake, a nonclimbing terrestrial snake and a sea snake are compared. Because the heart of a climbing snake (*left*) is close to the head, the brain remains well supplied with blood; the pooling of blood in the tail is insignificant because of the animal's narrow body and tight skin. In the terrestrial snake (*middle*), which normally does not climb but is shown here on a vertical rock face, the heart is nearer the body's midpoint. Blood pooling is pronounced because the vessels are distensible and expand in response to increased pressure in the lower body. Thus the blood is not circulated as effectively as it is in the tree snake. In the sea snake (*right*) the heart is about at the body's midpoint; pooling does not occur because the tendency for blood pressure to distend the vessels is opposed by external water pressure.

Since these initial experiments were carried out we have found that the ability to regulate blood pressure, although it is present in all terrestrial snakes, varies in relation to the snake's habitat. Arboreal snakes have a greater ability to regulate pressure in an upright position than nonclimbing species, for example. These differences also correspond to the levels of blood pressure that are maintained by the various species.

Seymour and I measured resting blood-pressure values for a diverse number of species and discovered we could consistently relate a snake's blood pressure to its behavior and habitat. In the five or six arboreal species we tested, arterial pressure in a horizontal position ranged from 50 to 90 millimeters of mercury, whereas in the five or six aquatic species we tested, blood pressure was much lower, ranging from 15 to 39 millimeters of mercury. Semiaquatic species, such as sea snakes that lay their eggs on land, and such nonclimbing terrestrial species as the rattlesnake had intermediate levels of arterial pressure.

It is reasonable to speculate that the high blood pressures of arboreal snakes are largely a secondary consequence of better muscle tone in the vessels of these species. By constricting the blood vessels, vascular muscles increase the vessels' resistance to blood flow and thereby elevate the pressure. Whatever their cause, higher blood pressures minimize the possibility that gravity will impair blood flow to the brain when the snake is in a head-up position. For example, if the passive pressure drop brought on by the orientation shift is 39 millimeters of mercury at the head of a meter-long sea snake, when the snake is out of water, its cranial vessels may collapse, whereas those of an arboreal snake will still have a pressure of from 20 to 60 millimeters of mercury. (It should be noted that in this example only the passive change of gravitational pressure caused by tilting is subtracted from the normal, resting blood pressures described above. The example does not consider other factors affecting pressure, such as the pumping action of the heart.)

After establishing that a snake's blood pressure varies with its ecology, I wanted to test the susceptibility of different species to blood pooling, which I could do by measuring changes in the volume of a snake's tail during tilting. Working at the University of Kansas, I placed the tail of a snake in a small tube and sealed the tube so that it was airtight. I then placed the entire snake inside a larger plastic tube attached to a pivot apparatus similar to the one used at Monash. The small tube was connected to a plethysmograph, a device that records changes in volume as they are revealed by air-pressure changes. As the volume of a snake's tail increases (owing to blood pooling), air pressure in the tube increases and is read by the plethysmograph as a percentage change in volume.

In snakes that have poor physiological control over blood pressure, a head-up position led to fluid accumulation and an increase in tail volume; in those with relatively good control, tail volume changed only slightly. Data from these experiments indicated that blood pooling in arboreal species is at least 30 percent less than it is in aquatic and nonclimbing terrestrial species. Sea snakes experienced extensive blood pooling in the lower body. The pooling explains why blood pressure drops at the body's midpoint during head-up tilting in these snakes. Pooling reduces the amount of blood returning to the heart, thereby reducing cardiac output and causing central blood pressure to fall.

I extended these results with another series of experiments carried out at the University of California at San Diego in collaboration with Kim P. Gallagher. We injected semiarboreal rat snakes with radioactively labeled microspheres—beads 25 microns (thousandths of a millimeter) in diameter—that lodge in capillaries in numbers proportional to the amount of blood flow those capillaries receive. Radioactivity in different tissues is then compared with the radioactivity of blood drawn from an artery. The comparisons enabled us to determine the volume of blood that was circulating to various organs.

We found, for example, that when a rat snake is oriented head up at a 45-degree angle, blood flow to many of the organs and muscles in the lower half of its body is reduced, whereas blood flow to critical anterior organs such as the lung, heart and brain is essentially unchanged. The selective reduction in blood flow results from vasoconstriction: the contraction of smooth-muscle fibers in the walls of the blood vessels. By selectively narrowing certain blood vessels (predom-

SEA SNAKE swims freely in the Pacific Ocean near Fiji. Buoyed by salt water, the snake is essentially weightless and is immune to the effects of gravity. If the snake is taken out of the water and held vertically, however, it may suffer from circulatory failure.

RATTLESNAKE *Crotalus viridis,* like many terrestrial snakes, occasionally adopts a more vertical position, say as it prepares to strike. Its circulatory system is able to adjust, at least temporarily, to the resulting changes in gravitational pressure.

inantly in the lower body in this case), the vasoconstriction increases pressure at the snake's midpoint and promotes blood flow to tissues where the vessels are less constricted. A similar phenomenon occurs in humans and other tall mammals when they suddenly stand up after being in a horizontal position.

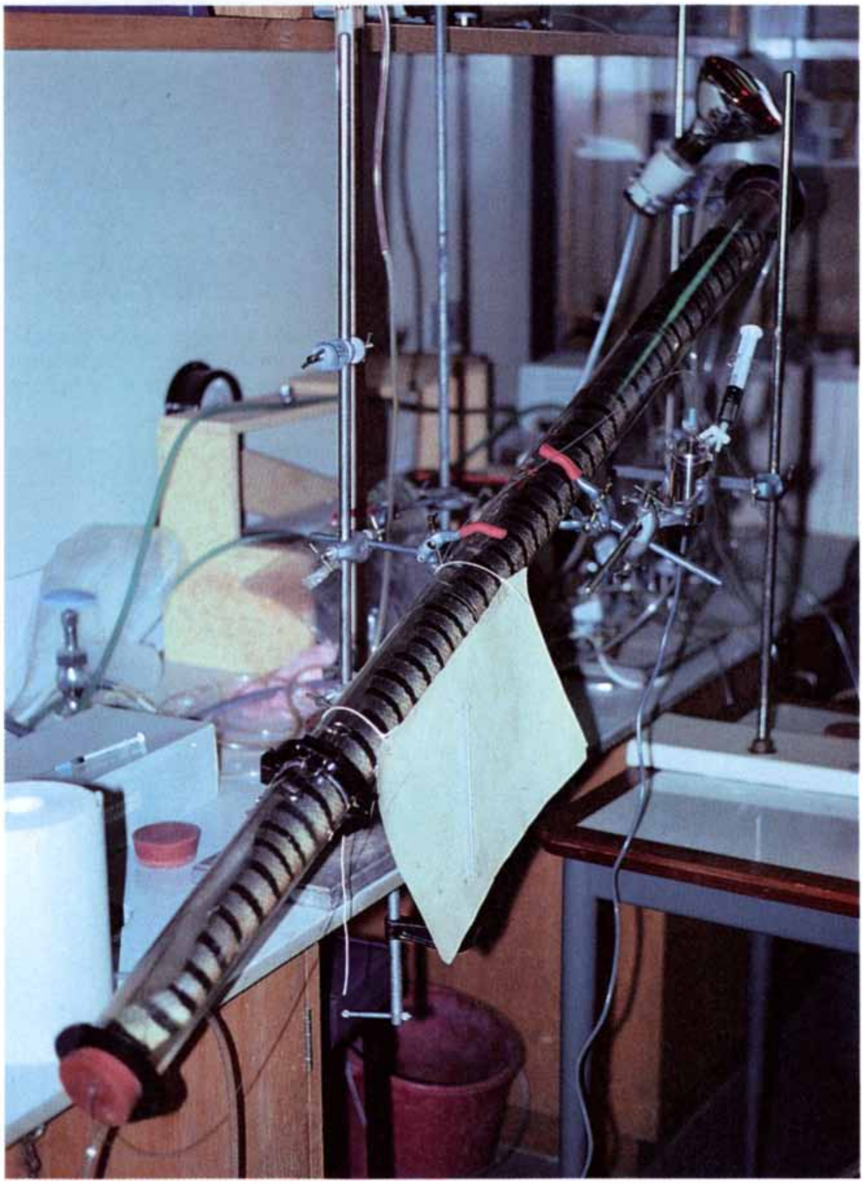
I have focused on physiological changes that take place when snakes assume a head-up position. It must be remembered, of course, that some snakes also assume head-down positions, particularly when they descend vertically or hang from the branch of a tree. How is blood flow to the tail maintained and excessive cranial pressure avoided when a snake is oriented with its head down?

The cardiovascular adjustments are essentially reversed. The snake's heart rate slows and the smooth muscle surrounding the blood vessels in various tissues relaxes, partially offsetting the gravitational increase of pressure near the head. Because venous volume in the head is small compared with that at the posterior end of the body, and because the head is encased in a hard cranium, pooling is insignificant.

Snakes have adapted in other ways to their varied habitats. Certain anatomical features, such as the position of the heart, are also consistent with their various lifestyles. Snakes (having lost their limbs) lack a pectoral, or shoulder, girdle and therefore do not have the same limitations on heart position that most four-legged animals do. In mammals, for example, bones associated with the pectoral girdle restrict the heart to the chest cavity. But in snakes the ends of the ribs are free and the cylindrical body cavity is unobstructed by bony structures for its entire length. Consequently the heart in aquatic snakes can be close to the middle of the body, a position that minimizes the work involved in moving blood to both ends of the body; in nonclimbing terrestrial species the heart is generally about a fourth of the body's length from the head; in arboreal species the average distance from the head is as little as 15 percent of the overall body length. The reduction in the distance from the heart to the head helps to ensure that the brain is adequately perfused with blood regardless of the body's orientation.

John Donald, a postdoctoral fellow in my laboratory, recently demonstrated that the blood vessels posterior to the heart in rat snakes and other arboreal species are richly invested with nerves, whereas the blood vessels anterior to the heart have considerably fewer nerves. Nerves of various types may be present in both sets of vessels, but their precise functions are not known. The pattern of association of nerves and blood vessels suggests, however, that the nerves play an important role in regulating the tone of the muscular walls of the vessels, particularly the posterior vessels most susceptible to blood pooling.

The nerves that control vasoconstriction in most animals are connected by reflex loops to special sensory receptors called baroreceptors. The exact location of baroreceptors in snakes has not yet been identified, but they are thought to be both in and near the heart, as they are in most of the vertebrates in which they have been identified. Baroreceptors innervate the walls of blood vessels, where they are stimulated when pressure within the vessels increases and the vascular wall begins to stretch. Nerve impulses from the baroreceptors modulate heart rate and cause the smooth muscle in the vessel walls to contract by way of a reflex arc involving the brain. The combined actions of the heart and smooth muscle serve to return arterial pressure to its regulated level, a type of control called negative feedback.



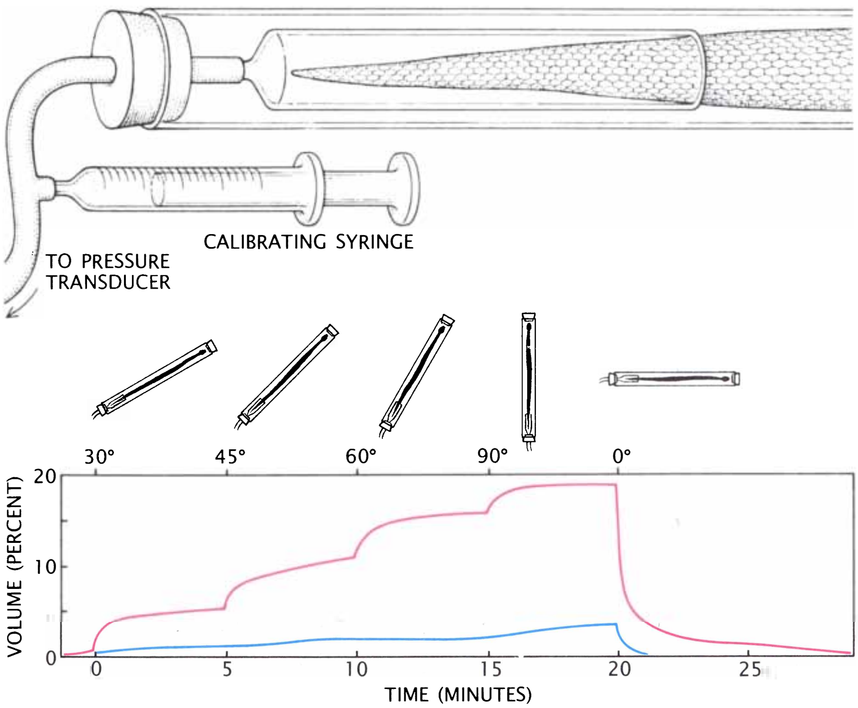
TILT APPARATUS consists of a plastic tube in which a snake can be rotated to various positions. Here a sea snake is shown head up at a 45-degree angle. A pressure transducer connected to a catheter inserted in the snake's dorsal aorta measures blood pressure at the snake's midpoint; when the snake is inclined, the pressure decreases, an indication that blood is accumulating in the sea snake's lower half.

The probable location of the baroreceptors in or near the heart suggests yet another advantage of the anterior heart in arboreal snakes. The effects of gravitational pressure are greatest at the ends of a snake; therefore the closer baroreceptors are to the head, the more effective they will be in controlling gravitational disturbance and preserving brain function.

Two minor disadvantages to having a heart that is unusually close to the head must be mentioned. One is that when an arboreal snake is head down, it may have trouble maintaining blood flow to the tail (although blood flow to the tail is much less critical than blood flow to the brain). The other is that whenever a snake is head up, blood from the tail must travel almost the entire length of the venous column—against the force of gravity—to return blood to the heart. How are such feats accomplished?

Unlike the veins of mammals, those of snakes do not appear to have internal valves to prevent backward flow. Instead the uphill movement of blood is assisted in three ways: by baroreceptor-mediated contractions of vascular smooth muscle, by the movement of skeletal muscle, which compresses the snake's veins, and by tight skin. Arboreal snakes that have been climbing for a while often pause momentarily to wiggle their bodies, causing undulating waves of muscle contraction that advance from the lower torso toward the head. The advancing contractions compress the veins, forcing blood forward and increasing central venous pressure near the heart. The behavior improves venous blood flow to the heart so that it can maintain arterial blood pressure.

Similar behavior can be induced in the laboratory. When I experimentally removed from 30 to 50 percent of the blood volume from rat snakes, lowering their arterial pressure to an average of 36 percent below normal, the animals responded by wiggling. The wiggling response in turn increased their cranial pressure to roughly normal levels. Because wiggling behavior cannot be similarly induced in aquatic species, it appears to have evolved specifically to assist blood circulation in snakes that occupy arboreal habitats. Other body movements also improve circulation, but they do not usually elevate blood pressure as effectively as the stereotyped wiggling.



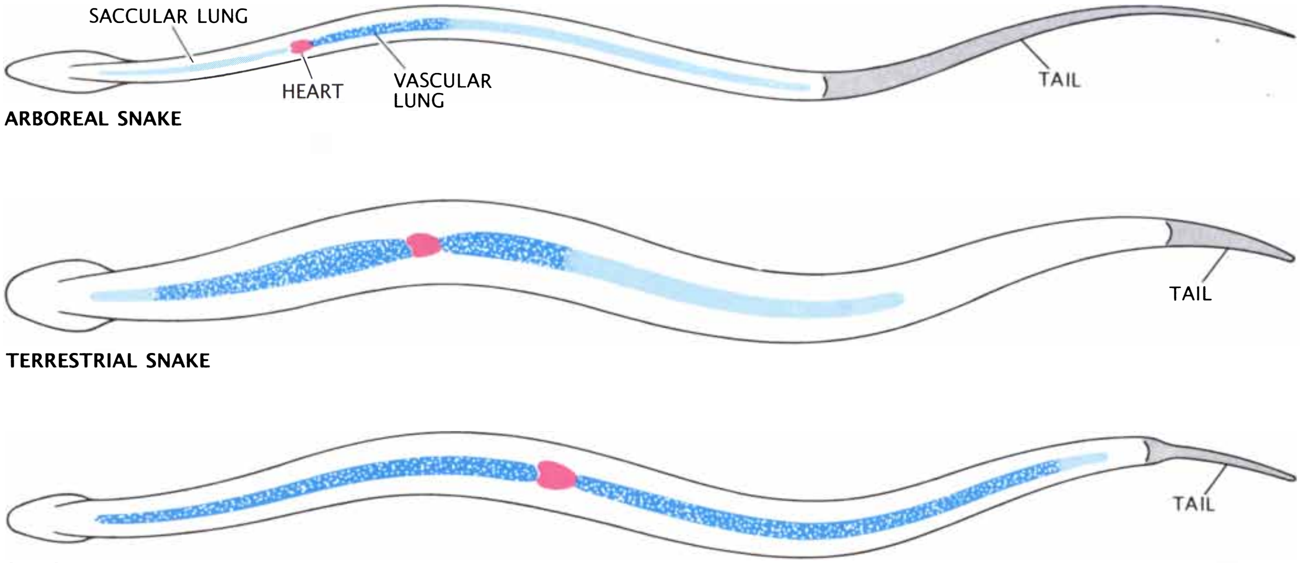
PLETHYSMOGRAPH measures the increase in body volume caused by blood pooling. The tail of a snake is inserted into a small tube, which is then sealed and connected to a transducer that records pressure changes. The plunger of a calibrating syringe lets the experimenter change the pressure by increasing or decreasing the volume by a measured amount. The pressure changes within the tube are calibrated in this way and the results are recorded on a graph as is shown at the bottom. A rattlesnake (*C. viridis*), which is not adapted to climbing, shows a significant increase in tail volume owing to blood pooling as its tilt angle increases (*red*). In contrast, a gopher snake (*Pituophis melanoleucus*), which climbs frequently, experiences a minimal increase in tail volume (*blue*). When the snakes are returned to a horizontal position, the tail volume decreases abruptly, indicating that at least 75 percent of the fluid had pooled in the blood vessels and had not filtered out into the tissue spaces.

Body type also appears to be an important factor in counteracting gravitational pressure. Snakes specialized for arboreal living tend to have slender bodies with firm muscle tone and tightly adhering skin. The small body circumference and tight tissues resist stretching caused by blood pooling. The *g* suit worn by fighter pilots during high-speed maneuvers functions the same way. Similarly, tall mammals such as humans, horses and giraffes have tight skin and connective tissue around their lower legs, which counteract the tendency of vessels to dilate, whereas short mammals such as rabbits do not.

Aquatic and nonclimbing terrestrial snakes, whose cardiovascular systems are affected minimally, if at all, by gravitational pressure, have more flaccid bodies with looser skin. The nonclimbing terrestrial snake *Python regius*, for example, has a ratio of body circumference to body length that is three times as great as its arboreal relative *Corallus enhydris*. Similar correlations of anatomy and habitat can be found among species in other families. In the Colubridae, which contains many of the commoner North American snakes such as the garter and king snakes, arboreal snakes may be as much as 10 times slenderer than their terrestrial relatives.

The size and shape of a snake's lung also reflect its habitat and behavior. Many tissues of the body are susceptible to edema as a result of gravitational pressure, but few are more likely than the lungs to be seriously impaired by fluid retention. The reason is that fluid, which collects in the lungs, increases the distance across which blood and air must diffuse and thereby reduces the transfer of respiratory gases. In order to reduce filtration of fluid into the lung tissue, blood pressure in all tetrapod vertebrates, including snakes, is lower in the lungs than it is in the body's other tissues.

The evolution of most snake lungs into a single long membranous chamber poses no problem in a horizontal position, but a long lung presents special problems for arboreal species. Gas exchange takes place through radial pockets (analogous to the saclike alveoli of mammals) in the spongy, mem-



LUNG ANATOMY varies according to a snake's habitat. The lung of arboreal snakes (*top*) is vascular (that is, rich in blood vessels) for a short region (*dark blue*) behind the animal's heart (*red*). At both ends the lung differentiates into a long saccular region (*light blue*), which lacks the blood vessels involved in gas exchange. In terrestrial snakes (*middle*) the lung has a somewhat longer vascular region near the heart. In sea snakes (*bottom*) the lung consists almost entirely of vascular tissue.

branous walls of the lung. The region where gas exchange takes place is richly endowed with blood vessels and is referred to as the vascular lung. The remainder of the lung, which extends for varying distances depending on the species, may be entirely devoid of blood vessels involved in gas exchange and is called the saccular lung.

In a snake oriented vertically, gravity increases pressure both in arteries and in veins, which form a continuous fluid column extending the length of the vascular lung. These pressures are transmitted to capillaries, placing the lung at risk of severe edema. Because the risk of edema increases in direct proportion to the length of lung vasculature, reducing the length of the pulmonary vessels would seem to be the best solution to gravitational pressure. Examination of lung anatomy in various snakes confirms that the length of the vascular part varies according to habitat.

In aquatic snakes the vascular tissue extends almost the entire length of the body cavity (although in some species a short saccular tip may be present). In arboreal species the vascular tissue is much shorter and may occupy less than 10 percent of body length, usually extending a short distance posterior to the heart. The result of the short vascular lung is that the pulmonary blood vessels of arboreal snakes are not subject to significant gravitational pressures even when the snakes are oriented vertically. The vascular lungs of nonclimbing terrestrial and semiaquatic species are generally intermediate in size.

To demonstrate the effects of gravity on the lung of an aquatic snake, I measured pulmonary blood pressure in the olive sea snake, *Aipysurus laevis*. Snakes were anesthetized and their pulmonary vessels catheterized. When the anesthesia had worn off, each snake was placed in a dry rotating plastic tube. As predicted, blood pressures increased in the lower sections of the lung as the tilt angle of the tube increased. Subsequent microscopic examination of lung tissue from these snakes revealed evidence of severe edema as well as ruptured capillaries in the lower lung. The greater the tilt angle—and therefore the length of the vertical blood column—the greater the damage. When snakes were tilted in salt water, no such effect was demonstrated. In its normal aquatic environment the snake avoids edema, even when it swims vertically, because water pressure collapses portions of the lung and reduces the length of the blood column exposed to lung gas. (Parts of the lung collapse because lung gas compresses as the gravitational pressure of the surrounding seawater increases.)

These physiological experiments show that snakes, because of their elongated form and diverse habits, are valuable models for studying cardiovascular design and regulation. The adoption of arboreal habits in particular has necessitated several important anatomical and physiological changes. The heart has moved to a more anterior location and the vascular lung has been shortened; blood pressure is more tightly regulated; blood vessels show specialized patterns of association with nerves; there is a reduction in the expansibility and diameter of the body wall, and specialized behaviors enhance the flow of venous blood toward the heart. Judged by their cardiovascular systems, snakes are highly specialized and adapted animals. Perhaps understanding their mechanisms of cardiovascular regulation will someday help physiologists to understand how gravity affects human beings, particularly in the context of space travel.

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Canal Builders of Pre-Inca Peru

The engineers of Chimor built canals to carry water from rivers to fields as much as 70 kilometers away. In the end they were defeated by relentless geologic forces

by Charles R. Ortloff

Making water run downhill would appear to be the easiest thing in the world. Yet when the source of the water is a river 40 kilometers from the fields that need to be watered, it can be a difficult business. This is essentially the problem that faced the ancient engineers of the kingdom of Chimor, a society that dominated the northern coast of Peru from about A.D. 1000 until its conquest by the Incas. Chimor was a "hydraulic society": in the arid landscape of the coastal Andean foothills the Chimu were completely dependent on irrigation to provide enough food to support their people. As a result they became expert hydraulic engineers, capable of surveying canal routes with great accuracy and constructing canals with considerable efficiency.

As it happens, the Chimu needed every bit of technical expertise they could muster, because their environment was changing in a way that threatened the canals. In response to the plate-tectonic and spasmodic seismic movements of the South American coast, the rivers that run down from the Andes continually modify their beds as the support landscape is distorted. For the Chimu the net result was that the flow in existing canal systems was constantly decreasing as the supplying river entrenched and stranded canal inlets. The picture was further complicated by the destructive rains that result from El Niño disturbances of temperature and ocean currents. But the Chimu engineers were up to the task. For hundreds of years they modified their canals, innovating and adapting new design strategies to keep pace with the changing physical environment. Their achievements have recently been revealed by the first large-scale excavations of the canals in the region.

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The area once dominated by the Chimu is a rectangular strip that runs down the northern coast of Peru from the Cordillera Negra chain of the Andes to the Pacific Ocean. Its northern boundary lies close to the southern boundary of Ecuador and its southern boundary lies at about the level of Lima. Along this coastal strip many rivers carve valleys from the Andean highlands to the Pacific, and it is in those river valleys that agriculture has always been concentrated. The origins of the Chimu are not fully understood, but it is known they were effective conquerors; by sometime after the beginning of the second millennium in A.D. 1000 they had come to dominate all the other groups in the adjacent coastal valleys. The heartland of this empire was centered in the valley of the Moche River, where the Chimu capital of Chan Chan lay.

At its height Chimu society was an agricultural society divided into several quite distinct classes. At the top was the king with his retinue. Then there was a relatively small nobility. Below the nobles was a tripartite urban lower class consisting of retainers, craftsmen (working in metals, ceramics and other materials) and transport workers. These groups were largely concentrated in Chan Chan. Outside the capital was a rural lower class that included the agricultural workers who provided the basis for subsistence.

It was apparently from the rural lower class that the labor power for building the canals was drawn. The administration in Chan Chan exacted from the populace a "labor tax" that was used to construct canals, sunken gardens and additions to the capital itself. It is thought that once the canal route had been surveyed, numerous work gangs of from 10 to 20 men were assigned to excavating and clearing rock along the canal path. The tool kit of the work gangs included bronze implements and stone hammers. Hoes with stone blades were used for digging and wicker baskets served for carrying away soil. Major boulders in the canal path were progressively reduced in size by lighting fires around them and then dashing water on them to spall off flakes.

Once constructed by these methods, the canals carried water mainly from November through May, which is the rainy season in the highlands. Such a pattern of water availability was sufficient to support a considerable range of crops, including beans, corn, squashes and gourds of various types, spices and many different types of fruit trees, along with cotton. Generally, crops were grown in serpentine furrowed fields situated alongside the canal at a slightly lower elevation. Channels from the canals brought water to the growing surface; the channels were activated by temporary barriers that raised the water level to drop-structure weirs and thus diverted the flow to the field systems.

Many canal systems conforming to this general plan were constructed by the Chimu engineers. In this article I shall concentrate on the two that were closest to the heartland of Chimor: the Moche Valley system and the Intervalley Canal, which brought water to the Moche Valley from the Chicama River valley (the next one north of the Moche Valley). The history of these two systems is closely tied to the destiny of the capital, and indeed of Chimu society. Moreover, their evolution provides an excellent illustration of the resourcefulness of the canal builders in trying to preserve the canals against the changes imposed by their environment.

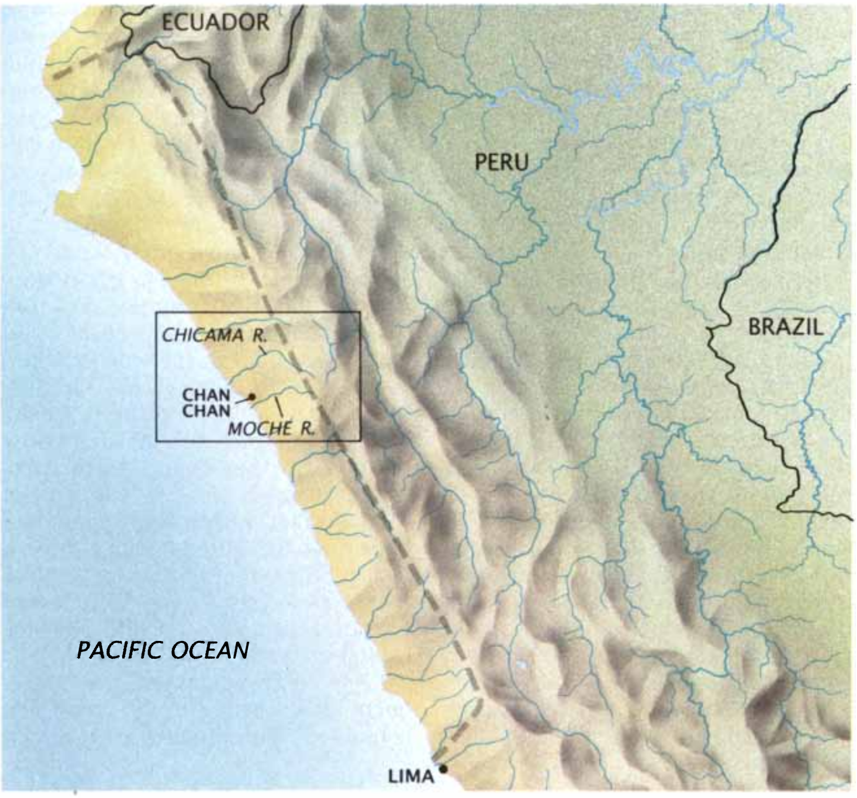
Perhaps the most significant of those changes was the continuous reduction in flow rate through the canals. The reduction was due in turn to interactions among the great tectonic plates that tile the surface of the earth. Just off the coast of South America the Nazca Plate dives under the large South American Plate, in what is known to geologists as a subduction zone. One result of the subduction is that the west coast of South America is gradually being lifted up and distorted. As the coastal region is uplifted, the rivers there must reestablish an equilibrium of their channel-bed slope, which they do largely by cutting down through previously deposited silts. As I shall explain, such retrenching can have disastrous consequences for a gravity-fed canal system. Coastal uplift also causes distortion of long canal segments; some canals that once carried water by gravity now run uphill.

Other environmental factors affected the canals. The uplift of the Pacific Ocean beaches exposed large quantities of sand, which was carried inland by onshore winds. The sand aggregated into huge dunes that moved inland a few feet per year, creating an "inflationary" environment. The sand was also moved back to the sea by less well understood forces, resulting in a "deflationary" environment. The overall sand layer over the bedrock could change considerably in the course of a few hundred years. In addition, the El Niño deluges caused by warm currents off the coast, which may occur in their severest form about every 50 years, possess tremendous destructive power. In 1982, for example, 90 inches of rain fell in one week, washing out the Pan-American Highway and stranding large areas of the Peruvian countryside without food. Such rains would have wreaked massive damage on the earthen-bank Chimu canals.

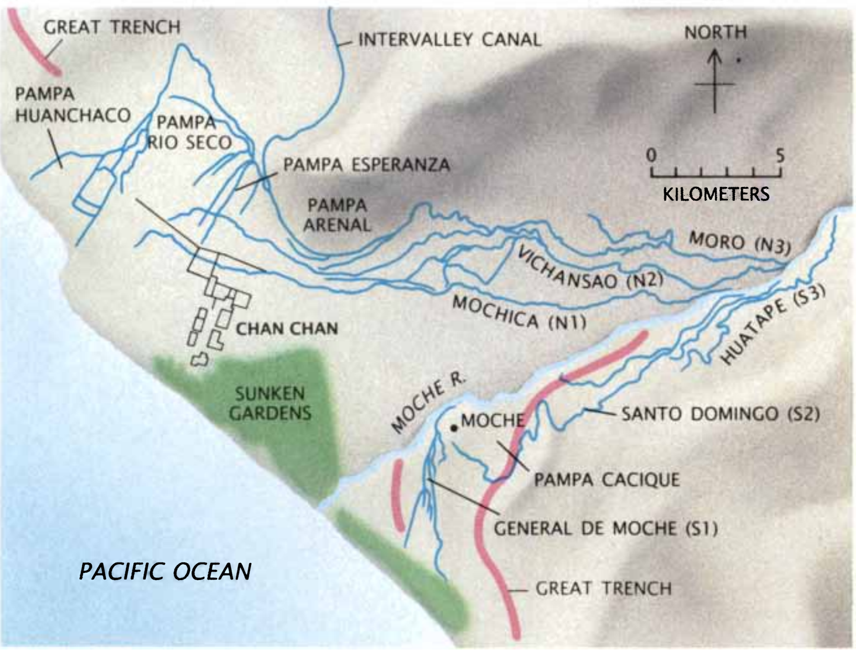
These challenges were met by a series of gradual innovations over a long period. The earliest canal-building style in the Moche Valley was originated by the predecessors of the Chimu: the people of the Mochica culture, who reached their peak between A.D. 100 and 800. These early canals, or "great trenches," were deep trenches through an inflationary landscape containing much sand. The gently sloping, sand-filled environment was easily traversed by the large trenches, and many were built in the Moche Valley. Trenches with inlets in the Chicama River irrigated the northern Moche Valley, including the northernmost reaches of the Pampa Huanchaco, which formed part of the crucial "breadbasket" region near Chan Chan known as the Three Pampas area. A trench originating in the Moche River itself watered the Pampa Cacique and coastal zones near the old Mochica capital of Moche.

As tectonic uplift and the consequent downcutting of the riverbeds continued, however, the great-trench

INTERVALLEY CANAL is among the greatest engineering accomplishments of the Chimu, who occupied northern coastal Peru before being conquered by the Incas in about A.D. 1450. The Intervalley Canal winds 72 kilometers from the valley of the Chicama River to the valley of the Moche River, the Chimu heartland. As the photograph shows, the canal winds along the foothills of the Andes at a low slope. To maintain that slope, earthen terraces were necessary; one is shown at the center.



KINGDOM OF CHIMOR occupied the northern coastline of Peru from the Andes to the Pacific. The broken line shows the Chimu dominion at its zenith in A.D. 1300. In this region human society has always clustered in the valleys of the rivers that run down from the Andes. Irrigation water is available in the rivers from November to May.



NETWORK OF CANALS near Chan Chan, the Chimu capital, reveals a pattern of decreasing availability of agricultural land. The earliest canals in the Moche Valley were "great trenches" that plowed straight across the sandy landscape. The trenches were replaced by contour canals of low slope. Because of the downcutting of the riverbeds that results from plate-tectonic forces, the early canal inlets on the north side of the Moche (*N3*) and the south side (*S3*) eventually became stranded, or raised above water level, in spite of repeated modifications to recapture river flow. They were later replaced by systems (*S2, S1, N2, N1*) watering successively smaller areas.

system became less workable. The reason is one that would continue to plague the Chimu engineers right through the end of their civilization. The inlets carrying water from the river to the canal were carved on the side of the river valley. As the river cut down into a new bed, the inlet was left progressively higher above the bottom of the river. As a result the flow into the canal decreased. Ultimately the canal inlet might be stranded, or literally left high and dry.

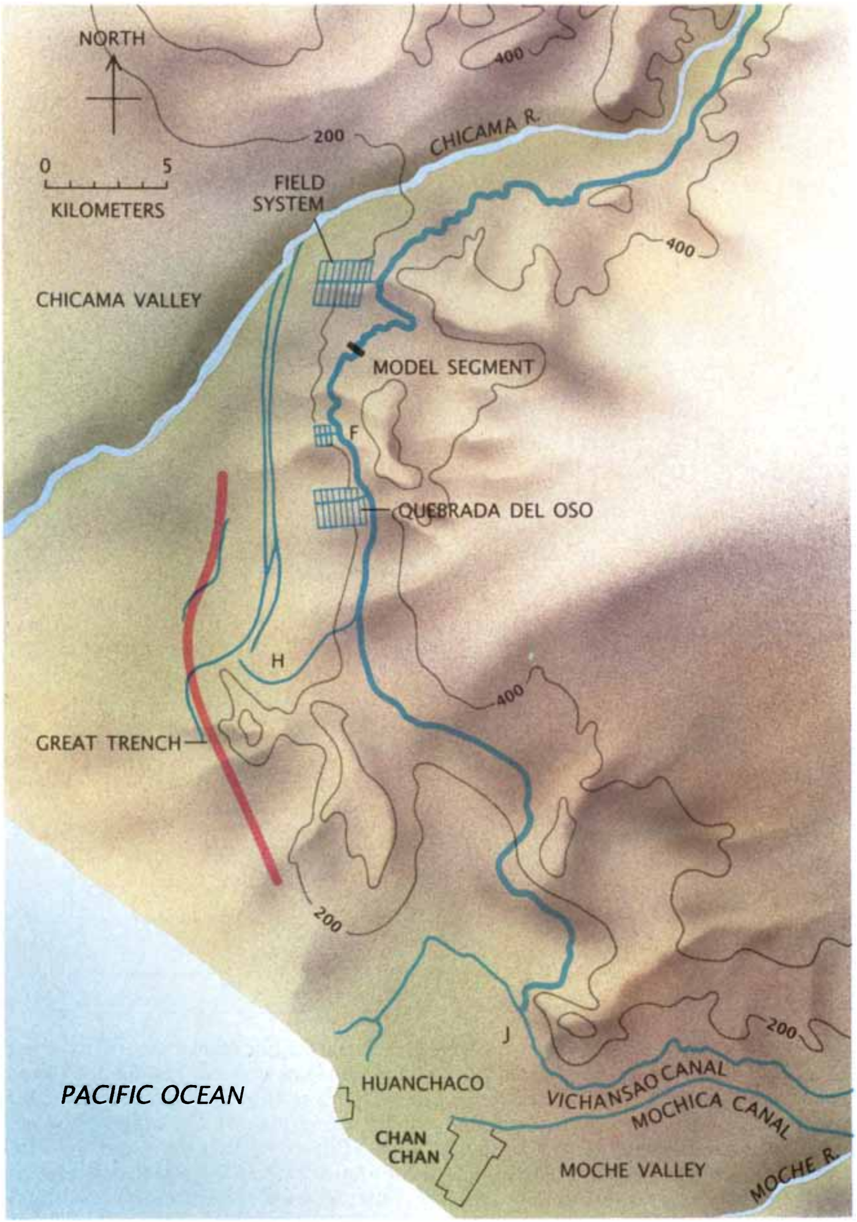
In a trench system the answer to the problem is to deepen the inlet, allowing water to flow into it again. Yet the inlet cannot be deepened by itself; if water is to flow, the entire trench must also be deepened accordingly. Such deepening may be effective for a while, but in the long run it causes a considerable problem. In order for the water to run out onto the fields, the canal must be above the growing surface. As a trench-canal system is repeatedly deepened, more and more land is lost to irrigation. Indeed, such deepening ultimately pushed agriculture out of the Pampa Cacique region altogether.

The solution to the problem was to replace the trench canals with a completely new type of system: contour canals. Contour canals closely follow the contour lines of the landscape in order to maintain a small, constant slope as they descend. As opposed to the simple trenches, contour-canal systems require precise surveying skills to find the correct path. They also mandate elaborate "fill structures," such as aqueducts (crossing the mouths of quebradas, or rain-deepened canyons) and terraces (to carry the canal smoothly along the sides of the rugged Andean foothills). These techniques were probably introduced in an evolutionary manner to deal with specific circumstances. When they were all in place, however, they formed the basis of a potent new system.

One of the keys to the new arrangement was the placement of the inlet as far as possible upriver. Clearly the higher upriver the inlet was placed, the greater was the area of downslope land that could be watered by the canal system. The highest inlet point was determined by the bedrock configuration of the Andean foothills. The simple stone-and-bronze tool kit of the Chimu was adequate for digging in the soft fluvial soils deposited by the river, but it was by no means up to slicing through granitic mountains. Therefore the highest possible inlet was on the Moche River, just where the river leaves the foothills and traverses the fluvial delta of its own valley. This is precisely where the inlets were located when the early, maximum-reach contour canals were constructed by the Chimu. These highest-elevation contour-canal systems were situated on both sides of the Moche River; the northern system irrigated the rich Three Pampas area and the southern system provided irrigation water for the Pampa Cacique.

The new contour-canal systems recaptured land that had been abandoned when the trench system failed. Yet, like the trench canals, the contour canals were vulnerable to the downcutting action of the river. As the downcutting proceeded, the inlets of both the northern and the southern system tended to become stranded. Since the inlets had been intentionally placed far upstream against the base of the Andes, the only option when they were rendered useless was to move them downriver. The geometry of the river valley, however, together with bedrock obstacles along the river route, dictates that only certain points along the river are suitable for running the canal out onto the valley floor. The inlets of both the southern and the northern system were moved downstream twice in separate construction phases as higher inlets were stranded in succession.

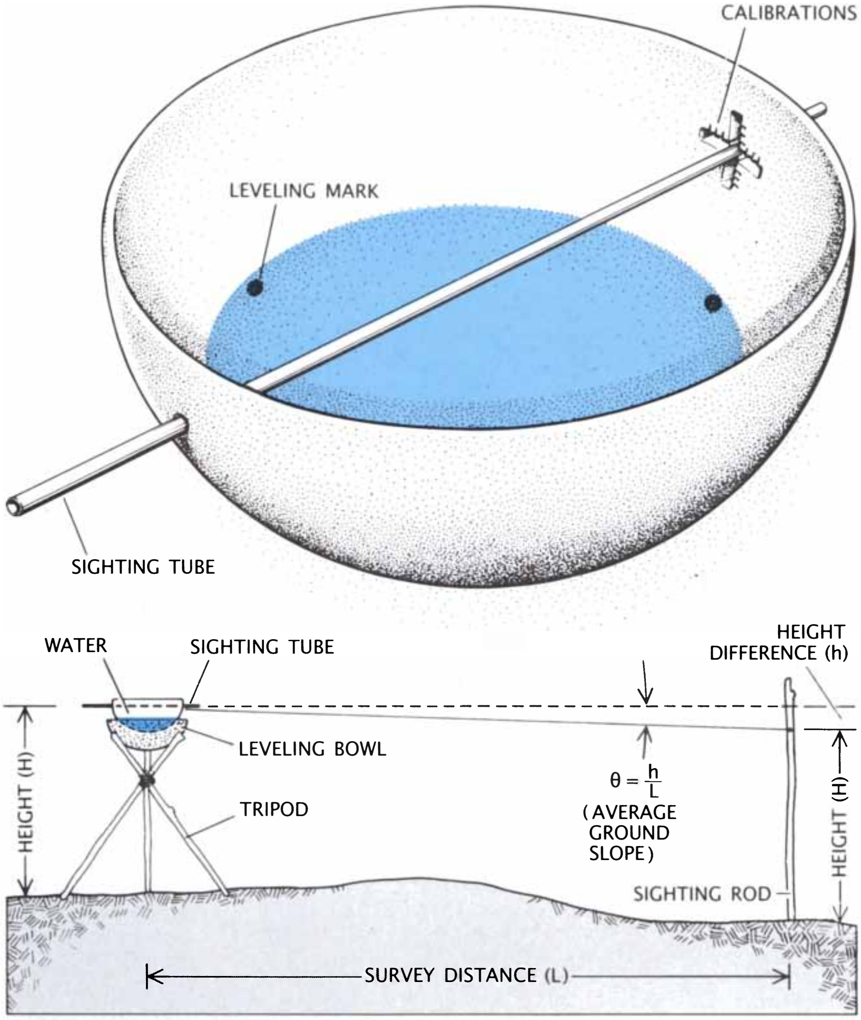
Each time the inlet was moved downstream considerable downslope land was lost to cultivation, because the lower system could not provide water to the highest areas that had been watered under the previous arrangement. Indeed, by the time of the final northern system, the Chimu had lost so much land that the engineers were forced to direct the irrigation water into certain compounds of Chan Chan itself and exploit what had been part of the urban center as farmland. Before being forced to that alternative, however, they turned to an expedient they hoped would save them: the Intervalley Canal.



ROUTE OF INTERVALLEY CANAL was laid out in an effort to save the Chimu canal system by importing water from the Chicama River to the Moche Valley. The Intervalley Canal intersected the Vichansao Canal on the north side of the Moche Valley (*point* J) in an attempt to maintain and increase the flow to the agricultural regions near Chan Chan, which included the pampas Huanchaco, Rio Seco and Esperanza. Feeder outlets also watered fields along the canal route (*as at point* H).

The Intervalley Canal extended 74 kilometers from the Chicama River to the contour-canal systems on the north side of the Moche Valley. By joining the Intervalley Canal to the existing contour-canal system the Chimu engineers hoped to restore agricultural production in the Three Pampas area. Indeed, by constructing additional low-slope special branches of the Pampa Huanchaco canal system near Chan Chan, they hoped to expand the area under cultivation based on water supplies from the Intervalley Canal. The flow rate throughout the intervalley system was designed to match the rate required by the Three Pampas field systems at maximum usage. Although the Intervalley Canal certainly functioned as far south as Quebrada del Oso, distortions along its length led to its being abandoned before hookup with the Vichansao Canal could be accomplished. As a result most of the Three Pampas fields fell into disuse, and near-river agriculture was possible only by means of the lowest downriver canals.

Both the sequence of Moche Valley systems and the Intervalley Canal attest to the innovative practices of the Chimu engineers. One major set of innovations concerned the shape and construction of the water channel itself. This process can be seen quite clearly in the canal on Pampa Huanchaco near Chan Chan. The earliest phases of the system appear to have been nothing more than trenches dug



CHIMU SURVEYING DEVICE was reconstructed by the author from concepts suggested by an artifact in the Huaraz Archaeological Museum in Peru. The device (*upper panel*) consists of a bowl pierced by a hollow sighting tube that passes through a small hole on one side and a calibrated cruciform opening on the other. The bowl is filled with water and the bowl orientation is adjusted so that the water wets the three dots on the inner surface. In operation (*lower panel*) the water provides an "artificial horizon," or absolute horizontal plane. When the sighting tube is adjusted to the center of the cruciform opening, it is parallel to the water surface. A rod of known height (*H*) equal to the height of the sighting tube above the ground is placed a known distance (*L*) away. With the calibrations on the cross-shaped opening, the average ground slope (θ) can readily be measured by sighting the top of the rod.

in sandy soils; the excavated remains reveal cross-sectional profiles characteristic of water erosion of sandy soils.

In about A.D. 1100 a devastating El Niño flood seems to have largely destroyed the Pampa Huanchaco canal system along with other systems. The disaster apparently gave the hydraulic engineers the opportunity to rebuild the system on the basis of new knowledge. The rebuilt segments are less sinuous than their predecessors. Moreover, the new canals were stone-lined and had a smaller cross section than the earlier ones.

Most remarkable, however, is the fact that the cross section of the reconstructed canals approximates the shape modern engineering shows is the most hydraulically efficient among the class of trapezoidal sections: the half hexagon. Such sections minimize the wetted perimeter for a given area of the channel to give it the maximum rate of flow. These innovations reduce channel resistance and help to maintain a high flow rate even in the face of the continuously decreasing supply to the system. The reduced cross-sectional area also increased the water depth, avoiding the stranding of feeder inlets leading to the fields.

A significant aspect of the contour-canal design is that in order to irrigate the maximum land area, the canal leading away from the river must start at an inlet far upstream and run approximately along the constant-slope contour of the valley floor that includes the maximum downslope land area possible. The lower the canal slope is, the more land downslope of the canal can be watered by it. It follows that the canal system will have a very slight slope. Indeed, the Pampa Huanchaco bed slopes are on the order of .009 for most of the system: a drop of nine meters in every 1,000. This low, constant slope no doubt entailed some sophisticated means of measuring slopes and choosing the best route. Yet the archaeological record has not yielded any evidence of a written Chimu language or mathematical notation. How was the surveying done?

One possible answer comes from ideas suggested by a Chimu ceramic I examined in the Archaeological Museum at Huaraz in Peru. The ceramic is a cylinder that has a hole on one side and a cross-shaped cutout opposite the hole; a leveling bowl is fastened to the top of the cylinder. Based on the design and the implied function of this ceramic as a surveying device, I constructed a simplified instrument based on the same principles. The bowl has a hole on one side and a cruciform cutout on the opposite side. Calibration marks are placed on both the vertical and the horizontal arm of the cutout. In addition, three marks on the inner surface of the bowl define a plane surface parallel to a hollow sighting tube when the tube extends through the hole and the center of the cross-shaped cutout.

When the bowl is filled with water and is then placed in a larger, shallow container mounted on a tripod and filled with sand, the position of the bowl can be adjusted until the water level matches the marks on the inside of the bowl. The water's surface then defines an "artificial horizon" to which the sighting tube is parallel. The tube can be moved vertically and sighted through onto a rod of known length held upright a known distance away. This procedure would yield the vertical angle. The horizontal angle could be determined by means of some fairly simple calculations. I have constructed a working model of this surveying device and used it to make accurate measurements under field conditions. It is not difficult to imagine larger and more finely calibrated versions that would produce even better results.

Although the Pampa Huanchaco canal provides insights into the innovations of which Chimu engineering was capable, it is the massive Intervalley Canal that offers the most information about Chimu ideas on optimum design. One feature of the Intervalley Canal is the presence of many segments that exhibit interesting variations in their cross-sectional geometry. Clearly these variations are not accidental; the Chimu were too skilled as builders for that to be so. What, then, was their function?

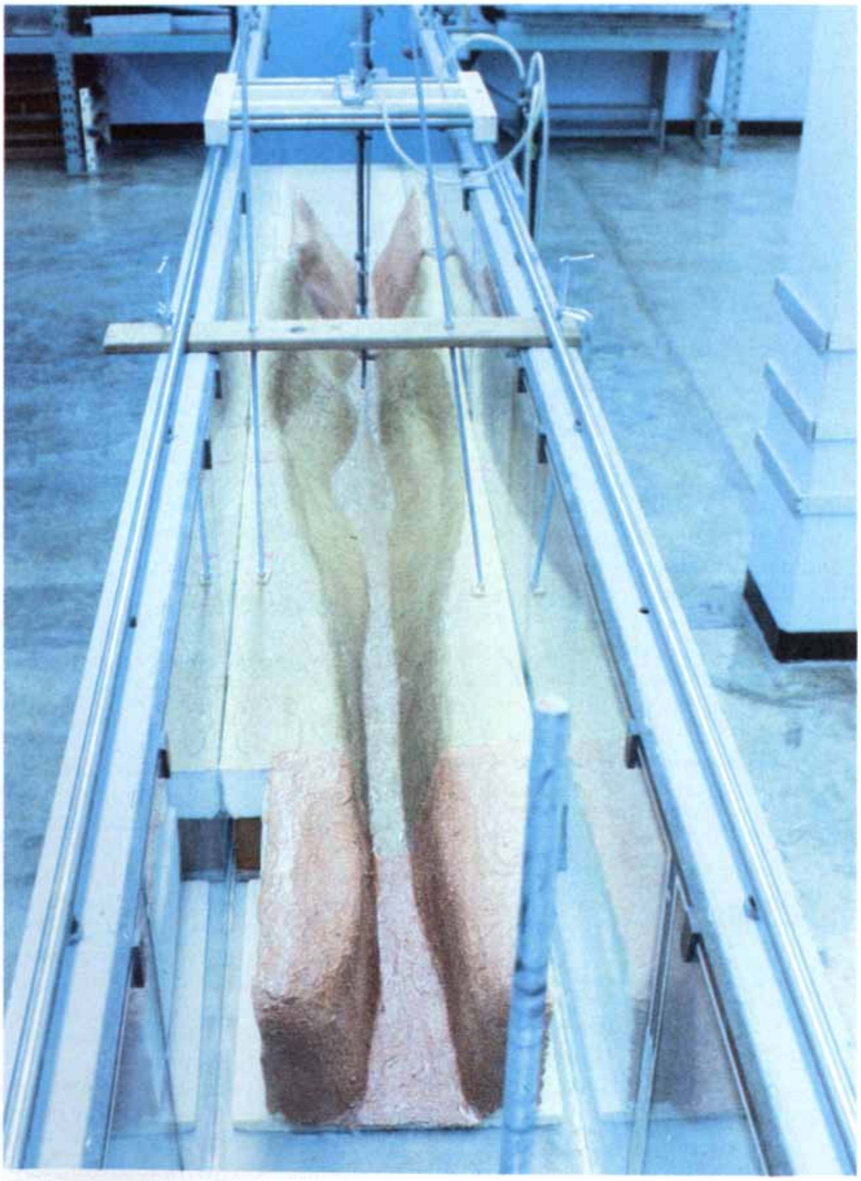
A clue is given by the fact that many of these segments lie immediately upstream from large aqueducts (such as the ones that carry water across the mouth of a quebrada). Since aqueducts are large and labor-intensive, it is plausible to assume that the curiously shaped segments were designed to preserve the aqueduct from the effects of erosion during sharp changes in the flow rate resulting from floods. One way to test this hypothesis would be by computer simulation, but computer simulation of open-channel hydraulic systems is as yet an imprecise art. Therefore a scale model of a channel section just upstream of an aqueduct was constructed in order to observe its behavior under various flow conditions.

The results of these experiments (conducted at the hydraulics laboratory of San Jose State University) were revealing. The canal segment was tested over a range of different flow rates at the inlet. In hydraulics this range is generally described by means of a quantity called the Froude number. The Froude number is the ratio of the velocity of the moving fluid to the wave speed of small gravity waves that occur in shallow water in channels as a result of any momentary change in the local depth of the water. The wave speed is proportional to the square root of the depth. Hence a low-depth, fast-moving canal flow (such as one resulting from heavy rainfall) would have a Froude number greater than unity, whereas a deep, slow-moving stream would have a Froude number less than unity.

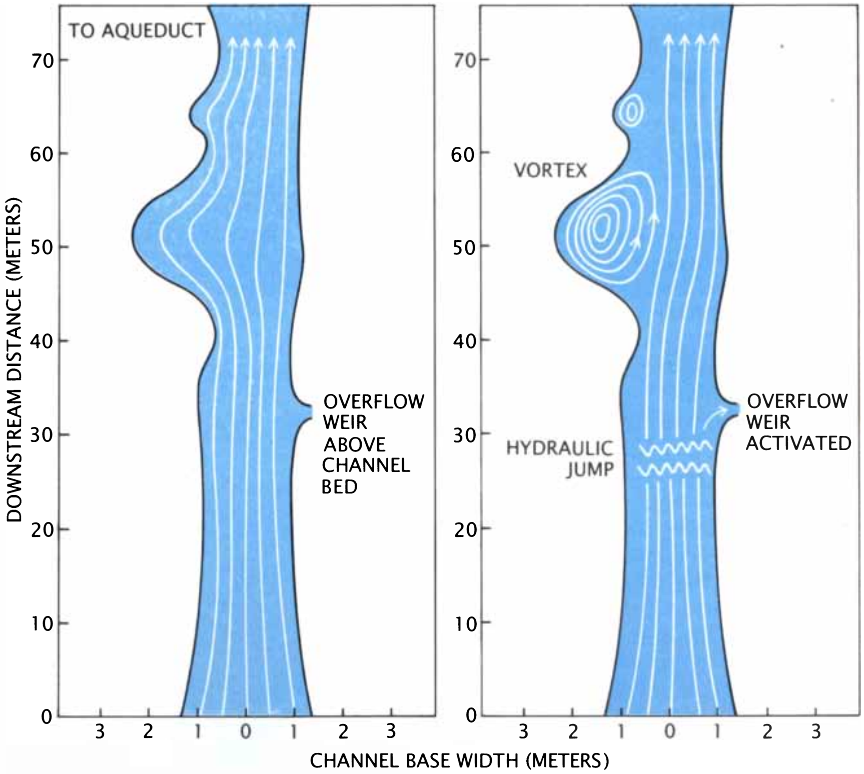
The behavior of the model segment was observed over a range of inlet Froude numbers from much less than unity to much greater than unity. Remarkably, it was found that the higher the inlet Froude number, the lower the outlet Froude number. Now, the outlet Froude number can be taken as a measure of the fluid's capacity to damage aqueduct wall linings by erosion. Therefore the Chimu engineers reduced erosion on aqueducts by installing upstream segments that drastically reduced the erosive capacity of the flow, even as its velocity increased.

Detailed analysis of the model segment's behavior showed that this feat was not accomplished in a simple way. In order to understand this behavior one must have some knowledge of different patterns of flow in an open channel, which hydraulic engineers refer to as hydraulic regimes. A subcritical regime corresponds to a Froude number less than 1. The flow height may asymptotically approach either normal or critical depths depending on initial flow depth for small values of the bed slope. At the normal depth the flow is uniform and parallel to the channel bottom for channels of rectangular cross section. The normal and critical depths are theoretical values that depend on the shape of the channel, the wall roughness and the slope used to characterize the flow regimes.

A supercritical regime, on the other hand, corresponds to a Froude number greater than 1. These rapid flows on steep-sloped channels asymptotically approach the normal depth provided the initial flow depth is less than the critical depth. Additionally, such



MODEL CANAL SEGMENT was constructed by the experimental-composites laboratory of the FMC Corporation and installed in the hydraulics laboratory of San Jose State University. The segment is from the Intervalley Canal, and it lay upstream of an aqueduct. It was tested in the laboratory under a wide range of inlet Froude numbers to determine what function the variations in channel width and cross section might have served. Some results of the tests are shown in the illustration on the next page.



RESULTS OF TESTING model segment in the preceding illustration are shown. The top-view streamlines indicate the path of particles in the channel. For inlet flows that are subcritical (*left*), expansion of the flow in the channel reduces its velocity. For supercritical flows (*right*), a standing vortex forms in the cavity. The edge of the streamline pattern acts as a "virtual wall," effectively narrowing the channel. In addition, the narrowing of the channel creates supercritical choke conditions that cause a hydraulic jump. After the jump the channel widens and the flow remains subcritical. Thus for both subcritical and supercritical inlet flows the segment serves to reduce the outlet Froude number, protecting the downstream aqueduct.

flows can produce velocity and depth discontinuities in the form of "hydraulic jumps" in the presence of contractions in the channel or sudden bed-slope changes.

What is perhaps most significant is that subcritical and supercritical regimes behave quite differently when the channel widens. When a subcritical flow encounters a wider channel, it expands and decelerates. A supercritical flow, on the other hand, accelerates when its channel broadens while its depth decreases. These concepts provide the basis for understanding what happens in the model segment.

The segment itself is narrow upstream, widening about halfway down in a semicircular hollow. At low inlet Froude numbers the subcritical flow experiences a velocity decrease owing to expansion effects. As the inlet Froude number increases, a vortex appears in the hollow. At high subcritical Froude numbers (those near 1) the vortex streamline acts as a "virtual wall," which has the effect of a reduction in channel width. Downstream of the vortex the flow slows, again owing to expansion effects.

At a supercritical inlet flow the vortex apparently acts to produce a distorted streamline pattern sufficient to produce a "supercritical choke." The net result is a hydraulic jump standing upstream of the neck region. This flow discontinuity marks the abrupt transition from a supercritical regime to a subcritical one. Because the postjump flow is subcritical, downstream expansion can yield a velocity decrease.

As a result this unusually shaped section of the Intervalley Canal is effective in reducing the outlet Froude number (by reducing flow velocity and increasing flow height) and thereby preserving the lining of the downstream aqueduct. In addition, an overflow weir can drain off surplus water when the post-hydraulic-jump water height exceeds the height of the weir above the channel bottom. Since the postjump height increases with the inlet Froude number, the weir provides yet another protective feature to drain runoff flow from the channel. The use of canal cross-sectional shaping (together with changes in wall roughness) to produce a flow within a given Froude number range when the bed slope cannot easily be varied because of bedrock surfaces is the major hydraulics innovation of the Intervalley Canal. This sophistication behind such design innovations is particularly impressive in the absence of mathematical notation.

Yet in the end even such sophistication was not enough to prevent the collapse of the Moche Valley agricultural systems. The downcutting of the Moche River finally forced the abandonment of the upriver systems; the final canals (cut after abandonment of the Intervalley Canal) had inlets far downriver and were able to water only a small proportion of the early fields. Finally the Chimu even began to cultivate land within the walls of Chan Chan that could be served only by the lowest canal system.

The reduced area of land under cultivation may well have been one of the factors that made the Chimu capital vulnerable to conquest by the Incas, a conquest that had been realized by A.D. 1450. What is most striking about the kingdom of Chimor, however, is not its end. It is the fact that in the face of an environment that was constantly deteriorating for agricultural production, a civilization with simple instruments was able to develop the innovative, adaptive engineering techniques needed to sustain progress and cultural continuity for nearly 500 years.

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SCIENCE AND BUSINESS

Unorthodox economics, alcohol on the road, vindicating a computer

Disequilibrium

Might bacteria someday help to explain international debt?

Sheltered in a former convent not far from the center of Santa Fe, N.Mex., a few economists spent 10 days this past summer thinking about how proteins evolve. They also began wondering why it is that as sand is slowly poured atop an existing sandpile, avalanches of various sizes form and tumble down the sides. At the same time a handful of natural scientists—physicists, computer scientists, even a biologist—mused over the mechanisms of the stock market and pondered over why some countries develop faster than others.

Although most have left Santa Fe, these 20 or so investigators are continuing to hunt for new ways to explain economic activity by applying insights from other scientific disciplines. A few have proposed radical breaks from economic dogma; others have urged caution. "We don't want to be belligerent vis-à-vis conventional economists," adds W. Brian Arthur, an economist at Stanford University. "But it seems now is the time to break out." Portrayal of the economy as a relatively predictable system that moves in an orderly fashion has yielded important insights, Arthur says; he hopes that loosening or abandoning such assumptions may lead to the next generation of advances.

This leap from the conventional was initially spurred by a bank. In 1986 John S. Reed, chairman of Citicorp, found himself staring at a $15-billion problem in the guise of the unpaid—and possibly unpayable—loans Citicorp had made to developing countries since the late 1970's. Reed attributed much of the problem to flawed advice. At the time, the models used by economists indicated that rapid growth would continue and the loans would be repaid with interest. A decade later, however, there were no models to help Reed tackle the monstrous debt developing nations had accrued. And so Reed, who holds a degree in metallurgical engineering, appealed to the hard sciences. Come up with a new model to explain how the global economy works, he challenged them. Do whatever you like, he went on, but make sure it is not too conventional.

"The occasional forays by physical scientists into economics have usually, but not always, been trivial," says Kenneth J. Arrow, a Nobel laureate in economics. Economists for their part have borrowed some mathematical tools from the natural sciences. Still, Arrow and Philip W. Anderson, a Nobel laureate in physics, found Reed's challenge intriguing. A 10-day workshop, with participants handpicked by Anderson and Arrow, at least seemed a good forum in which economists and natural scientists could swap ideas and techniques. They met at the fledgling Santa Fe Institute in 1987 and then again this September; an ongoing research program on economics has also been initiated.

The group has not yet produced any models that will help Reed to make his next decision, but Citicorp is patient. "The Third World debt problem is going to be around for at least 15 years," observes Eugenia M. Singer, a Citicorp vice-president. Instead the investigators have plunged into more fundamental issues: Does the economy move toward "equilibrium points," as economists have assumed for decades? Or might the economy evolve as an ecological system does, resulting from the interactions among coevolving organisms or agents? Is nonlinear behavior an important characteristic of the economy?

Dynamic equilibrium, a cornerstone of traditional economic models, is defined as a changing point where the supply of goods satisfies consumers' demand for them. Conceptually equilibrium is appealingly straightforward; it assumes, for example, that when prices rise, demand will fall, which in turn lowers prices. These forces thus dampen one another, pushing the system into equilibrium.

Yet even though the mathematical tools employed by economists have become more sophisticated, the models still seem to stray from reality. In an equilibrium framework economists are hard-pressed to account for persistent, irregular fluctuations in the economy—in particular last year's stock-market crash. Contrary to theories, technology has often widened rather than narrowed the chasm between wealthy nations and poor ones. Moreover, although economists can mathematically prove an equilibrium point exists, calculating the specific point is often impossible. Such complexity creates a philosophical stumbling block: if economists cannot find the solution to a problem, how can consumers and producers do so? Yet in spite of various attempts, Arrow says, no one has yet come up with a coherent and general substitute for equilibrium.

The investigators who attended the Santa Fe conference are now taking their shots at it. Consider their model of an evolving economy. In this constantly changing and unpredictable environment, agents simply try to survive by doing a bit better than they did yesterday. (Equilibrium models, on the other hand, assume consumers and suppliers consistently act optimally in an environment they understand.) Coevolving agents both learn to adapt to their environment and change it as they do so.

The workers expect to test the idea using machine-learning theories developed by John H. Holland, a computer scientist at the University of Michigan. Holland's "classifier" system will simulate a miniature stock market populated by "agents" (sets of rules) that trade money for stocks. The classifier generates new rules by combining successful rules and eliminating unsuccessful ones, a computing technique called a genetic algorithm. Holland and Arthur will monitor which rules prove successful under various conditions. "We hope to show that starting from very simple rules, the market will organize itself into a very complicated psychological state," Arthur says. Such results would prove that stock-price movement reflects much more than financial parameters such as interest rates and dividends. Although that conclusion may not surprise many stockbrokers, it would break with conventional economic theory.

Others among the investigators are hoping to understand economic complexity in terms of "self-organizing criticality," a concept pioneered by Per Bak, a physicist at the Brookhaven National Laboratory. When a system of this nature, such as a pile of sand, reaches a threshold, it reorganizes itself through "big and little avalanches" in a statistically predictable way, explains Richard G. Palmer, a physicist at Duke University. Anderson and Palmer think this description might well fit the diffusion of new technology through the economy. By analyzing data on the growth and output of industries, they hope to find structures statistically similar to those of other self-organizing systems.

Economists have long studied other cases of nonlinear behavior, where small differences in initial conditions cause widely divergent behavior in the long run. The Santa Fe Institute participants are pursuing a host of such ideas. Among them is the possibility that the product that becomes successful in the marketplace may not be the technologically superior one. Instead the choices of the first consumers may create positive feedback that influences later buyers. Another idea is that the rate at which a new technology emerges in a country may depend on how long related technologies have been in use as well as the cost of adopting the new technology. In a developing nation, for instance, a change in farming techniques could create such a demand for fertilizer that it triggers the development of a local chemical industry.

To be sure, the meshing of ideas from different disciplines may lead to more work rather than to neat solutions. Last year the Santa Fe participants buzzed with excitement over the possibility of describing the turbulence of the stock market by means of chaos theory, a subdiscipline of nonlinear dynamics. Now many are convinced that although chaos may describe individuals' activity or microeconomic behavior, data on broader, macroeconomic trends still conform to regular cycles, blurred by "noise"—noneconomic factors such as politics or the weather.

The investigators also caution that any physical model must be extensively reworked before it can describe economic activity properly. "Talking to physicists can help us," says Timothy J. Kehoe, an economist at the University of Minnesota, "but then it's a matter of doing hard work." Yet Santa Fe could break new ground, Arrow says, both by stimulating interdisciplinary projects and by shifting economics away from the stiff mechanism of equilibrium toward a "groping" system more akin to the evolution of ecological systems. *—Elizabeth Corcoran*

One for the Road

Will alcohol-fueled cars take off or backfire?

Alternative fuels may one day cure many energy and environmental ills. But a new law that tries to take the first step toward using them is already mired in controversy. In mid-October President Reagan approved a law that gives car makers a break on fuel-efficiency standards if they produce vehicles that can run on alcohol fuels as well as gasoline. Although many environmentalists endorse the use of alcohol fuels, they argue that the new law is not likely to decrease pollution or reduce U.S. dependence on foreign oil supplies.

The alcohol fuel of choice is methanol, generally derived from natural gas. (Ethanol, an alcohol fuel often mixed with gasoline to boost octane levels, costs at least twice as much as methanol.) California already has 550 experimental cars, most of which are built to run exclusively on M85, a blend of 85 percent methanol and 15 percent gasoline; New York City has six buses that run only on pure methanol. The "flexible-fuel vehicles" encouraged by the new law will run on whatever mixture of gasoline and alcohol is pumped into the tank.

The pros and cons of various fuels revolve about their emissions and the costs associated with each fuel. Proponents of neat methanol and M85 point out that the hydrocarbons they generate are less reactive and hence create less low-level ozone than the hydrocarbons from gasoline. According to a study by Ford of 20 cities, excluding Los Angeles, peak ozone formation could be reduced by between 3 and 13 percent if all cars in those areas used M85. Unlike diesel, methanol produces very few particulates and is therefore a much cleaner fuel for heavy trucks. Nevertheless, burning methanol also gives off the suspected carcinogen formaldehyde, which gasoline emits in minute quantities.

Neat methanol results in lower levels of hydrocarbon emission than M85 does, but the pure fuel has some hazards. It is toxic even though it is odorless and colorless, and it burns with a virtually invisible flame that can make it difficult to see a methanol fire. Methanol's low vapor pressure can also make it hard to start a methanol-powered engine in cold weather. Those drawbacks have led the eight-year methanol project run by the California Energy Commission to turn to M85.

Vehicles designed to burn only M85 or neat methanol raise what Charles R. Imbrecht, chairman of the California Energy Commission, describes as the "chicken and egg" problem: in the absence of cars that use methanol, service stations will not refit tanks to store the fuel, but without service stations, consumers are loath to buy cars that lack ready fuel supplies. The flexible-fuel vehicles should help to solve this dilemma, Imbrecht says; drivers can buy M85 when it is available or fill the tank with gasoline when it is not. (Earlier this year ARCO and Chevron agreed to install as many as 25 M85 pumps each in California service stations.)

Convincing consumers to buy methanol will still be difficult. In October, M85 was selling at about 85 cents per gallon, a price comparable to unleaded gasoline, even though it yields only about half the fuel mileage. Methanol proponents believe the price will drop as supplies increase. They also point out that methanol's octane number is much higher than that of the more expensive premium gasoline, which should make it attractive to owners of high-performance cars.

Drivers who top off half a tank of methanol with gasoline, however, may be harming the environment more than helping it, say critics of the flexible-fuel strategy. Mixing large quantities of gasoline with methanol increases the vapor pressure of the fuel, so that highly reactive hydrocarbons escape into the atmosphere, producing even more ozone than gasoline does, according to critics. "If a methanol vehicle is good, then you should just mandate the use of methanol," says Clarence M. Ditlow, executive director of the Center for Auto Safety.

New York City's Department of Environmental Protection would like to agree. This past summer the department wrote to car makers around the world asking if they would take part in a program to develop cars that run only on neat methanol. Many of the cars used in Manhattan belong to public or private fleets. The department says it could install methanol pumps at city-owned service stations and would hope to convince the stations that fuel private fleets to do the same.

Where all the methanol will come from is another complex issue. It costs almost twice as much to make methanol from coal or biomass as it does from natural gas. Although the U.S. has large reserves of natural gas, cheaper sources of gas are found in a number of developing nations. Even if methanol does not trim net U.S. fuel imports, experts say, it may reduce the country's vulnerability to fuel cartels.

Paradoxically, critics of the law argue that it may actually increase the use of gasoline by giving car makers who produce flexible-fuel vehicles credits on fuel-economy standards. Environmentalists say that requiring automobiles to meet specific efficiency levels has helped to cut gasoline use and reduce pollution. Weakening the standards, Ditlow adds, will allow manufacturers to turn out cars that need more gasoline. *—E.C.*

A Different Engine?

An unbuilt prototype may get another chance

The work had already exceeded its budget a dozen times and was 16 years behind schedule. Prospects for renewed funding looked bleak. And yet the inventor remained confident in his work. "Who," he demanded, "possessing one grain of common sense, could look upon the unrivalled workmanship of the Difference Engine No. 1, and doubt whether a simplifed form of the same engine could be executed?"

By 1842, however, the British government was less impressed than the inventor, Charles Babbage, and refused to invest another penny in the project. Profoundly discouraged, Babbage never finished building a machine; nonetheless, he has become known as the intellectual father of the computer. Now, three years shy of Babbage's 200th birthday, the Difference Engine may get another chance.

Workers at the Science Museum in London have been building a piece of the calculating mechanism described in Babbage's plans for his second Difference Engine. The subsystem will be able to add two two-digit numbers (with a carry), explains Doron D. Swade, curator of computing at the Science Museum. The hope is then to raise some £200,000 to £500,000 for building an entire Difference Engine.

"The accepted wisdom is that Babbage failed to complete the machine because of the limits of techniques of the day," Swade says. He argues instead that Babbage was frustrated more by politics, circumstances and his own temperament than by the technical difficulties of precisely machining intricate parts. By the time Babbage died at the age of 78, his London neighbors knew him as an eccentric who waged a long and fierce campaign against organ grinders.

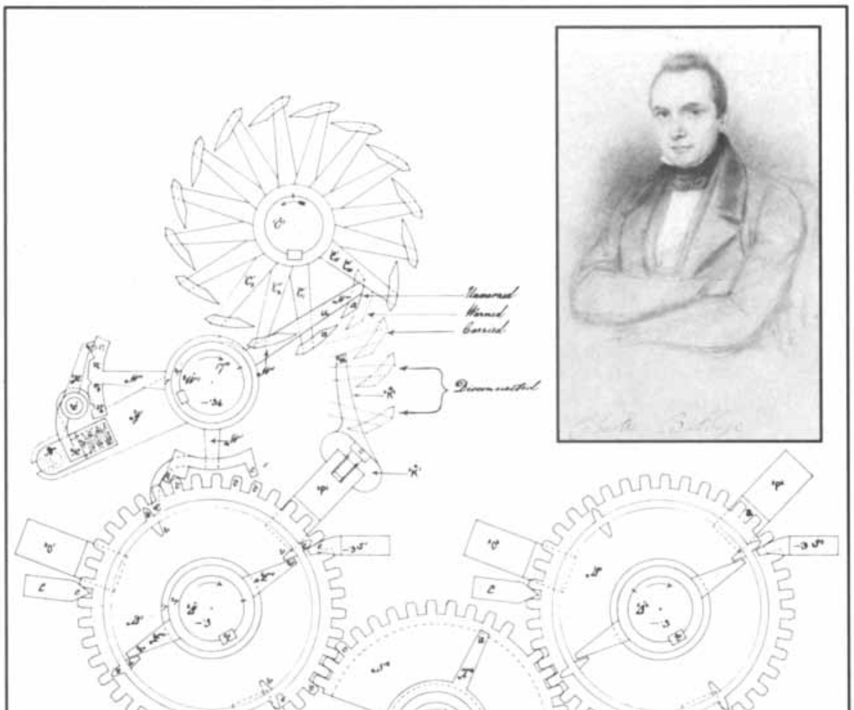
The idea of a Difference Engine was born in about 1812 when Babbage began dreaming of a calculating machine that could churn out perfect mathematical tables. In his design, gears labeled with numbers would turn to add the numbers. The mechanism could be adjusted to calculate various numerical series and polynomial equations; all an operator had to do was turn a crank for the results.

After building a small demonstration model, Babbage offered to construct a large machine for the British government that would produce navigational tables. He predicted the project would take no more than three years and would cost a few thousand pounds. The government contributed its first £1,500.

By the mid-1830's Babbage had become preoccupied with designs for a more sophicated machine, the Analytical Engine, which he envisioned programming with punch cards. It too went unbuilt, as Babbage began sketching out the second Difference Engine. After having invested some £17,000, government officials became convinced that the inventor's success was "problematical" at best and—in a move applauded at the time—decided to drop the project.

Vindicating Babbage will not be easy. Even though he produced a raft of detailed drawings of the second Difference Engine, he neglected to include such details as the dimensions, tolerances and materials of the parts. (Swade expects that the fully built machine will measure 10 feet long, six feet high and 1½ feet wide and will have several thousand parts.) Although Swade says computer simulations of parts will save both time and money, the workers will try to remain faithful to the construction techniques Babbage had at his disposal.

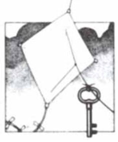
"We have very little doubt it will work," Swade asserts, echoing Babbage's enthusiasm. Swade believes the machine will be finished in time for Babbage's birthday celebration on December 26, 1991—provided the museum collects enough money. *—E.C.*



INVENTOR AND HIS DEVICE: Charles Babbage, in an 1841 pencil portrait, and one of his drawings of the addition mechanism for the Difference Engine. The illustrations are courtesy of the Trustees of the Science Museum, London.

THE AMATEUR SCIENTIST

The distorted images seen in Christmas-tree ornaments and other reflecting balls



by Jearl Walker

The reflections from a shiny ball, such as might decorate a Christmas tree, form a strangely distorted panorama of you and your surroundings. As though honored, you cannot help but be at the center of the display regardless of how you look at the ball. The mutual reflections of two adjacent balls produce two seemingly endless series of images that shrink toward the point at which the balls touch. A cluster of three adjacent balls is even more arresting, particularly if it is on a dark background. The plentiful images are dazzling, and the region between the balls may appear to be a dark triangle that has encroached on the balls, marring their sphericity. What accounts for these images?

In 1972 Michael V. Berry of the University of Bristol published a study about reflections from such spheres as a Christmas-tree bauble, a steel ball from a bearing and a certain type of lawn decoration. As it happens, Berry is the author of an article—on a different subject—in this issue of *Scientific American* [see "The Geometric Phase," page 46]. Each sphere serves as a convex reflector, yielding miniature and distorted images that seem to lie within the sphere. A larger ball, such as one of the lawn decorations, works better, because the images it yields are larger and more distinguishable. Within the sphere one sees a world that is more bizarre even than Lewis Carroll's looking-glass world.

Reflections from three shiny lawn decoration balls

If you place a large ball in the center of the lawn and look down on it, the world appears to lie within the ball's circular cross section, which I shall call the image plane. In it your eyes lie at the center and your head is surrounded by the sky. The edge of the lawn (effectively the horizon) forms a circle within the image, and trees that border the lawn stretch toward the center of the image. Tall buildings also stretch toward the center, but they are weirdly distorted with wide bases and narrow tops. Your own image is also warped: your feet seem too large and your body thins grotesquely toward your head like that of a cartoon character. The grass of the lawn rings the edge of the image plane.

The images you see are due, of course, to the reflection of light rays by the ball [*see top illustration on opposite page*]. A ray that originates from your eyes reflects back to you from the top of the ball; the ray travels down what I call the center line and then back up it. That is why the image of your eyes will always be at the center of the image plane. Rays that originate from other objects reflect and then travel to you at some angle to the center line. Berry pointed out that the extreme case is a ray that barely skims the side of the ball and is deflected negligibly by the reflection. Since it is approximately tangent to the ball, I shall call it a tangent ray. It marks the boundary of what you can see. Any point on the ground nearer to the ball than the origin of the tangent ray is hidden from view. Everything else in your surroundings has an image in the ball, except of course where your body happens to block rays from reaching the ball.

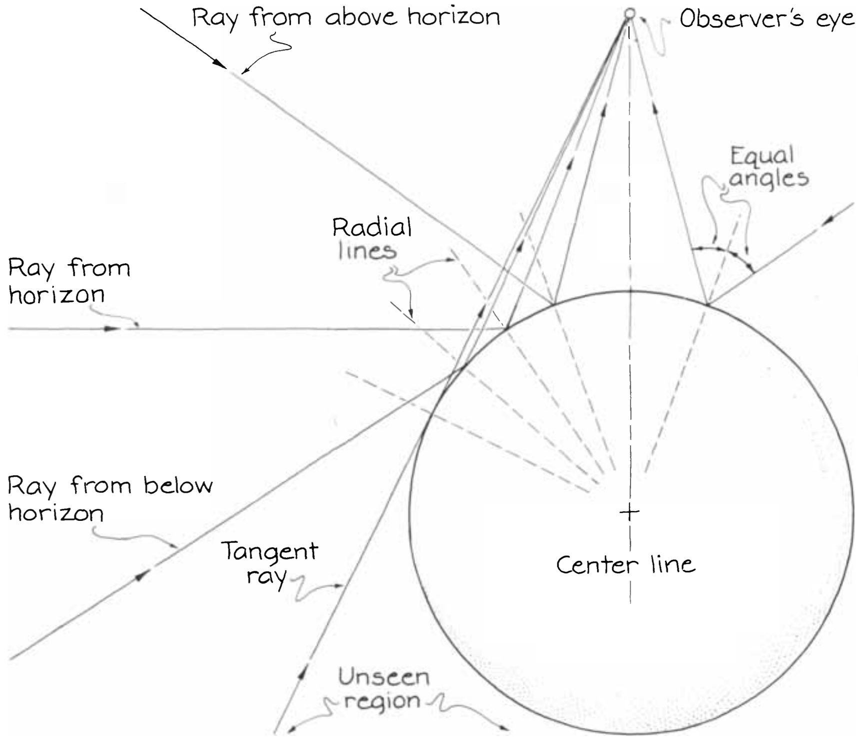
One of the rays you see originates at what is effectively the horizon, and it approaches the ball along a horizontal path. Rays that reflect higher on the ball than the horizontal ray approach the ball along a path that is angled downward, and they are said to originate above the horizon. Rays that reflect to you from points on the ball lower than the horizontal ray approach the ball from a path that is angled upward, and they are said to originate below the horizon. (This last set of rays is important in the discussion that follows. Notice that these images of the ground lie above the middle of the ball and between the points where the horizon and tangent rays reflect.)

Each reflection obeys a firm rule: The initial ray and the reflected ray must have the same angle with respect to the radial line that runs from the center of the ball to the point where the ray strikes the ball's surface. In the case of the tangent ray the angles between the two rays and the radial line are both 90 degrees; in the case of the ray from your eyes the angles are zero. How the horizon ray reflects depends on the distance between you and the ball. If the distance is large compared with the ball's diameter, the angles for the horizon ray are about 45 degrees and the reflected ray is approximately vertical. If the distance is short, you see another horizon ray that reflects somewhat higher on the ball. The angles involved in the reflection are then larger and the reflected ray slants away from the vertical toward you.

The dark triangle that appears when a cluster of three balls rests on a dark background was noticed by Bob Miller, a San Francisco artist. His display of it can be seen at that city's marvelous playland of science, the Exploratorium. I wondered about the triangle and also about the multiple images of the balls and the sky that are created in the cluster of balls. How exactly do light rays reflect to make the images, and which ball gives rise to any particular image?

Initially I thought the task of identifying the images was virtually impossible. Every time I looked into a cluster of three garden-decoration balls and tried to draw more than a few of the images I became hopelessly confused. I therefore removed one ball and studied the images in the remaining two. In each ball there was then a series of at least a dozen images surrounding the point where the balls touched.

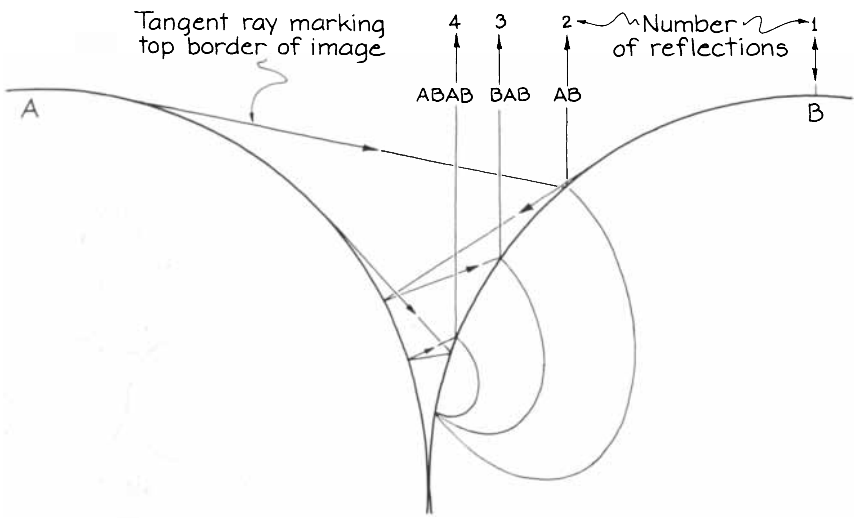
The array is similar to the multiple images you see if you stand between two parallel mirrors. In each mirror you see a series of images of that mirror's frame and the other mirror's frame. The largest image is due to rays that leave the opposite mirror and then reflect to you from the mirror you face. The next image is due to rays that leave the mirror you face, reflect from the opposite mirror and then again from the first mirror. The extra distance traveled by this set of rays makes the image smaller. Each additional image involves one more reflection and so is smaller than the preceding image.



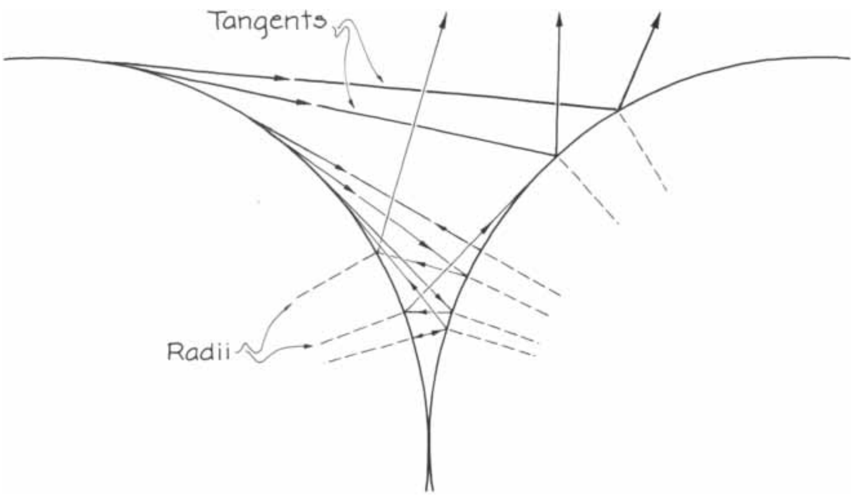
How rays reflect from a shiny ball

When you look at reflections in adjacent balls, you see an edge of a ball instead of a mirror frame, and the images shrink faster than images in flat mirrors because of the curvature of the reflecting surfaces. Some of the reflections are shown in the illustration below. The top of ball *B* bears an image of the sky that is due to rays reflecting once. The next-lower image comes from ball *A*. Its top border is due to a tangent ray from *A* that reflects to you from *B*. Just below the border you see an image of the sky that has reflected twice—once from *A* and once from *B*.

Somewhat farther down there is an image that comes from *B*. The top border is due to a tangent ray leaving *B*, reflecting from *A* and then from *B* again. Just below the border you see an image of the sky that has been reflected in the sequence *BAB*. The rest of the images that you see in *B* are



Reflections from two adjacent balls



Reflections of a tangential ray as it is successively angled downward

similar: the images alternate between being reflected first by *A* or by *B*, and each time the top border of the image is due to a tangent ray.

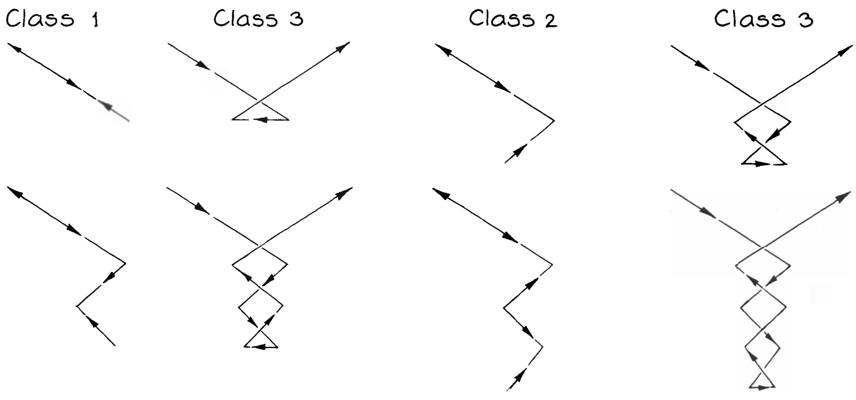
Wondering if the reflections could be catalogued better, I studied the tangent rays from *A*, starting with one that leaves high on the ball and is reflected by *B* toward the right [*see illustration above*]. Imagine what happens if you watch a videotape in which the initial ray from *A* is slowly angled down along the side of *A*, always staying tangent to the ball. During the descent the resulting ray reflected by *B* swings leftward through the vertical and then toward *A*, and the reflection sequence is *AB*.

Stop the tape when the final ray, like the initial ray, is tangential to *A* and note that at that moment the light happens to be reflected along a radial line through *B*. Such a reflection sends the light back along its previous path, so that it reflects tangentially from *A* again. When you restart the tape, the light reflects three times in the sequence *ABA*, and the final ray begins to swing rightward through the vertical and then toward *B*. When it reaches *B*, again stop the tape and examine the light path. Note that the lowest segment of the path is horizontal. This feature indicates that the ray's path is symmetrical left and right. Since the initial ray is tangent to *A*, the final ray is tangent to *B*.

Continue the tape. There are now four reflections in the sequence of *ABAB*, and the final ray swings leftward through the vertical and back to *A*. Stop the tape when it reaches *A*. Just then the lowest segment of the light path reflects along a line that is radial to *A*, and the light is sent back along its previous path and so ends up being tangential to *A* again.

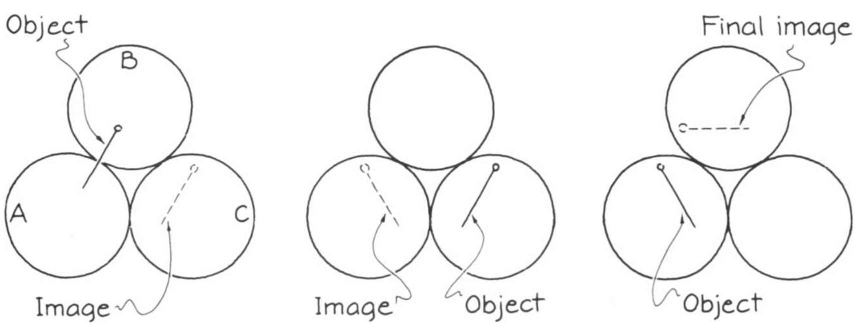
This much is enough to predict the rest of the taped sequence. An extra reflection is added whenever the final ray becomes tangential to one of the balls. The shape of the light path at that moment can fall into one of three classes that are characterized by the angle of inclination of the lowest segment of the path. In describing the classes I shall call the ball from which the light initially reflects the "original ball" and the other ball the "opposite ball." In class 1 the lowest segment is radial to the opposite ball and the final ray is tangential to the original ball. In class 2 the lowest segment is radial to the original ball. In class 3 the lowest segment is horizontal, which gives left-right symmetry to the path, so that the final ray is tangential to the opposite ball.

If you replay the tape and note the path class when an extra reflection begins, you will find a sequence of 1, 3, 2, 3, 1, 3, 2 and so on. Every other time the lowest segment is horizontal and the path is symmetrical. At intermediate times the lowest segment alternates, slanting first toward one ball and then toward the other. The paths underlying long sequences of reflections can be understood by sketching them in a simplified way that still retains the general shape of each path [*see upper illustration at left*].



The general shapes of the light paths

After this analysis I moved the third ball back into place. Where any two balls touched I saw a series of images that resembled the series I had seen in just two balls. The difference was that within any one image of a ball there were now two images, one larger than the other. Inside each of them were two more images, one larger than the other. If you ignore details of the sky in the images and concentrate only on their shape, the array is fractal, repro-



Multiple reflections in a cluster

ducing the same pattern on an ever decreasing scale.

In order to identify which ball gives rise to which image, I applied a common technique for multiple reflections. When light rays from an object reflect at a surface such as a flat mirror or a shiny ball, an image is said to be created inside the surface. If the rays then reflect from a second surface, the image inside the first surface serves as the object for the second reflection and an image appears inside the second surface. In a sequence of multiple reflections you can start with the original object and go through the reflections by steps in this way. Each time an image serves as an object for the next reflection, until an observer intercepts the rays and sees the final image.

The bottom illustration on the opposite page demonstrates the technique for a sequence in which rays from the sky are first reflected by *A* and *B* and then in the order *CAB* before they are seen on the side of *B*. The first reflections are not shown, but the combined images of the sky that are produced in *A* and *B* are represented by a line joining *A* and *B* and having a dot at the *B* end. In the first part of the illustration the next step in the sequence is indicated. The images in *A* and *B* act as objects, and images of them appear in *C*. The second part of the illustration shows the next step: the images in *C* act as objects, and new images appear in *A*. In the third part of the illustration those images act as objects and the final images appear in *B*, which you see on the side of that ball. Note that with this technique you can determine where the sky image that is first reflected by *B* ends up. It is to the left of the sky image first reflected by *A*.

The reflection sequences in the illustration are *ACAB* and *BCAB*. After repeating the analysis for other possible sequences, I constructed a map of many of the images seen in *B* [*see upper illustration at right*]. Observe that they form levels in the map (and on the ball) and that the ones on a lower level (lower on the ball) are smaller than the ones on a higher level (higher on the ball).

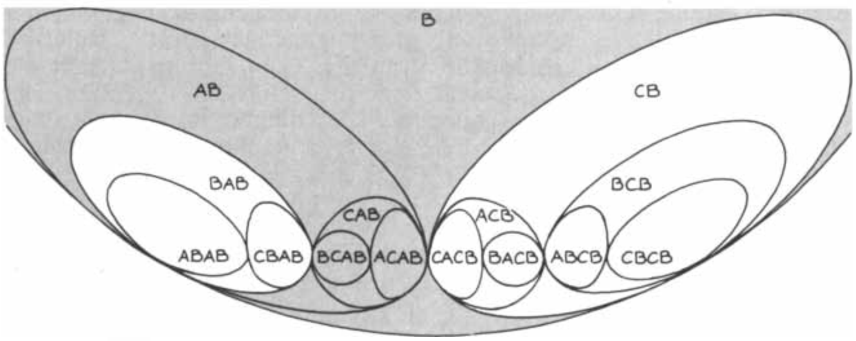
I shall work downward through the shaded ovals in the map until I reach the images I have just described. The top level is labeled *B* and corresponds to the top of the ball, where light rays from the sky are reflected directly to you. On the left side of the next level there is an image of the sky that is first reflected by *A*. It surrounds the point where *A* and *B* touch and is part of the series seen when only *A* and *B* are present. Within that image are two more images. The one on the right is an image in which the rays undergo a reflection sequence *CAB*. Within that image are two more images that correspond to the sequences *BCAB* (on the left) and *ACAB* (on the right). These are the sequences that were shown in the preceding illustration.

You might like to add more layers to the map. The images get smaller and the layers become more crowded. In my perspective of *B* the shrinking images of the sky approach a "limit line" that runs from the point where *A* and *B* touch to where *B* and *C* touch. On the visible part of the ball below the limit line are images of the ground.

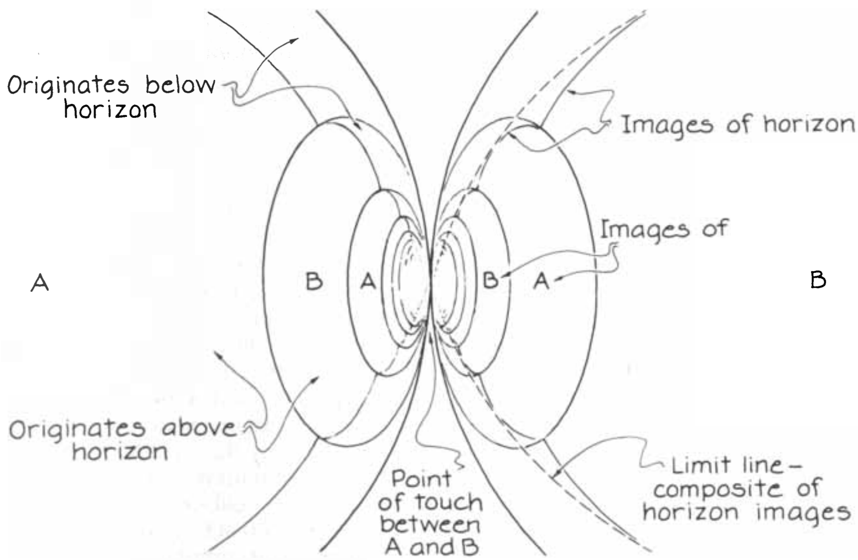
What is the limit line? It is a composite of images of the horizon—the far edge of the ground or whatever is the background to the balls [*see lower illustration below*]. When you view the balls up close, you see that the horizon is curved in all the images; when you are farther away, the curvature is imperceptible and the horizon sections seem to lie along a straight line. The limit line that extends from where *A* and *B* touch joins smoothly with the limit line that extends from where *B* and *C* touch, and their composite forms one side of the triangle in Miller's demonstration. The other two sides are formed by similar limit lines in the other balls. Below a limit line (in the interior of the triangle) you see only images of the ground that are reflected at least once by the balls. In the center of the triangle you see the ground directly. And so, if the ground is dark, then the entire interior of the triangle is dark, and that is the source of the dark triangle in Miller's demonstration.

FURTHER READING

REFLECTIONS ON A CHRISTMAS-TREE BAUBLE. M. V. Berry in *Physics Education*, Vol. 7, No. 1, pages 1-6; 1972.



A map of the images in ball B



The limit line formed by two balls

COMPUTER RECREATIONS

Random walks that lead to fractal crowds

by A. K. Dewdney

"The most useful fractals involve *chance*... both their regularities and their irregularities are statistical."

—BENOIT B. MANDELBROT, *The Fractal Geometry of Nature*

Is it a zinc ion, a bit of soot or a staggering drunk wandering about on the display screen? Does it join others of its kind to form a metallic flower, a dark patch or an insensible crowd? The answer depends only on one's imagination, but—flower, patch or crowd—the shape of the aggregate structure is unquestionably fractal; its fractal dimension (which is between 1 and 2) can even be measured.

A fractal, such as the one in the illustration on the opposite page, is created by a program called SLO GRO. It directs a succession of particles to wander aimlessly about the screen until they eventually encounter a collection of stationary kindred. As soon as the encounter takes place, the particle's motion is frozen. As several hundred particles accumulate one by one in this way, the collection slowly develops the irregular branches and tendrils characteristic of fractal shapes.

The SLO GRO program was inspired indirectly by an article that appeared in this magazine two years ago [see "Fractal Growth," by Leonard M. Sander; SCIENTIFIC AMERICAN, January, 1987]. The article described the particulate growth process I have outlined above, which goes by the name of diffusion-limited aggregation, or DLA.

Several intrepid souls with the kind of adventurous spirit that characterizes this department's readership did not wait for me to pick up on DLA-simulation programs but wrote versions of SLO GRO for themselves. In particular, my hand has been forced by Eric M. Smiertka of Santa Clara, Calif. With little more than an elementary programming course under his belt, he wrote a successful version of SLO GRO. Not content with merely watching his fractal grow, he measured its dimension as well.

The DLA process might well represent the diffusion of zinc ions through a two-dimensional electrolytic solution. When ions come in contact with an aggregation of metallic zinc at an electrode, they immediately bond with their atomic mates in the aggregate. Particles of soot that are wafted hither and yon before meeting other soot particles clinging to some substrate also seem to follow the same process, although in their case the cohesion is electrostatic in nature.

The most colorful (albeit the least realistic) model for a DLA process involves a succession of drunks wandering about in the dark until they stumble on a crowd of insensate comrades; lulled by the sounds of peaceful snoring, they instantly lie down to sleep. An aerial view of the slumbering crowd by morning light might well reveal the same fractal shape found in a zinc cluster or a soot patch.

The key to modeling the diffusion part of the DLA process is a "random walk." Each step of a random walk in two dimensions is taken in one of four randomly selected directions: north, south, east and west. (Sometimes a random walk also allows intermediate directions such as southeast, but I shall stick with the more restrictive version.) The top illustration on page 118 outlines a typical path made by a particle on a random walk. The particle seems to meander aimlessly. Watching such a particle on the screen, one can be excused for having serious doubts that it will ever reach a given destination. But the particle does have a goal (to be somewhat teleologic): to reach the crowd of fellow particles accumulating at the center of the screen.

It all starts when SLO GRO places a single particle at the center of the computer screen. A particle is then set on a random walk from a random point on a large circle centered on the initial particle. After a long and arduous journey the particle happens on the stationary particle and stops. As soon as that happens SLO GRO will dispatch another particle on a similar journey from another random point on the circle. Particle after particle collects at the site of the original one and a strange shape emerges within the circle: a treelike growth with oddly twisted branches and twigs. The shape results from the tendency of a randomly walking particle to run into an outer part of the crowd long before it encounters a cohort much deeper in the crowd; twigs are more likely to grow from branches than from the core, so to speak.

All of this takes time. As Smiertka says, "It takes four or five hours to run the program on my IBM XT, so I just let it run overnight." The algorithms described below give rise to a somewhat faster version of the program, but of course the duration of a run depends on how many particles one wants to accumulate.

The diffusion algorithm (SLO) is a bit easier to write than the aggregation one (GRO). For the sake of simplicity I shall confine all the action to the inside of a circle 200 pixels in diameter. To choose the point on the circle from which a given particle begins its random walk, SLO computes a random angle in one instruction and then in the next two instructions works out the coordinates of the point on the circle that defines that angle:

$$\begin{aligned} &angle \leftarrow random \times 360 \\ &\quad x \leftarrow 100 \times \text{cosine}(angle) + 100 \\ &\quad y \leftarrow 100 \times \text{sine}(angle) + 100 \end{aligned}$$

The computer itself must choose a random number labeled *random*. Because such a number lies between 0 and 1, it must be multiplied by 360 to yield a random angle between 0 and 360 degrees. (For systems that employ radians instead of degrees, *random* must be multiplied by 2π, or approximately 6.283.) The next step calculates the *x* coordinate of the point on the circle that lies at that angle by multiplying 100 (the circle's radius) by the cosine of the angle. The third step works out the *y* coordinate of the point with the sine function. Because most popular programming systems place the origin—the point with coordinates (0,0)—in one corner of the screen, I have added offsets of 100 to both coordinates in order to center the circle on the screen. Of course, this will work only on a screen that happens to be 200 by 200 pixels. Readers must work out ideal offsets based on the dimensions of their own screen.

Having chosen a starting point for the particle, SLO must now set it in motion with the following algorithm (which is embedded in a loop):

select ← *random*
if *select* ≤ .25
  then $x \leftarrow x + 1$
if *select* > .25 and ≤ .5
  then $x \leftarrow x - 1$
if *select* > .5 and ≤ .75
  then $y \leftarrow y + 1$
if *select* > .75
  then $y \leftarrow y - 1$

The motion rules are spelled out explicitly in terms of a random variable called *select*. Depending on where (in which of four equally likely ranges between 0 and 1) *select* lies, one coordinate of the particle is increased or decreased by 1. In this way the particle moves randomly either up, down, left or right by one pixel.

What is not spelled out explicitly are the two conditions under which the particle's motion must be stopped: whenever the particle has wandered outside the circle from which it originated or whenever it has arrived at a pixel adjacent to the accreting mass of pixels constituting the fractal crowd. In the first case SLO GRO simply extinguishes the particle; if it did not, the particle could quite easily wander off the screen into an endless electronic night. In the second case SLO GRO fixes the particle to the spot where it encounters the growing cluster, as though it were transfixed by the sight of a fractal Medusa.

These instructions are incorporated into a *while* conditional statement at the beginning of the random-walk loop that animates the particles. Excursions outside the circle are curtailed by simply keeping track of the particle's distance from the center of the circle. The distance is computed every time new values of x and y become available. (Actually SLO GRO computes the square of the distance. This saves a little time, since a square-root calculation is avoided.)

distx ← $x - 100$
disty ← $y - 100$
distance ← *distx*² + *disty*²

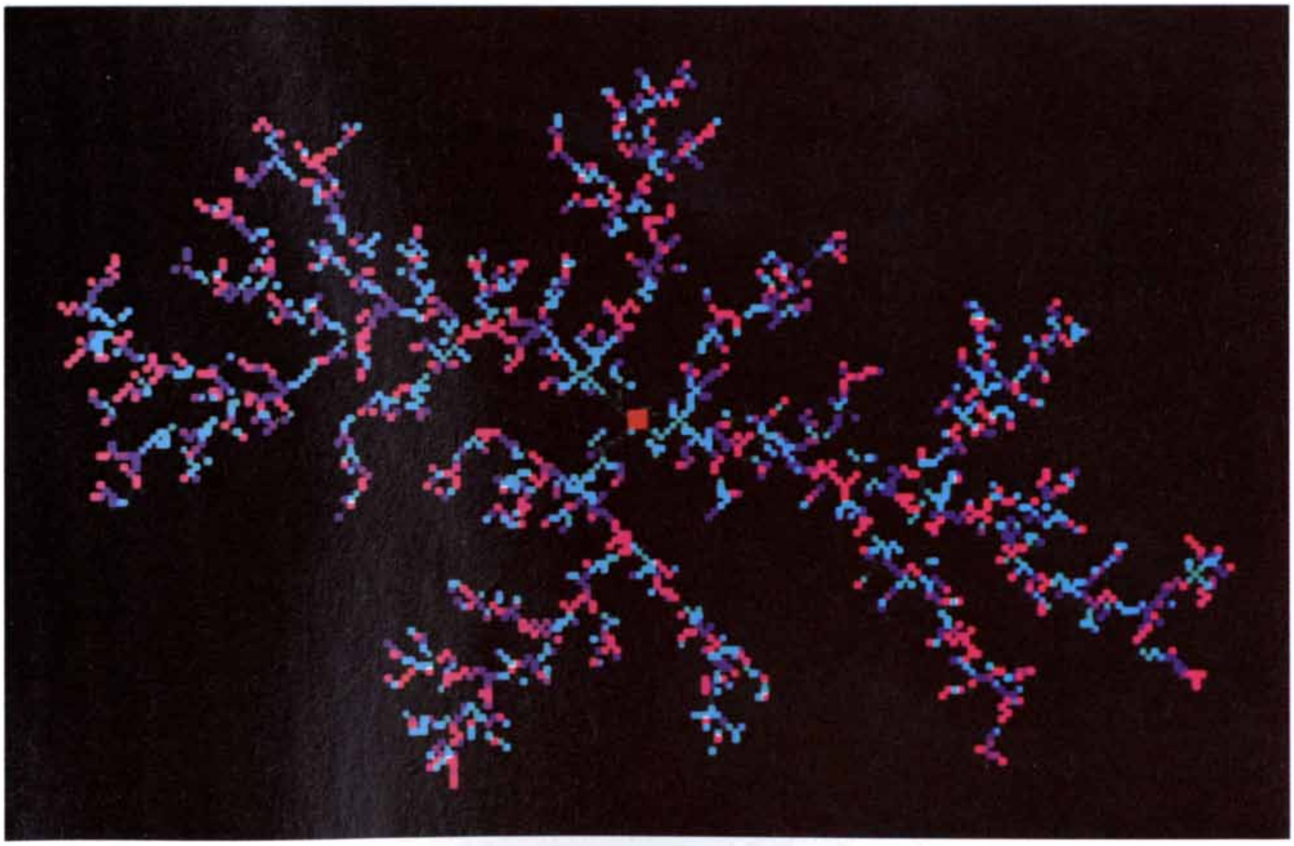
The *while* condition tests how far the particle has traveled from the center of the circle by comparing *distance* with the square of 100 (plus 1). If the condition is violated, the program will exit from the loop and start anew with another particle.

How does one determine the other condition, namely whether the particle has joined the crowd? To answer the question SLO GRO maintains two lists, one for each coordinate of every particle in the crowd. The lists are arrays called *crdx* and *crdy*. The "seed" particle initially placed at the center of the screen happens to have coordinates *crdx*(1) = 100 and *crdy*(1) = 100. If in its peripatetic career a particle comes in contact with the crowd, SLO GRO executes the instructions:

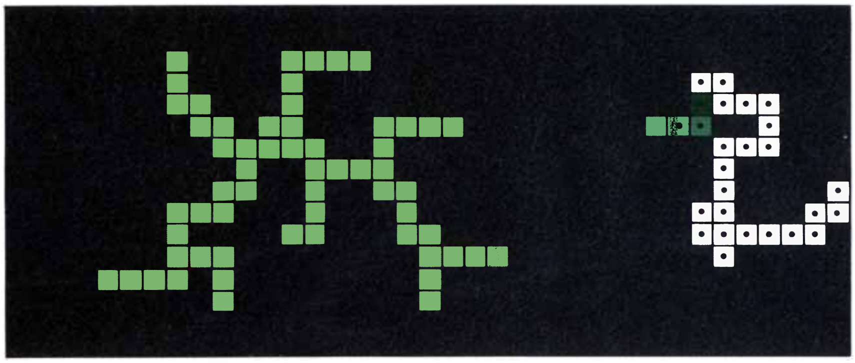
crdx(*count*) ← x
crdy(*count*) ← y

As its name implies, *count* keeps count of the number of particles in the aggregate. At the beginning of SLO GRO it has the value 1; every time a new particle is added to the aggregate, *count* increases by 1.

But how does GRO know when a particle has reached its colleagues? The simplest contact algorithm compares the coordinates of each of the



Kevin Eber's fractal crowd



A staggering drunk may or may not reach the crowd

four pixels surrounding the particle in its current position with the coordinates of the pixels kept in the lists *crdx* and *crdy*.

```
for n ← 1 to count
    x1 ← x + 1
      if x1 = crdx(n) and y = crdy(n)
         then contact ← true
    x1 ← x − 1
      if x1 = crdx(n) and y = crdy(n)
         then contact ← true
    y1 ← y + 1
      if x = crdx(n) and y1 = crdy(n)
         then contact ← true
    y1 ← y − 1
      if x = crdx(n) and y1 = crdy(n)
         then contact ← true
```

I have used here a so-called Boolean variable labeled *contact*. Such a variable takes the values true or false (or, equivalently, 1 or 0). Just before the *while* loop begins, *contact* is given an initial value of false.

```
draw  point (100,100)
count ← 1
crdx(1) ← 100
crdy(1) ← 100
while  count ≤ 500

  [choose point on circle]

  distance ← 0
  contact ← false
  while distance < 10001 and not contact
      erase  point(x,y)

      [motion algorithm]

       draw point(x,y)

      [compute distance]

      [contact algorithm]

   if contact = true
      then count ← count + 1
           crdx(count) ← x
           crdy(count) ← y
```

A list of the complete SLO GRO algorithm

All the essential features of SLO GRO have now been described except for an outer *while* loop that keeps SLO GRO going until *count* reaches some desired number of particles, say 500. The complete SLO GRO algorithm is displayed at the bottom of this page. The parts that have already been described in detail are represented by appropriately labeled boxes. The parts that have not been explicitly described include instructions that initialize variables and erase and draw particles. (Tyro programmers are warned that the commands to "erase" and "draw" should not be taken literally: in real programming systems these are not viable commands. Instead both operations are done by means of other commands that color pixels.)

Fractal crowds, such as those produced by SLO GRO, can be categorized by a dimension that characterizes their rate of growth. In particular, consider the number of particles that lie within a circle of radius *R*. If a crowd more or less filled the general area of its growth, one would expect that a doubling of the radius would lead to a quadrupling of the number of particles inside the circle: the crowd's growth would be quadratic. In other words, one would expect the number of particles to be approximately proportional to R^2. On the other hand, if a crowd of particles took on a linear shape with little or no branching, doubling *R* would merely double the number of particles within the circle. The crowd's growth would be linear, that is, proportional to *R*. It turns out that fractal growth tends to be faster than linear growth but slower than quadratic growth: the number of fractal particles in a circle of radius *R* is proportional to R^d, where *d* is a number between 1 and 2.

For that reason a plot of the number, *N*, of particles in a SLO GRO crowd versus the pixel radius *R* on ordinary graph paper yields a curve somewhere between a straight line (the result of linear growth) and a parabola (the result of quadratic growth). It is tricky to tell what fractional power was at work in the growth of the crowd merely by examining such a curve. The task is made easier if one plots the points on so-called log-log graph paper.

Log-log graph paper has horizontal and vertical coordinates that double, triple or increase by some other factor that depends on the unit chosen. If one plots *N* versus *R* on log-log paper, a strange thing happens to quadratic curves: they turn into straight lines! Why? Remember that, for quadratic growth, every time the radius doubled, the number of particles quadrupled. On log-log paper this represents a regular upward step of four units for every two units across the graph, which happens to be a straight line of slope 2. In fact, growth rates proportional to R^3 appear as straight lines of slope 3 on log-log paper for the same reason.

That last observation tells us what to do once the points corresponding to all pairs of *R*'s and *N*'s have been plotted on log-log paper. If the shape is a fractal, the points will all lie about a straight line (except near the end of the line, where the crowd tends to peter out). The slope of the line approximates the fractional dimension of the crowd.

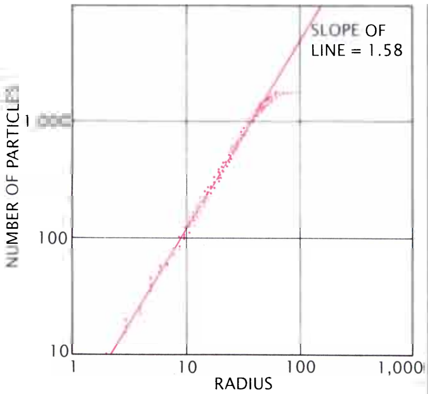
Smiertka did exactly that for one of his SLO GRO creations; his graph appears on the opposite page. The slope of the growth line is 1.58. The estimate is slightly smaller than those published in the scientific literature, but that hardly diminished his pleasure in carrying out the measurement. Smiertka has gone on to experiment with different rules governing particle attachment and to measure the fractal dimension of the resulting DLA fractals.

As I mentioned above, other readers wrote versions of SLO GRO. Scott Camazine of Ithaca, N.Y., concedes that his particles do not always move randomly and that they sometimes seem to "invade" the aggregation. But his graphic images of fractals have convinced me that his program probably has got the basic details of DLA right. He will send his program (for IBM PC and compatible computers) to readers who write him at 36 Dove Drive, Ithaca, N.Y. 14850.

Kevin Eber, a graduate student in journalism at the University of Colorado at Boulder, wrote a version of SLO GRO in which all the particles arise at random points along the left edge of the screen. With the help of his friend

Jon Saken at the university's Center for Astrophysics and Space Astronomy, he was able to produce the fractal crowd shown on page 117. Eber changed the color of his particles every 100 iterations as a quick way to estimate the number of particles that have collected on the display screen.

Finally, I should mention Marlin Eller, who wrote from Hiroshima, Japan, to describe a program called SOOT. It resembles SLO GRO in all respects except that the diffusion takes place in the opposite direction: particles are emitted at the center of the screen and wander until they happen on a surrounding circle or some other particle of soot. In this way tendrils are made to grow inward until eventually the emitter becomes clogged.



How to estimate a fractal dimension

In mining the banks of the Continuum River for primes in the July issue, I inadvertently introduced some fool's gold into the poke: the numbers 51, 57 and 111 are not primes, as hundreds of readers pointed out. Furthermore, old Yuke, my mining mentor, committed an error of his own in proving the infinity of primes: after supposing a number n to be the last prime, he multiplied all primes from 2 through n and added 1 to the product. He called the resulting number p. When the tyro said, "Don't tell me that p is prime!" Yuke should have pointed out that p was not divisible by any of the primes in the supposedly finite collection. This means that either p is prime or there is another prime (not in the collection) dividing p. Either way, there is a new number that is "prime as all get-out."

When it rains, it pours on the banks of the Continuum; several subtler errors caught the eyes of some readers. A few noticed that the program SLUICE2 could slush its way through many more primes than I had indicated. I proposed an iteration limit of one million, but the limit is actually about a million squared, since only primes up to the square root of the limit need be stored in the array p. Samuel D. Yates of Delray Beach, Fla., received numerous requests for a list I described in the July column of all primes greater than 1,000. What Yates actually has is a list containing all known primes that have more than 1,000 digits.

In the August column I described the hodgepodge machine, a cellular automaton constructed by two West Germans, Martin Gerhardt and Heike Schuster of the University of Bielefeld. The hodgepodge machine imitates beautifully the waves of color that ripple across certain excitable chemical mixtures. The waves sometimes develop edges that curl into spirals, producing a riot of Paisley forms. This does not necessarily mean, as several readers seemed to think, that chaos lurks in the coiling waves of excitation; one should not confuse chaos with hodgepodge.

I offered to distribute an algorithmic outline of the program called HODGEPODGE. The outline, requested by many readers, enabled me not only to expand on the instructions needed to create chemical reactions on screens at home but also to clear up some points in the article. First, the parameter g must take on integer values between 1 and 20. Also the variable A, the number of infected cells in the neighborhood of a particular infected cell, counts the particular cell itself in the total.

There is not enough space to mention all the creative approaches taken by some readers to the hodgepodge challenge. I must, however, mention Donovan Smith of El Cerrito, Calif., who squeezed the hodgepodge rule into one dimension. Smith sets up initial states in a strip of cells across the top of his display screen. When his linear automaton is let loose, successive strips reveal intriguing patterns of healthy pasts giving way to infected futures. After one overnight run Smith discovered a configuration that repeated over and over again like an endless succession of rebounding one-dimensional waves.

FURTHER READING

THE FRACTAL GEOMETRY OF NATURE. Benoit B. Mandelbrot. W. H. Freeman and Company, 1982.

FRACTAL GROWTH. Leonard M. Sander in *Scientific American*, Vol. 256, No. 1, pages 94-100; January, 1987.

STATEMENT OF OWNERSHIP, MANAGEMENT AND CIRCULATION (required by 39 U.S.C. 3685). *1A.* Title of publication: Scientific American. *1B.* Publication number: 00368733. *2.* Date of filing: September 27, 1988. *3.* Frequency of issue: monthly. *3A.* Number of issues published annually: 12. *3B.* Annual subscription price: U.S. and its possessions, 1 year $24; all other countries, 1 year $35. *4.* Complete mailing address of known office of publication: 415 Madison Avenue, New York, N.Y. 10017. *5.* Complete mailing address of the headquarters or general business offices of the publisher: 415 Madison Avenue, New York, N.Y. 10017. *6.* Full names and complete mailing address of publisher, editor, and managing editor: Publisher, Harry Myers, 415 Madison Avenue, New York, N.Y. 10017. Editor, Jonathan Piel, 415 Madison Avenue, New York, N.Y. 10017. Managing Editor, Armand Schwab, Jr., 415 Madison Avenue, New York, N.Y. 10017. *7.* Owner: Scientific American, Inc., 415 Madison Avenue, New York, N.Y. 10017; Holtzbrinck Publishing Holdings Limited Partnership, 521 Fifth Avenue, New York, N.Y. 10175; Handelsblatt GmbH, Kasernenstrasse 67, Postfach 1102, 4000 Düsseldorf, Federal Republic of Germany. *8.* Known bondholders, mortgagees, and other security holders owning or holding 1 percent or more of total amount of bonds, mortgages or other securities: none. *9.* For completion by nonprofit organizations authorized to mail at special rates (DMM Section 423.12 only). The purpose, function, and nonprofit status of this organization and the exempt status for Federal income tax purposes: Not applicable to this organization. *10.* Extent and nature of circulation: *A.* Total number of copies (net press run): average number of copies each issue during preceding 12 months, 841,384; actual number of copies of single issue published nearest to filing date, 847,040. *B.* Paid and/or requested circulation: *1.* Sales through dealers and carriers, street vendors and counter sales: average number of copies each issue during preceding 12 months, 147,766; actual number of copies of single issue published nearest to filing date, 143,640. *2.* Mail subscription (paid and/or requested): average number of copies each issue during preceding 12 months, 484,711; actual number of copies of single issue published nearest to filing date, 484,242. *C.* Total paid and/or requested circulation (sum of *10B1* and *10B2*): average number of copies each issue during preceding 12 months, 632,477; actual number of copies of single issue published nearest to filing date, 627,882. *D.* Free distribution by mail, carrier or other means, samples, complimentary, and other free copies: average number of copies each issue during preceding 12 months, 36,247; actual number of copies of single issue published nearest to filing date, 35,317. *E.* Total distribution (sum of *C* and *D*): average number of copies each issue during preceding 12 months, 668,724; actual number of copies of single issue published nearest to filing date, 663,199. *F.* Copies not distributed: *1.* Office use, left over, unaccounted, spoiled after printing: average number of copies each issue during preceding 12 months, 18,623; actual number of copies of single issue published nearest to filing date, 31,876. *2.* Return from news agents: average number of copies each issue during preceding 12 months, 154,037; actual number of copies of single issue published nearest to filing date, 151,965. *G.* Total (sum of *E*, *F1* and *2*—should equal net press run shown in *A*): average number of copies each issue during preceding 12 months, 841,384; actual number of copies of single issue published nearest to filing date, 847,040. *11.* I certify that the statements made by me above are correct and complete. (Signed) Harry Myers, Publisher.

BOOKS

Again the Christmas piñata is filled with science books for young readers

by Philip and Phylis Morrison

Voyagers

THE LOG OF CHRISTOPHER COLUMBUS, translated by Robert H. Fuson. International Marine Publishing Company, Camden, Me. 04843 ($29.95).

The aspirant High Admiral of the Ocean Sea with his three ships cast off from the port of Palos on Friday, August 3, 1492, "half an hour before sunrise," bound for the Canaries on his bold voyage straight west to India and the Great Khan. Once at sea, "I decided to write down everything I might do and see ... from day to day." Written in his own hand in Castilian Spanish, not his mother tongue, it was the "most accurate and complete ship's log" ever made up to that time. On his return in the spring he gave the original to the queen, his sponsor. She generously commissioned an exact copy for the admiral himself, which he received in the fall of 1493. But both documents had vanished from all view by the 1550's, truly lost treasure.

The Dominican scholar Fray Bartolomé de Las Casas was a family friend and an admirer of the admiral from the day Columbus landed after his great discovery. Las Casas spent a lifetime in Spain and in the New World preparing his famous *History of the Indies* (he died at 92, his big book not yet fully polished) but sometime along the way he himself had seen and abridged the log, much of it, although not all, a direct copy. That manuscript abstract, found only in 1790, is the chief source for nearly all we know of the log, with a little extra that Las Casas put into his own book and some citations in a biography written by Columbus' son.

Here it is in lively English, "from day to day," modernized, annotated and ornamented with a variety of apt illustrations. It is wonderful to read what Columbus noticed, puzzled over and named of his strange New World. Perhaps it is even more wonderful to see how slowly he came to recognize against hope that the Taino islanders he first met in his voyage through the Bahamas and on to Cuba and Hispaniola were neither rich in gold nor likely subjects of the Great Khan.

There is even a modern subplot, with many detailed little sea maps. At about ten o'clock on the eve of the first Columbus Day, the admiral had himself spied a light that "looked like a little wax candle bobbing up and down.... At dawn we saw naked people, and I went ashore." Just where was his landfall? By now there have been 40 or so learned proposals; the latest decision for Samana Cay (among the 723 candidate low Bahamas) is well defended by nautical scholar Fuson, although without the true text of the log—or maybe even with it—small discrepancies of distance and direction remain. Someday the archaeologist's spade may tell us more. Adventure, intrigue, hope, discovery, uncertainty and plenty of argument lie in this book: history as it was written, mostly on the spot, fascinating and accessible to almost any good reader.

THE AMUNDSEN PHOTOGRAPHS, edited and introduced by Roland Huntford. The Atlantic Monthly Press ($35).

Roald Amundsen was born in 1872 into a well-to-do shipowning family near Oslo. Driven by passion for polar exploration, he had served out a year's apprenticeship in the Antarctic ice by the time he was 25. A few years later he set off in his own ship to traverse the daunting Northwest Passage. He became the first to make it by ship after centuries of attempts, weaving through the icy labyrinth of the Canadian Arctic islands in three years.

Amundsen was preempted by the claims of Cook and Peary just as he was organizing to seek the North Pole in 1909. He immediately went south instead. Among the first explorers to grasp the effectiveness of the Eskimo adaptations to the polar world, he reached the South Pole on schedule in 1911 without tears, using fine Norwegian skis and skiers in Eskimo furs, and 100 sled dogs that were fed first on seal meat and then on one another.

He was broke, though; he had spent the family money. The Norwegian government did make some inadequate grants, books and newspaper rights were a help, but it was long lecture tours that meant ready money for a famous man. On the American leg alone of his world tour to pay South Pole debts, he delivered about 160 public lectures within half a year. "I had no rest, day or night... I was just part of a lecture machine."

Popular lectures certainly required visuals, even before television. The standard still camera of the period took pictures about three inches by four. Projection meant positive film transparencies, always mounted between glass plates. It was fashionable to tint those black-and-white slides by hand. They were fragile and heavy; lecturers hated to lug them and found no use for them after the tour.

Of Amundsen's hundreds of lecture-tour slides only a few cracked and faded examples survived him. In 1986 an exhibition was arranged in Norway for the anniversary of his 1926 dirigible flight across the pole to Alaska, and the organizers sought new souvenirs. It was then that a relative found in her Oslo attic an old wood crate of his, labeled Horlicks Malted Milk. It contained no powder or tablets but 200 surprising slides instead, probably unused duplicates.

They fully record his three finest expeditions: the Northwest Passage, the South Pole and the Northeast Passage along the Siberian coast at the close of World War I. Here they are, Rip van Winkle photographs from adventures of our own century, reproduced at full size in tints you might have seen in the lecture hall. With them are maps and vivid accounts of all three expeditions. It is enough to describe just one picture, the last one made at the South Pole. Four men face the dark little tent they left to mark the place. The Norwegian flag flies free in the midsummer wind above their ship's pennant, all rendered in the artist's colors. "I left ... some words to Scott who, I must assume, will be the first to visit the place after us." He was.

WIND AND SAND: THE STORY OF THE WRIGHT BROTHERS AT KITTY HAWK, by Lynanne Wescott and Paula Degen. Foreword by Oliver Jensen. Eastern Acorn Press, distributed by Harry N. Abrams, Inc. (paperbound, $19.95).

The story of the brothers Wright

from 1900 through 1911 is told here almost entirely through their own photographs and words. Most of the photographs are reproduced from the plates they exposed and then developed in their own darkroom; most of the text is from their letters and diaries written at the time. There is a fine introduction that makes clear how much what they did was reasoned, empirical, full of common sense. Step by step they went from doubt through resolution by trial and error. There were long winters of data collecting in the wind tunnel and summers with hundreds of daring test hops on the dunes. Finally they took active control in the air and won powered flight.

Those two bicycle mechanics, high school graduates able to calculate and translate French and German when it was necessary to, brilliant engineer-craftsmen and tireless dreamers, are here in word and image. Their two-room Dayton bicycle factory and repair shop is shown, where first they built a gasoline engine to run lathe and drill press, and six years later built one to fly. The Wrights are seen time and again in cap and shirtsleeves on the sands or near the flimsy camp buildings they put up at Kill Devil Hill. The ambience, as Oliver Jensen notes, is certainly that of the old silents, some newly found Chaplin or Keaton feature, a tale of two awkward but infinitely resourceful young men who confound the authorities.

We see the $4 launching track that "amused Mr. Chanute considerably" (Langley had spent $50,000 on his, only to splash into the Potomac), the spruce-and-fabric Flyers getting better year by year, and the famous shot of the first powered takeoff, snapped at the right split-second by coastguardsman John T. Daniels (Orville on the wing, Wilbur running at the wing tip). The last photographs show their engineless soaring tests in 1911. Wilbur, five litigious years behind him, was wistful: it is "much more pleasant to go... for experiments than to worry over lawsuits."

PITCAIRN ISLAND COOKBOOK, by Irma Christian. Illustrations by Rozemaryn van der Horst. Irma Christian, Publisher, Pitcairn Island (paperbound, postpaid, $12 by air; $10 by surface mail).

Rocky Pitcairn Island, a little larger than New York's Central Park, lies alone in the deep ocean. One way it is 1,000 miles to Easter Island, and the other way 400 or 500 miles to the nearest atolls of French Polynesia.

Pitcairn's annual holiday is just ahead; it commemorates the bold act by which a dozen or so mutinous English seamen and their new Tahitian wives committed themselves to independent life in an uninhabited place as isolated as any in the world. Offshore in Bounty Bay on January 23 a dinghy-size replica of H.M.S. *Bounty* will burn once again; indeed, in 1990 that day will mark exactly 200 years since the men set fire to the real warship, burning their last sure link to the outside world.

This delightful hand-lettered cookbook can quickly knit a bond between today's 50 Pitcairners and readers far away. All cookbooks are intimate, and the author, with help from her friends, has artfully heightened the effect. We share a birthday party, its massive first course rich in garden produce and the time-honored feast dishes of mid-Pacific islands: grated potato, banana, yam, arrowroot and pumpkin, wrapped in a big banana leaf and oven-baked. Then "the sweet parade" begins, the table loaded now with ice cream, fruits and puddings. True to the British tradition, this elaborate spread is known simply as "tea." Most islanders grow their own sugarcane in their garden plots (fresh molasses is delicious), but they import many another delicacy, for instance butter and canned corned beef. The staple food is fish; some goats and sheep wander the hills and everyone raises chickens, but there is no room for cattle.

Author-publisher Irma Christian appears in one drawing at work with microphone and telegraph key (she is both a professional and an amateur radio operator). We see and read of a few other islanders, of the cooperative store, an island map, the best-known views, the rain-storage wells, gardens, breadfruit. Here is the author's full family tree, beginning with the first settlers, among them Fletcher Christian. Because the scale of human life on Pitcairn is so easy to grasp in time and space, this gentle book begins to make large matters clear: how much our land forms our lives, what spell is cast by history, the nature of human community. Even ordering the book is a little adventure for a young person or a class: first find the island on the map. Are address, money and postage correct? When will the book come? Do not worry, Pitcairn's bicentennial is a good year off. The recipe for yellow guava roly-poly will arrive in time.

Physical Sciences and Technology

SUPERPOWER: THE MAKING OF A STEAM LOCOMOTIVE, written and illustrated by David Weitzman. David R. Godine, Publisher, Inc. ($19.95).

The Locomotive Works in the western Ohio town of Lima stand quietly now where the silvery Nickel Plate and Baltimore & Ohio rails meet, on the high line toward the Wabash River. But once the hearth roared there where a good number of all the nation's steam locomotives were once made. Acres of wood-block floors in 49 red brick buildings, their doorways fit for giants, are still there to see. Plenty of steel ingots and coke and a few brass whistles too came in by rail; out each day rolled new engines, heavier and more impressive year by year.

The two-foot-long double spreads of this book cannot quite hold the full-length ink drawing of the magnificent titular subject, engine A-1, Order Number 1070. It was the first 2-8-4 Berkshire sent from the Lima Loco for testing by the Boston & Albany in April of 1925. A-1 was the prototype for 600 more of the 3,000-horsepower, 200-ton species over 25 years. Lima priced its locomotives by the pound, "like potatoes and beans," said chief design engineer Will Woodard, who can estimate A-1 at about $184,000 almost as soon as he is asked.

About two dozen splendid drawings follow the huge birth, material by material, form by form. In the drafting shop paper and pencil (and even more ethereal, the forming ideas and numbers) came first of all. Then came fir and oak, of which the cunning patterns were made for the big sand hollows formed by the foundrymen to confine molten iron and steel. In the forge the steam hammers shook South Lima as hot steel blanks were pounded into drive rod and crankpin. Largest and noisiest was the boiler shop, all air hammers and flying rivets.

Locomotives were not made by tools and machines but rather with them, by living men (apparently there was not one woman at the Loco). We see these men in most of the drawings, and hear them vividly in the text. Here the author has extended his visual mastery to serious oral history; he based his novelist's account on the records and on the real people he met who recounted their days at the Loco. The hammermen always won the tug-of-war; the drawings make it plain why. The boilermakers, often a little deaf, were a clan—husky kinfolk with a good deal of family resemblance.

Our insider's visit has a guide: a tall Lima boy called Ben (not built for the boiler shop, he was told at once, and "besides, you've got no family there") who has just taken down his first time card as we enter unseen with him. First in his family, Ben had stayed in high school to graduate before going to the Loco, where his father was a machinist and his Grandpa Joe, who recalled his boyhood spent around the blacksmith's shop in a Finnish village, was a veteran forgeman. On the closing pages the plant foreman himself teases green Ben a bit, but as the apprentice leaves, just able to manage a smile, Mr. Schnell calls cheerfully: "You'll be raised to 30 cents."

Steam locomotives were last made in the U.S. in 1953; even automatic stokers and the long grates they enabled the fireman to tend, with no shovel in hand, could not preserve steam on the rails. The expensive but thermally efficient diesel-electrics need no water stops, no ash removal and no grate repairs, and they could burn cheap oil from both gulfs. Someday there will be warm nostalgic stories like this one from a diesel shop too.

CYCLES OF FIRE: STARS, GALAXIES AND THE WONDERS OF DEEP SPACE, by William K. Hartmann, paintings by William K. Hartmann and Ron Miller, with Pamela Lee and Tom Miller. Workman Publishing (paper, $14.95; cloth, $27.50).

The flat plain is a geologist's mystery, all right; to the horizon it is studded with huge aligned but slanting boulders. This might be some unique earth scene, the outcome of ancient processes of tilt and erosion. But the garish light belies that recognition; we see a fuzzy scarlet sun-star, too large a disk for any sky of this earth, and near it a small, brilliant blue second sun in theatrical contrast. The author, both astronomer and artist, has imagined for us a planet in orbit around the binary red giant Antares with its companion, and has painted a puzzling landscape under those exotic suns. Perhaps 100 such paintings—four artists have taken brushes to the task—bedeck the big book in colors both somber and bright.

The text is a general reader's serious introduction to astronomy. It begins with an account of the life and death of stars, the planets we know and many we so far only surmise, and goes on to galaxies as hospitable as our Milky Way—as well as those infected by a center marked by the emission of fierce opposing jets. Galaxies wheel in collision, space strewn with their tidal tails of stars consigned to enter the dark spaces. The work ends with informed conjecture about alien life. Here the paintings have more of the look of home: lightning, oceanscapes and a reptilian fossil on some ice-beset planet. William Hartmann's comments on the time span open to kindred cultures are cogent.

It is the concreteness of these images that implicitly extends their claims beyond the knowledge and analogies on which their credibility rests; we see the influence of forms known only to X ray and radio, and we enjoy liberties of color saturation, contrast and surface brightness. Words are less seductive. Given a little sense of doubt, any earnest reader (high school and up) will learn from the striking views, if less than the artist did. The work is dedicated to Jules Verne, among others, Copernicus to Hubble; he would have liked it, although the anonymous voyages here reported are flung far wider than any of Captain Nemo's.

ARMS & ARMOR, by Michele Byam. Alfred A. Knopf, Inc. ($13.99).

Rather like some remarkable specialized museum, this book presents 27 spreads in sharp color photography, each spread tightly limited in topic, with a dozen examples all of one kind. The entire sequence offers a compact history of small arms, weapons, armor and apt ornament. The opening pages on prehistoric weapons show a chert hand ax, and duly following near the end we reach "bizarre hand weapons," with a curved Gurkha knife. On each spread there is a paragraph of text, along with brief captions. The information is accurate; spot figures from old books decorate the pages. India, Japan and North American Indians are included in full spreads. Only the intricate crossbow does not receive the technical description it deserves. There is no artillery or the like; these are all personal implements. Tomahawk, war flail, chain mail, quiver, cuirass, derringers and a couple of hundred other objects are shown and defined.

Developed in England and France, the series from which this example comes includes skeletons, sports, birds, trees and much more. This one—to be sure, it can be seen as a case of the devil having very good images—can be certified as of real interest to many small boys.

THINKABOUT FLOATING AND SINKING, text by Henry Pluckrose, photography by Chris Fairclough. Franklin Watts, Inc. ($9.90).

For the youngest readers or for the read-to, the pages present related photographs, attractive and colorful, with a line or two of text. First we see the surface of water, from open ocean to the child's bath. Kids float, boats float and sink, as do toys, logs and bottles, one capped and one filling with water. There are a toy balloon and a real buoy, people in kayaks and sailors with life jackets.

The set has a clear conceptual linkage. The purposeful photographs do focus more tightly than an approach that examines a child's environment more widely. Yet action is implied: talk and exploration are suggested by the pictures, and a final little inquiry using a bowl of water is explicit. The series of small books by a well-known London educator of young children can help parents and teachers to extend and develop interest out of "everything in our environment."

ICE CREAM, written and photographed by William Jaspersohn. Macmillan Publishing Company ($13.95).

In clear photographs and firsthand reporting, this Vermont author explains for young readers a state resource, the far-famed firm of Ben & Jerry's. On the title page we meet two experienced youngsters who cheerfully demonstrate the consumption of ice cream cones of high quality. For 40 pages of brief text and 70 photographs more we travel the squeaky-clean production chain, from cows to supermarket freezer. We meet founders Ben and Jerry, and a good many others by name as well.

First the whole milk from local cows yields up cream and skim to the whirling separators. Then sweetness enters, by way of sugar. The raw brown crystals are imported from distant tropical cane fields and heaped into a sheltered little mountain at the mouth of the Mystic River, and clear, much-filtered syrup is shipped to B. & J. A few good drawings help to explain the machines that perform such processes as pasteurizing, homogenizing, blending in chips and chunks, and the automatic filling of cartons. These steps are all rather simple; the key mystery, refrigeration, is elided, probably wisely, as being within everyday home experience.

Once they broke up the Heath Bars to make the delectable crunch ice cream by dropping each boxful from a stepladder. Nowadays they do better by hurling the box from above the head repeatedly to the floor: technological progress. These steps all deal with ice cream that is semisoft; it is hardened for final shipment by spending three hours spiraling its way up through a tall freezer. Promotion is certainly no light matter. Note the Cowmobile giving away samples, and

Rick, the sales manager in blue jeans, beside a map on which Ben & Jerry's quality ice cream can so far mark sales in only half of the states, roughly one spoonful for every gallon of all U.S. ice cream. Onward, Rick! It's made to be eaten.

FUN WITH STRING, by Joseph Leeming. Illustrated by Charles E. Pont. Dover Publications, Inc. (paperbound, $3.50).

Another bargain reprint preserves a good little book first published in 1940, a "collection of string games, useful braiding & weaving, knot work & magic with string and rope." There are plenty of books on each of those disciplines, but this is a single work introducing the reader neatly to the illusory, utilitarian and decorative aspects—a few dozen examples apiece, each in a page or so with indispensable drawings.

A modest topological illusion: the magician ties three overhand knots in a length of clothesline. He puts all three loops over his left hand, holding one end between the fingers. (There is one right way to do this, shown here.) Two people can pull on the two ends to render the rope straight and free of knots. There are a dozen rope escapes as well. Then we learn the working knots, 50 or so, including those suited for making fast to rings, hooks, posts and jugs. Next come fancy ornamentals. Splice a grommet or work up a square-knot bag. (The last is described as a diversion of sailors, but in recent decades it has grown into a cottage industry under the name of macramé.) There is a little on netting, and even on the art of braiding, up to a pair of braided jute sandals. The last pages treat a number of the best-known string games—cat's cradle generalized. For readers at any age with a doer's taste either for theater or for quiet work alone, this opens a rich overall view; it serves also as a guide to handcrafts still vigorous worldwide.

Encyclopedias and Field Guides

CROCODILES AND ALLIGATORS, by Marie Farré, illustrated by Diz Wallis. **GRAINS OF SALT,** by Dominique Joly, illustrated by Sylvaine Pérols. **LIVING IN INDIA,** by Anne Singh, illustrated by Aline Riquier. Young Discovery Library, 217 Main Street, Ossining, N.Y. 10562 ($4.95).

Three little books, each 36 pages within stiff covers, glow colorfully to stand in for all 120 titles that will one day complete the set. Originating in France and now part of an international effort in nine lands, it professes to be "the world's first pocket encyclopedia for children." The set begins with the sacred crocodiles of Egypt, fed on cakes and honey. That book ends with the Lewis Carroll verse on welcoming little fishes in "with gently smiling jaws." In between we learn how crocodiles and alligators differ and about their antiquity, their many eggs hatching to precarious survival, the plovers that pick their teeth, their skins and the need for protection—and the useful hint that if you ever are chased by a crocodile, "run in zigzags."

Salt is treated as essential; taste it in your tears. Washed eternally to the sea from traces of salt in the rocks, it was and remains the yield of salt pan and deep mine, here depicted in both ancient and contemporary versions. Camel caravans, the Great Salt Lake, underground churches sculpted of salt, the salt lick and the trade that in the end made salt (still invaluable) no longer rare are all here. You are even admonished to avoid too much salt, and reminded of the uses of "salt" in speech, from that one skeptical grain to the salt of the earth.

Worthy treatment of a nation such as India is a more difficult test of the series, here passed with real flair. The book rightly opens with a crowded and colorful street scene, to go on to farmers and the monsoon, to show villages both in Kerala and in Rajasthan, to savor fragrant spices on a banana leaf, to admire saris, jewels and that striking red forehead spot. Temples, festivals, meticulous dance and improvised music and a myriad of kites appear, yet balance is kept by a look at the mightiest film industry and at a satellite-tracking station. Only Himalayan snows are absent.

The texts' lightheartedness, catholicity and Cartesian precision and the plentiful paintings (not forced into a uniform style) distinguish this first-rate series for curious children five through 10. Each small book has a small index.

FAMILIAR FOSSILS, NORTH AMERICA, by Sidney Horenstein. The Audubon Society Pocket Guides, Alfred A. Knopf, Inc. (paperbound, $4.95). **FISHES: A GUIDE TO FRESH- AND SALT-WATER SPECIES,** by Herbert S. Zim and Hurst H. Shoemaker. Illustrated by James Gordon Irving. **FISHING,** by George S. Fichter and Phil Francis, illustrated by Tom Dolan, Ken Martin and Harry McNaught. Golden Press (paperbound, $3.95 each).

Expert, enthusiastic and handsome, the little pocket book on fossils is not truly a field guide: it locates the wonderful *Eurypterus,* state fossil of New York, no closer than "locally abundant" in that state. But it is a pictorial guide to these well-known invertebrate fossils, with a description, the size and a paragraph on the life and time for each genus shown. The photographs are so attractive and fascinating that they make up for the absence of sharper clues to the chase. One gets the feeling, probably realistic, that many young people nowadays shop for fossils, although the enthusiastic author does outline the basics of the actual hunt among the rocks. Local knowledge has to be added, available from clubs, museums, state surveys and colleges. Ginkgo, seed fern, corals, trilobites, crinoids, belemnites: "It is always surprising after digging in sandy silt all day to turn up what looks like a bunch of cigars." (Cretaceous belemnites are widespread in North America.)

In the guide called *Fishes* the fishes are painted in abundant variety, from cod and puffer to marlin and sea horse, from green sunny to steelhead. A page or so tells something of the life and importance of each group. The great commercial schools of sardines and menhaden are not forgotten. The huge, harmless whale shark, largest fish of all, draws a friendly page, and so does the strange ocean sunfish. There is a list of aquariums and marine stations. This book is a useful reworking of a standby now three decades old.

Fishing tells the hunter's side of the guide to the fishes. It too is a revision of a classic. It starts out with a long, illustrated list of kinds in saltwater and fresh, each with a few lines about where, when and how to go after them. It does not disdain little sunnies, with pictures of seven kinds. Bait, tackle and its use—lines, rods and reels, bobbers, sinkers, hooks, even bow and arrow—are presented here compactly but broadly. Fly casting is outlined—although it is to be doubted that one can learn so subtle a knack from a book. Party boats and trophies earn a couple of knowing pages. It is all here very briefly, a good start for practical young fisherfolk, who also can read how to clean, scale and fillet their catch—and it is fine for young dreamers too. Good fishing!

Mathematics and Its Uses

THE WORLD OF MATHEMATICS, edited by James R. Newman. Four volumes, boxed. Tempus Books, Microsoft Corporation, 16011 NE 36 Street, Redmond, Wash. 98073 (hardcover, \$100—\$79.95 during 1988; softbound, \$50). **READING THE PAST: MATHEMATICS AND MEASUREMENT,** by O. A. W. Dilke. University of California Press/British Museum (paperbound, \$7.95).

James Newman was the gifted lawyer and cultivated mathematician who during the 1950's established the style of this book column. In 1956 he published a long labor of love, this unmatched anthology of mathematics for the general reader. His easily carried learning and taste, and the wit and clarity of his introductions to the diverse material of the 133 articles he collected—both the work of mathematicians from Archimedes to Turing and the best of popular commentary, spoof, proof or paradox—earned his cornucopia of a book a justified triumph when it first appeared. It has since sold more than 200,000 copies. Out of print for years, it remains as good reading as ever. If you do not know it, seek it out; mathematical libraries and clubs for students at any level that somehow lack it certainly should have it.

Professor Dilke's small book "tries to show what a wealth of artefacts we have . . . which throw light on ancient mathematics and measurement." The author is a Latinist from the University of Leeds long concerned with Greek and Roman maps and surveying practices. His text does not neglect Egypt, Sumer and Babylon, and it includes a few closing pages on the Indian and Islamic work that followed antiquity, but the classical world holds center stage. Ten brief chapters tell more or less what to do in mathematics, mapping, surveying, time measurement, weighing, trade and recreational math—until the zero arrives.

We read a bit of the famous Rhind papyrus, copied by the scribe Ahmes in about 1575 B.C. from another papyrus already 250 years old. It treats of arithmetic and geometry, much concerned with pyramids. A value for pi is given—$(16/9)^2$—but the papyrus takes a most gingerly approach to the fraction.

We all know Roman numerals, but new to many will be the Milesian numeration: Greek letters that code for numbers. The letters early in the alphabet stand in order for the first 10 numbers, and letters toward the end for multiples up to 10,000; you could go beyond by compounding. The full system lasted from the sixth century B.C. until the fall of Constantinople. A wax tablet shown here bears some multiplication tables in the Greek system; another early manuscript clearly shows 1, 5 and 6 each raised to the powers of 1 through 5, all in Roman numerals. Here is a fragment of a marble plan of the city of Rome made in about A.D. 205; it is fairly true to scale, about one to 250, with some distortions. The other maps, like the weights and balances shown, are important but more familiar. The work is clearly and carefully written and could be read by any good young reader with help from dictionaries and friends.

ANNO'S MATH GAMES, by Misumasa Anno. Philomel Books, Putnam Publishing Group (\$18.95).

Again this artist has painted a few of his playfully pedagogical elves wandering among colorful small drawings with some logical end in mind, stirring the roots of mathematics for the youngest readers and the cheerfully read-to. No bright page has more than a few lines of text, and many have none. (There are useful pages of notes for parents and teachers.)

Anno offers four games. The first centers on noting what makes the differences within a set. It is all too easy at the start, one red circle in a strict array of blue squares. But then 16 pages—many without text—challenge both recognition and clarity of thought. Are the answers unique? Here Anno shows himself to be different, something we knew already. The notes praise the process of "creative struggle" that allows real development of a mathematical way of thinking. The association of cane and umbrella leads to a practical union; but with words and pictures a whimsical matrix comes to suggest a black carrot and a hateful lollipop. Playing cards are drawn in a variety of contexts to develop number as meaningful both for order and for quantity. Before long you are mapping a little group of houses using card notation.

The fourth game finds the elves at work with lengths, and the mapping goes from comparing kids short and tall to setting sticks in order. By the last page you have looked at ratio and proportion, arranging tubes of water with their lumps of sugar in a clever perspective view to seek the sweetest of all. It is not mathematical words but the intuitions on which meaning rests that capture the attention of this artist and his readers. A deceptively simple book, repaying serious work, it is at the opposite pole from the animated cartoons its appearance may suggest.

CALCULUS BY AND FOR YOUNG PEOPLE (AGES 7, YES 7 AND UP), by Don Cohen. The Math Program, 809 Stratford Drive, Champaign, Ill. 61821 (paperbound, \$12 including postage).

Trying to divide six cookies fairly among seven people? Third-grader Brad had the right idea: cut each one in half, share out as many as you can; again halve the pieces not shared until there are pieces enough to share, and continue. He quit at sixteenths, amidst lots of crumbs. But he could see that everyone got $1/2 + 1/4 + 0/8 + 1/16 + 1/32 + 0/64 + \ldots$ of a cookie. The sum is not hard to express in terms of more familiar series, once you notice that the missing portion of unity is itself a geometric series for $1/(1 - (1/8))$. Iteration is more powerful and more intuitive than dividing a round cookie into seven equal parts.

This spiral-bound book the size of your hand reports with infectious enthusiasm the work of many beginners in one fine teacher's classes over the decades, some of them highly gifted kids and some of them grown-ups with no particular mathematical bent. All were on their way to an understanding of slope and integral, natural logarithm and exponential. En route a good many famous problems were encountered, among them the proof of the snaillike divergence of the harmonic series (its first million terms add up to about 14.4, a sum given here to a dozen decimals), the Fibonacci sequence in pineapples and that glorious relation among *e*, *i*, pi, 0 and 1.

The crossings between recreational mathematics, modern calculators and the track of such pioneers as Newton and Euler make this breezy and personal account, more notebook than book, good fun for the mathematically inclined young person and helpful for any adults who seek freer but solid arithmetic teaching.

Tales from the Past

SEASONS OF SPLENDOUR: TALES, MYTHS & LEGENDS OF INDIA, by Madhur Jaffrey, illustrated by Michael Foreman. Viking Penguin Inc. (paperbound, \$7.95).

It was not in vain that Madhur Jaffrey's plump, fashionable, articulate and loving mother arranged the tools of the family trade for annual blessing: a family whose living had come from the arts of writing for 1,500 years sought that boon for school pencils and royal blue Quink. By the age of six Madhur had formed a "passion for stationery," and many years later we enjoy what has grown from it, her passion and talent for words, tales and their meaning.

In a lighthearted language that vibrates with immediacy, the author has arranged two dozen stories and anecdotes she recalls (with help from her friends) in an order appropriate to the Indian year, by season, holiday and moon. They include the most famous scenes of the great Hindu epics, of Ram and Lord Krishna, Shiva and Parvati and their elephant-headed son Ganesh, and the Monkey King Hanuman. These are known over all India. But there are also family stories and ceremonies familiar only to those "cheeky children," the 20 cousins who played, envied, doted and quarreled in Grandfather's big Delhi house years ago. The result is entirely Indian, complex, sophisticated, half in fun, half profound, just about all of it a delight to be read again and again. Readers from the youngest to the oldest can find a level that speaks to them. The deft illustrator journeyed to India to soak up color there; he returned, his work as brightly dyed by the sights of India and its art as Madhur's friends, enemies and "severest crushes" were dyed during Holi, the spring festival when everyone is drenched with color.

Two samples herewith, one a tale of verbal logic, fully at home in India. An arrogant king gained the boon that he could not be killed by man or beast, by any weapon, by day or night, on earth or in water, inside the house or out of it. He grew more and more evil and in the end had to be dispatched by Deity, who assumed a strange shape, half lion, half man; that creature took the miscreant into his lap on the palace threshold and clawed him to death just at dusk. (Work it out, and trust not in contracts.)

Or consider this search for magical blessing. During the full moon in October, moonbeams are said to transport a heavenly nectar. The young girls of the house were set that night to threading needles by moonlight, again and again, aiming at 110 times. If you were lucky, the nectar would enter intent eyes and make them shine brightly for life. Much rarer, your lips might even gain the nectar that can confer immortality. If all that fell through—sturdy practicality—Mother had prepared large trays of a fine confection of butter, sugar and semolina to expose to the moon's rays on the roof of the house.

The bright bargain book is a fragrant ladleful from the Ocean of Tales, given salt and life from the memories of that Delhi house and its vivacious people.

THE FLAME OF PEACE: A TALE OF THE AZTECS, by Deborah Nourse Lattimore. Harper & Row, Publishers ($12.95).

Not much is known of the stories of the Aztec people, whose great capital city we know today as Mexico. Here a talented young artist and writer has invented a credible Aztec myth for readers in the early grades, fashioned out of what little we do know of their life and beliefs in war and in peace.

Young Two Flint has lost his father in war. On the eve of a new battle, as temple fires burn and the warriors drink their maize porridge, Two Flint sets out to win peace. His mother had explained that peace can come only with the New Fire granted by Lord Morning Star. No one has ever before made his way to that Lord on his distant hill, but Two Flint, encouraged by a dream in which he is told to fight with his wits and not by the sword, sets out. He overcomes just so the nine Lords of Evil, one after another. Even grim Lord and Lady Death, all bones and dressed in bones, give way. He receives the sacred fire from the hands of Lord Morning Star, and as he brings it to the high altar, combat stops. Warriors embrace as friends, song scrolls bubble from their lips.

What is so striking about this book is its sustained style. The pages are tinted and framed to evoke an old codex, and numbered (base 20) in the Nahuatl way. The drawings that fill most of every page are very much the colorful, crenelated, writhing, intricate cartoons, conventional and yet recognizable, that make up the manuscripts we have, halfway between image and script. Fifty set sketches identified in the end papers, among them quetzal birds and obsidian spear tips, rainfrogs, corn cakes and pots of dye, are assembled into vivid scenes amidst exotic rivers and flowers and dazzling emblematic suns. Nothing and no one is commonplace. Deborah Lattimore has done all that, she writes, in the hope of satisfying the "two most critical audiences: scholars and children." Surely both will be delighted (although there is not one page about her sources for this rich display).

HOMINIDS: A LOOK BACK AT OUR ANCESTORS, by Helen Roney Sattler. Lothrop, Lee & Shepard Books ($15.95). **BEFORE THE INDIANS,** by Björn Kurtén. Columbia University Press ($29.95).

These books together neatly part the Old World from the New; open to curious readers in the upper elementary grades, they serve well as nourishing introductions to two exciting fields in paleontology for adults too. The hominid book is the briefer and simpler; it leans more heavily on its fine monochrome renderings. The illustrator's art has made these cousins and strangers into distinctive creatures, in the end individuals who win recognition as the fellow human beings they have become.

Björn Kurtén, a distinguished Helsinki paleontologist, offers a more detailed account, equally straightforward, informal and free of jargon, of the extensive evidence for the animals of America before the Paleo-Indians (direct ancestors of the Native Americans) arrived. Among all the bones of the New World there are documented remains of a crowded arkful, including giant Appalachian ground sloths, the zebras, hyenas, elephants and tigers of the plains, and Floridian llamas, vampire bats and fierce, carnivorous flightless birds. But nowhere is there any counterpart of that long African sequence of hominids becoming human. Just when men and women first arrived in America we are not quite sure, but it was late in the show; the early acts were long over.

Chapter by chapter, Helen Sattler describes the meager but coherent collections of bones and worked stone in context that have been pieced out across the Old World to put together the pedigree of human life. The scene is set mostly in eastern Africa, from the veldt to the Horn. Two-thirds of the story is over before we follow the "upright human" out of Africa, as far as the caves of Java, Peking and France. Hand axes and burned bone are presented, tools and fire, as the hominids gain dominion. Earlier the cats had held sway. A skull of a 12-year-old hominid from a South African limestone cave bears two marks that fit the canines of a fossil leopard found in the same cave; the child was not a resident but prey. The text names and pictures the species familiar in the literature but manages to make clear what many introductions blur: the tentativeness of the classification and the chain of descent, the importance of association and relative change. The Neanderthal folk, depicted with their rich grave goods and rituals, are given a modern appraisal as "sensitive, progressive people."

Kurtén tells us how remarkable fossil finds, in caves and tar pits, limestone sinkholes and lava blisters, canyon walls and river silt, have disclosed to us the New World game animals over three million years. One unexpected instance: bone by bone, the hunting lion has been traced in a number of subspecies, from the Rift to Europe, from Europe out to Mongolia, on to Vladivostok, across to the Yukon, down to Mexico, even to the tar seeps of Peru, at 40 sites in North America alone. In its glory the lion was present on five continents all at the same time, over a startling range of climates, the most versatile and widely distributed of any land mammal until the coming of humankind. Truly "the King of Beasts," the brainiest and strongest of all the cats, the lion prides hunted our forests and plains from Alaska to Florida. They left 76 individuals to be counted in the tars just off Wilshire Boulevard alone. The American lion vanished about 10,000 years ago. Why? Kurtén's last pages sum up the best present conjectures.

Biology

DINOSAURS IN THE GARDEN: AN EVOLUTIONARY GUIDE TO BACKYARD BIOLOGY, written and illustrated by R. Gary Raham. Plexus Publishing, Inc., 143 Old Marlton Pike, Medford, N.J. 08055 ($22.95).

These particular little dinosaurs were quite brave: they captured morsels of the food of the mammals and flew away. Commonly they are called starlings. In a dozen pages this biologist, teacher and stimulating writer reviews the chain of argument that allows his little play on words, for birds are almost as surely dinosaur posterity as we are the distant kin of long vanished apes. He turns then to the history and habits of the "brassy bird" that is in many ways a mimic of humanity. There is a clear list of a dozen specific behavior patterns you can watch for among starlings, and even an experiment you can do with decoys to test starling perception: they are drawn most readily by replicas that appear to be feeding.

A dozen other chapters with similar aim are here, admirable for young would-be biologists and a resource for teachers and parents. The microbes of fermentation are not hard to find in their garden of crushed grapes (one of 10 loosely covered comparison bowls planned to encourage colonial molds, bacteria and even protozoans), in microgardens of cottage cheese, cornstarch, peppercorns . . . and in tap, lake, pond or river water. The same point of view, with informed and detailed hints, brings mushrooms and lichens into knowing view, all the way to the taking apart and putting together of the lichen symbiosis.

Even the vast Cambrian explosion echoes in your little subacre, among worms and snails, pill bugs and other dry-land pioneers. How can pill bugs be so successful, given their closeness to sea life and their lack of certain key patents held by insects? A study of pill-bug design tells what we know; a few pages help you to find and culture specimens. Next come other arthropods, from jumping spiders to flies and beetles and moths and their coevolved flowers. The milkweed's hosting of bug and butterfly is nicely elaborated. Drawings, photographs and an informed but lively text draw out the evolutionary implications of the wonders that abound in the life around us, transmuted by insight out of the commonplace. Amusing, direct, visual, never condescending to the reader or to any other living form, this is a find. One hopes the author will visit the seashore soon and report what he watches there.

NO BONES: A KEY TO BUGS AND SLUGS, WORMS AND TICKS, SPIDERS AND CENTIPEDES, AND OTHER CREEPY CRAWLIES, by Elizabeth Shepherd, illustrated by Ippy Patterson. Macmillan Publishing Company ($13.95).

Key 1 starts out clearly: "The animal has legs. Go to 2. The animal has no legs. Go to 10." By Key 2 a young reader has found a new use for knowing how to count: if your animal has exactly 14 legs, the crusty little creature is an isopod, one of the pill-bug kind. Every creature named has its picture here, drawn very clearly—often twice, first in real size and then enlarged to allow nice distinctions, such as telling male spiders, with their tiny, fistlike feeler tips, from the females whose feeler tips look like feet.

The key divides in this way many times, pointing to all the creepy crawlies promised and many more. The language is kept simple: segments are referred to helpfully as body rings, and no Latin binomials appear at all. Plenty of behavior is described, both as part of the process and as interesting context. This key is not meant to help label animals stuck on pins, but for those who track and watch them alive, perhaps caged in a baby-food jar. (One to a jar, please; if two are together, one may eat the other. If you can, put the animal back where you found it.) There are many inserted minikeys—for example, one that parts jumping spiders from runners. The cicadas in the trees, buzzing louder and *louder,* roaches, houseflies and fireflies (but not clothes moths) are all here, among 100 or so identified forms. This is a cheerful, thoughtful small guide for readers who are like that themselves, with a backyard or a vacant lot they can visit, book in hand.

THE BEAVER FAMILY BOOK, by Sybille and Klaus Kalas, translated by Patricia Crampton. Picture Book Studio, Natick, Mass. 01760 ($14.95).

Once upon a time beavers dwelt in the woodlands of Austria in their snug lodges, working their engineers' way on ponds and streams in the wild forest. No longer.

A few years ago two naturalists set forth to seek out beaver newborns in some water-ringed lodge in the trackless Swedish forest. They found three web-footed, paddle-tailed little ones and brought them fondly back to a specially prepared hut by a stream in a wooded Austrian village, once beaver country. Klaus lived with the three little beavers; indeed, he became their new mother once they learned to take milk from the bottle and to cuddle in his sleeping bag early in the morning. They grew, and began to wake up hungry, now particularly fond of a "kind of spinach" (smacking their lips with pleasure over the mix of chopped thistle, nettle and meadowsweet). What beavers consider to be gentle nibbling turns out to be quite painful to a man's beard, and their coat cleaning wears big holes in his sweater.

By now the immigrants are a few years old; they have long since felled trees, built a beaver dam and two lodges much better than the artificial lodge they started with. A real beaver lake is in place, smoothly flooding over a piece of poplar and willow woodland. Someday this will be beaver country again. Small readers can enjoy learning about it from this easy text and its physically and emotionally intimate pictures ending in promise: a rosy sunrise over the beaver pond.

PLANTWATCHING: HOW PLANTS REMEMBER, TELL TIME, FORM PARTNERSHIPS AND MORE, by Malcolm Wilkins. Facts On File, Inc. ($29.95).

A first-class introduction to "how plants live, work and behave," making its strongest points with the aid of ingenious color photographs by the author (and his friends around the world) to explain real experiments, this book goes a long way to persuade us of something we impatient animals easily overlook: plants, although they usually move and change slowly, are intricate, active and powerful organisms. Any high school student—parents and teachers too—can follow the text, written freshly and quietly by a plant physiologist, professor of botany at the University of Glasgow.

The 18 chapters cover the subject pretty well, from a summary of evolved plant varieties and their life cycles to cellular structures and what they do. But neither diversity nor biochemistry is the focus here. Emphasis is kept on seeking the mechanisms behind visible function. We read and see plant plumbing (the fittings for pressure and for breathing, for timing and guidance, even for motion and heat generation) and the engineering of new plants—one tobacco cell, say, induced to become all root, all shoot or an entire tiny new plant.

Plants can tell up from down. Here are shots that show a corn seed, its tiny root turned horizontally, finding the vertical in a few hours. Electron-microscopic views make plain the tiny starch granules that drift to the lowermost walls of the sensitive root-cap cells whichever way the cells are tilted.

Plants respond to light in three distinct ways, with nary an eye. The photosynthetic chemistry in the green chloroplasts has the major story, neatly told here, although of course everyone knows of it at least vaguely. Here we learn also about the phytochrome system, the work of a blue-green pigment whose remarkable transitions between two forms (one absorbs red light and the other infrared) control many steps in plant development, for instance germination. In plants, "red [is] for go." The third response to light is exhibited here with admirable directness: the tip of a shoot, blue because it was photographed in blue light, curves adaptively toward the source—but the same tip, illuminated by green, yellow, orange or red light, remains straight and indifferent.

The control of flowering, fruiting and the dropping of leaves takes us to plant hormones. "Leaves do not simply die and fall off." They are actively and precisely cut off. The evidence is stunningly simple: a hawthorn branch was removed while in full leaf in August and was allowed to dry on the ground. Every dry leaf of that dry, dead branch remains attached in place; its fellow, allowed to remain on the tree, has instead shed all its leaves. A page follows the process in visible and in microscopic detail; we know of hormonal involvement, but the control code is still unread. It is hard to omit the tale of the strange gaseous hormone ethylene, emitted by and active in most plants, and now in wide use for commercial control of ripening and blossoming. The popularity of the aspidistra in gaslit Victorian England was surely due to its high tolerance for ethylene: other house plants gave up and went senescent in the presence of all that ethylene from coal-derived town gas!

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Tropical-forest species: going, going, going…

by Norman Myers

We are witnessing one of the most remarkable biological phenomena ever to overtake life on the earth. A single species, our own, is eliminating the planet's genetic stock more rapidly than at any time in the past, except possibly for those few occasions of geologic cataclysm when a mass extinction has depleted the earth's biotas. By the middle of the next century the earth seems likely to lose at least a fourth, probably a third, perhaps half and conceivably a still larger part of the millions of species that inhabit it. It is all happening in the space of just a few decades, the twinkling of an evolutionary eye.

What is the abundance and variety of species that make up the earth's biodiversity? Although we know there are millions of species, we have documented only 1.7 million. Informed estimates tell us there must be at least five million; recent research suggests there could be as many as 30 million insect species in tropical forests alone. We also know that the distribution of species worldwide is far from even. At least two-thirds of them and perhaps as many as 90 percent are concentrated in the Tropics.

There is a further dimension to the impoverishment that is overtaking the earth's biotas. Many species are losing entire subunits, in the form of races and populations, which greatly reduces their genetic variability. Even though these species are not being endangered in terms of their overall numbers, many of them, such as corn, rice and wheat, are suffering a critical decline in their genetic variety.

How fast are species disappearing? The "background rate" of extinctions during the past 600 million years or so (since multicellular life appeared) has worked out to a rough average of only one per year. The present human-caused rate is at least 1,000 times as great—and may soon become much greater still.

Although it affects many areas, biodepletion is nowhere more rapid than in tropical forests. These forests, although they cover only 6 percent of the earth's land surface, shelter at least 50 percent of all species. By early in the next century there could be little left of this biome.

The proximate cause of the loss is the growing number of impoverished forestland farmers. Consider Rondônia, a state in the southern sector of Brazilian Amazonia. Since 1975 the human population there has grown from 111,000 to well over a million. In 1975 only 1,250 square kilometers of forest had been cleared, but by 1987 the amount had expanded to almost 60,000 square kilometers; three times as large an area has been severely degraded.

To be sure, we may learn how to manipulate habitats to enhance the prospects for survival. We may expand our capacity to propagate threatened species in captivity, but in the main the damage—through delayed extinction effects—will have been done.

Climatic change may also render futile our best efforts to preserve wildlife habitats through such measures as establishing national parks. In Amazonia it is becoming apparent that even if a substantial proportion of the forest were to be safeguarded, there could soon be at work a hydrologic feedback mechanism that would allow a good part of Amazonia's moisture to be lost, desiccating the remaining forest. By the first quarter of the next century at the latest we may well be experiencing the climatic dislocations of a planetary warming, stemming from the buildup of carbon dioxide and other greenhouse gases in the global atmosphere. The viability of many protected areas will soon be threatened as vegetation zones begin to "migrate" away from the Equator.

Yet the impending mass extinction of species is far from being the entire story. A longer-term and ultimately more serious repercussion could stem from the disruption of the course of evolution itself. The bounce-back time after a mass-extinction episode (the recovery period needed for speciation processes to generate an array of species matching, in abundance and variety, what was there before) has generally been a few million years. The evolutionary outcome this time could be more drastic. Broad-scale depletion will surely apply across most if not all major categories of species, causing the bounce-back period to last for many more millions of years.

The mass demise of species would have immediate economic consequences, certain ones of which could be serious indeed. In 1970 a leaf fungus blighted U.S. cornfields from the Great Lakes to the Gulf of Mexico. America's great Corn Belt almost came unbuckled. The disease eliminated 15 percent of the entire crop, pushing up corn prices by 20 percent and causing losses of more than $2 billion. The situation was saved thanks to blight-resistant germ plasm whose genetic ancestry traces back to variants of corn from one of the plant's native habitats in Mexico.

Wild plants also contribute to our health needs. Half of the purchases in the neighborhood pharmacy, whether drugs or pharmaceuticals, derive from wild organisms. The full commercial value of these wildlife-based products worldwide is some $40 billion a year. How many more such opportunities lie hidden in the earth's genome? Investigators have taken a look at only 10 percent of all plant species and have examined only 1 percent of them intensively.

On top of these material benefits, species supply many ecosystem services. They help to maintain the quality of the atmosphere, control climate, regulate freshwater supplies, generate soils, recycle nutrients, dispose of wastes and control pests and diseases.

In the face of a bleak outlook there are signs—a few signs—that this long-sleeping issue is awakening. In response to a surge of citizen interest, the world's governments are moving to safeguard biodiversity. Biodepletion is being seen by scientists, administrators and business leaders as an issue deeply interrelated with those of energy, economic growth, population and climate change. It is no longer sufficient to respond to symptoms of problems. We must address their source. This will entail planning initiatives at a macrolevel of public policy with respect to a broad range of economic activities—agriculture, industry, technology and trade, together with associated factors such as population growth and poverty—all within a context of development that is intrinsically sustainable. This is the best way, and probably the only way, that we can ultimately safeguard enough habitat for millions of species, including our own.

NORMAN MYERS, a consultant on environment and development, has undertaken projects for the U.S. Department of State, the World Bank, United Nations agencies and the World Wildlife Fund, among others.

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