SCIENTIFIC AMERICAN

JANUARY 1992
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Where chaos lurks in the subatomic realm.

A little erbium makes optical signals go a long way.

Did sex evolve as a defense against parasites?

***Sea turtles** obtain navigational cues from the earth's magnetic field and the direction of ocean waves.*

To Those Who Have Ta
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Accordingly, the cabin of the LS 400 was designed to serve as your sanctuary.

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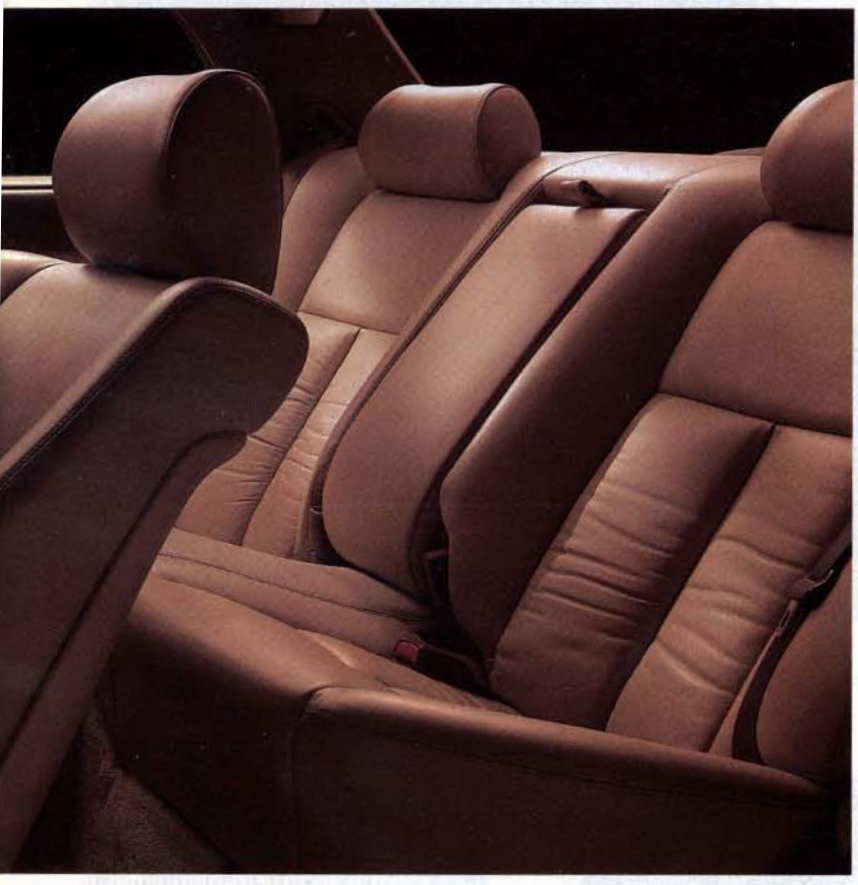

does; the cabin is so library-quiet, you have to listen carefully to be sure.

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The wheel, that is.

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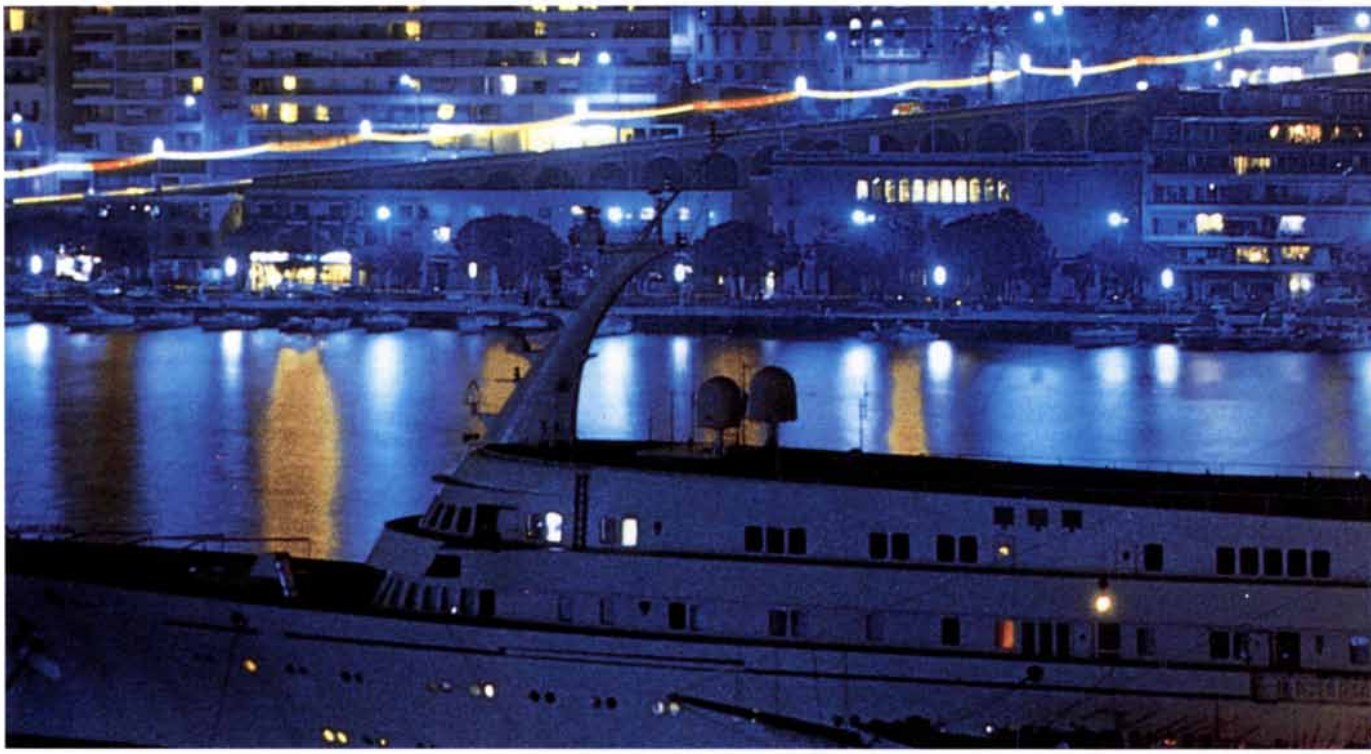

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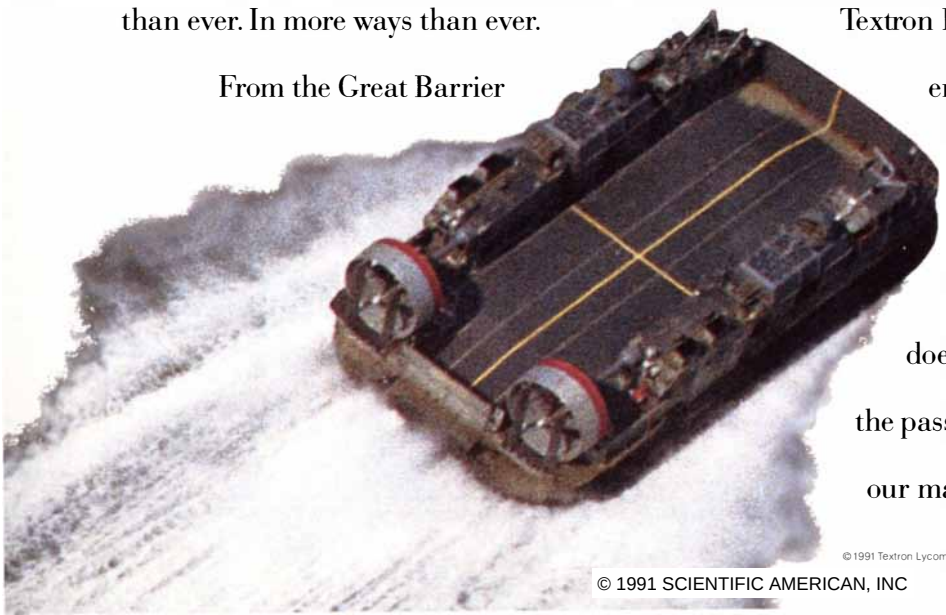
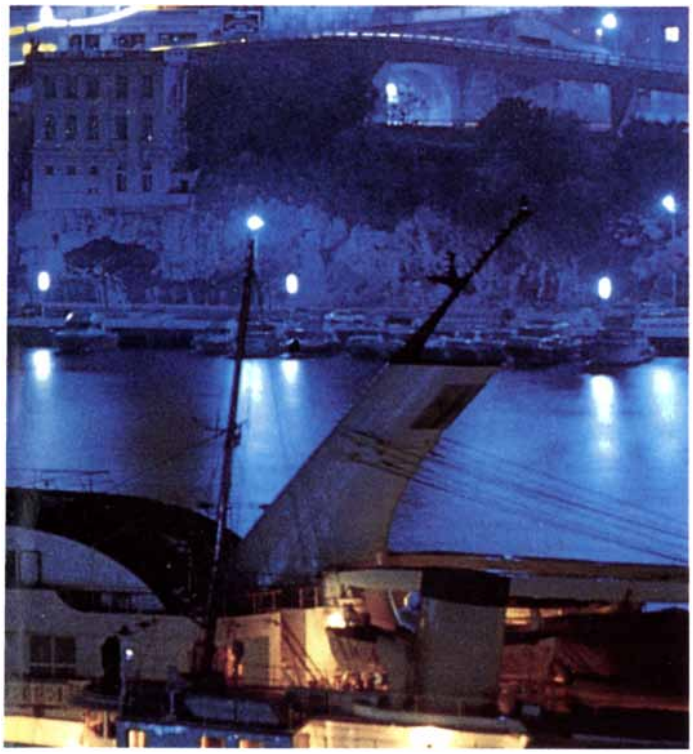


Of Montezuma Of Monaco.



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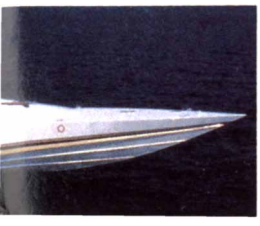

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January 1992 Volume 266 Number 1

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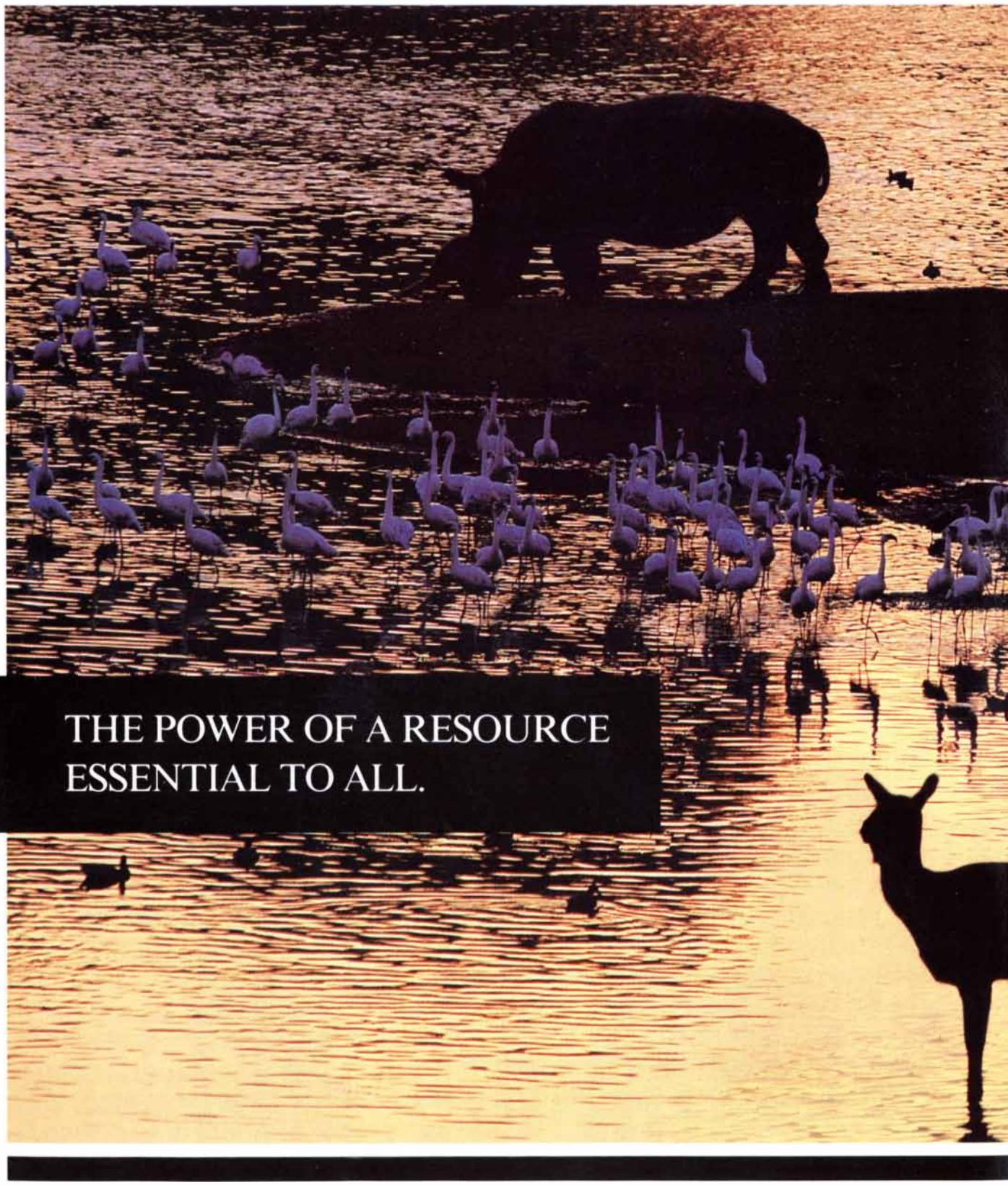

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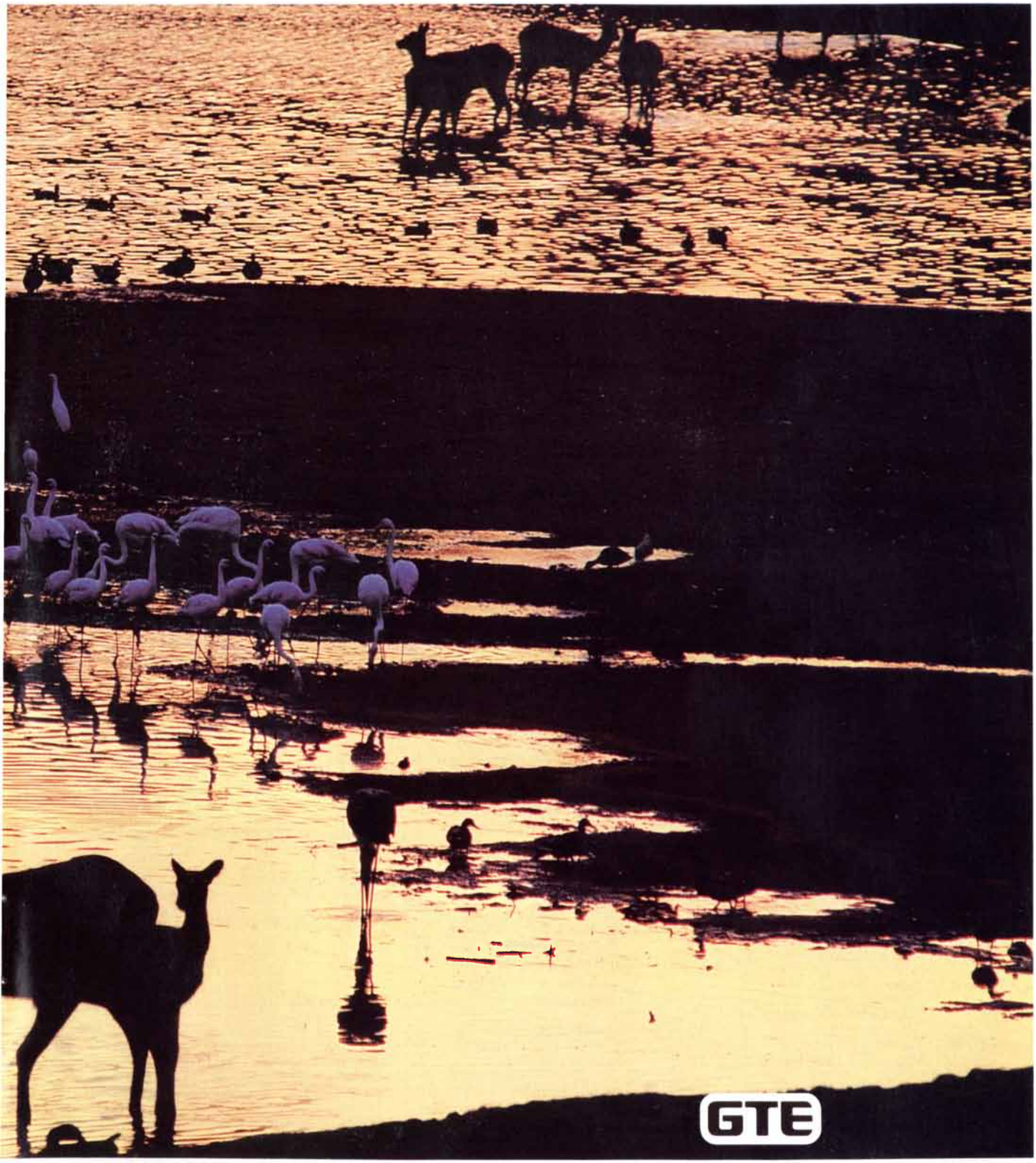

THE POWER IS ON

THE COVER photograph shows green turtle hatchlings (*Chelonia mydas*). This species, like other sea turtles, possesses extraordinary navigational skills. As hatchlings, they swim unerringly out to sea. As adults, they may migrate more than 1,000 miles from their feeding grounds to their nesting beach every few years. They apparently can use such environmental cues as the earth's magnetic field and the direction of ocean waves to guide their journeys (see "How Sea Turtles Navigate," by Kenneth J. Lohmann, page 100).

THE ILLUSTRATIONS

Cover photograph by M. Timothy O'Keefe/Bruce Coleman, Inc.

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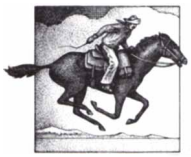

LETTERS TO THE EDITORS

Drugs and History

"Opium, Cocaine and Marijuana in American History," by David F. Musto [SCIENTIFIC AMERICAN, July 1991], is of singular value in comprehending the drug question. I wish to commend *Scientific American* for devoting space to the almost forgotten history of this great controversy, which goes back to the antidrug campaigns of President William Howard Taft and New York Governor Alfred E. Smith.

Musto's approach allows us to put into perspective the debate we are witnessing and to understand the sources of the extreme attitudes toward drugs that we have passed through since the 1960s. Whether we can avoid the excesses of the first drug epidemic remains to be seen, but Musto makes a persuasive case for thoughtful deliberation when framing a policy against the use and abuse of drugs. He is a national asset.

FRED W. FRIENDLY
Director of Seminars on Media and Society
Columbia University Graduate School of Journalism

Although I am familiar with Musto's writings and thankful for them, I was most disappointed with his article. He managed to spend several pages relating the historical events that led to the narcotics issues in American life without touching on any of the geopolitical ramifications; that omission renders his history empty to the point of being misleading. He did not even mention the two seminal events that led to our country's drug problem: the Civil War (which he discussed only out of context) and the war in Vietnam.

Musto states that unless we appreciate our history, we may "again become captive to the powerful emotions that led to draconian penalties...." I agree. Without the whole truth of that history, however, and without grasping its social, economic and political realities, that appreciation will be for naught.

DON SLOAN
Psychosomatic Division Director
New York Medical College

How can you print such nonsense as "the percentage of those who try a substance and acquire a dependence or get into legal trouble is not 100 percent" and "the technology of drug use promised an extension of our natural potential" [page 47]? The first statement is comparable to saying that "the percentage of Russian roulette players who do not get into serious difficulty is not 100 percent." The second has no validity except as a position advocated by the marginal lunatic fringe.

VICTOR BAGNO
Tufts University

Soviet Antiscience

Sergei Kapitza asks what is to be done about "Antiscience Trends in the U.S.S.R." [SCIENTIFIC AMERICAN, August 1991]. The answer is education, not prohibition. Tolerance of others' beliefs is surely central to the future success of that country. Whether these beliefs are fanciful, pseudoscientific wish fulfillment, offensive political principles or just someone else's religion is immaterial. Kapitza himself makes the contentious statement that if the Communist revolution were to have spread worldwide, then the Soviet Union's present crisis would not have occurred. That idea, depending on one's position, is a trivial tautology, a consequence of Trotsky's political philosophy or an untestable belief.

GRAHAME Y. BUSS
Amsterdam

Dark Side of Computing

As a frequent user of computers and networks, I read with interest the special issue "Communications, Computers and Networks" [SCIENTIFIC AMERI-

CAN, September 1991]. I was hoping, however, for a fuller discussion of the negative effects of computers on individuals and on society as a whole.

The bright new world of electronic communications casts a dark shadow. Computers increase the isolation of the individual. Computer conferences, computer counseling and network interactions are cases in point. How will computers transmit moral values? Will teachers be replaced by computers? Learning will always take an intellectual effort. Computers will make learning easier, but they will not create the desire to learn.

SANDOR FRECSKA
Lancaster, Penn.

After reading "Computers, Networks and Education" [SCIENTIFIC AMERICAN, September 1991], I have one question for its author, Alan C. Kay. Will children educated as he describes ever be able to write as well as he does?

NORAH DUCK
Scarborough, Ontario

Nicholas P. Negroponte's "Products and Services for Computer Networks" [SCIENTIFIC AMERICAN, September 1991] mentions the excellent idea of reading a menu of the coming week's television shows and electronically selecting which shows you want to watch. Parents could presumably lock out any shows they didn't want their children to see. That capability would remove the incentive for censorship movements that attempt to remove "objectionable" shows from television (although it wouldn't remove the urge some people feel to meddle in the viewing and reading habits of others, unfortunately!).

MICHAEL W. BELL
Rockford, Ill.

Doing a Dirty Job

Marguerite Holloway and John Horgan are to be commended for both the accuracy and content of "Soiled Shores" [SCIENTIFIC AMERICAN, October 1991], concerning the *Exxon Valdez* and Persian Gulf oil spills.

In the case of the Persian Gulf spill, the pressures of time, the cultural differences, the political sensitivities and the confusion about financial responsibility can probably only be appreciated by those who were or are actually there. The individuals and companies with which I worked showed the highest professionalism and integrity.

Thank you for your article.

DAVE GLENN
Spill Equipment Technologies Company
Twisp, Wash.

ERRATA

On page 48 of "Iron Deficiency," by Nevin S. Scrimshaw, in the October 1991 issue, the number of deaths caused by malaria is incorrect: malaria kills fewer than two million each year. Also, the anemic and healthy red blood cells pictured on page 49 were photographed by different techniques, which accounts for part of the difference in their appearances. During pregnancy, a woman loses a total of 900 milligrams of iron, contrary to the claim on page 50.

In "Mathematical Recreations" in the September 1991 issue, the behavior of the logistic formula is misstated. The system of generated numbers shows a single attractor when r is less than 3, two attractors between 3 and 3.45 and more attractors above 3.45.

On page 21 of the August 1991 issue, the affiliation of Julian Schwinger is misstated. He is professor emeritus at the University of California, Los Angeles.

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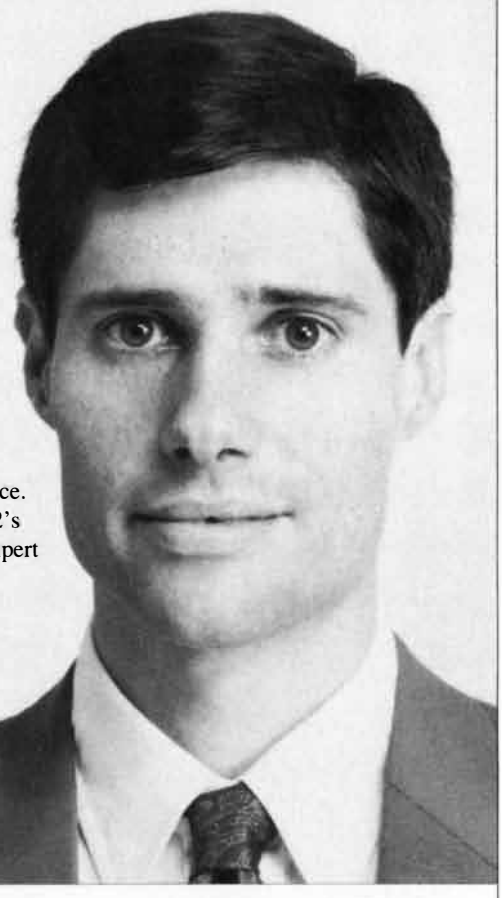

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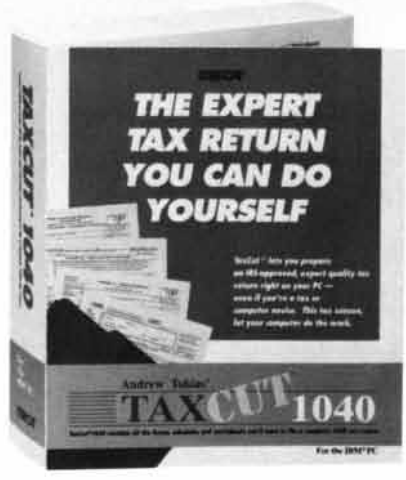

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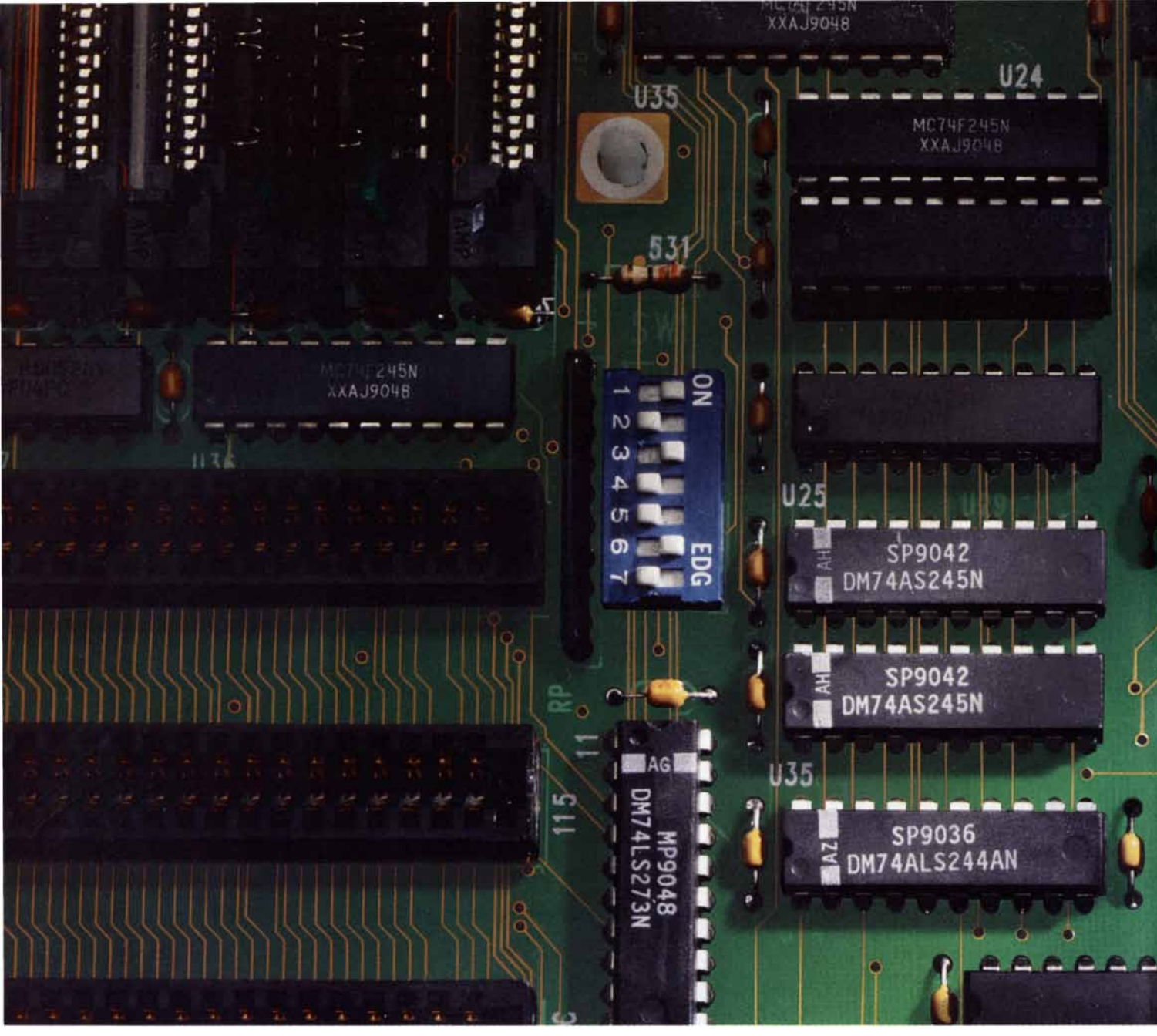

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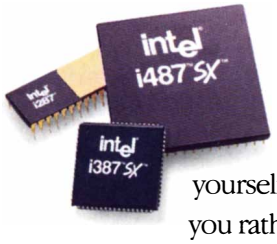

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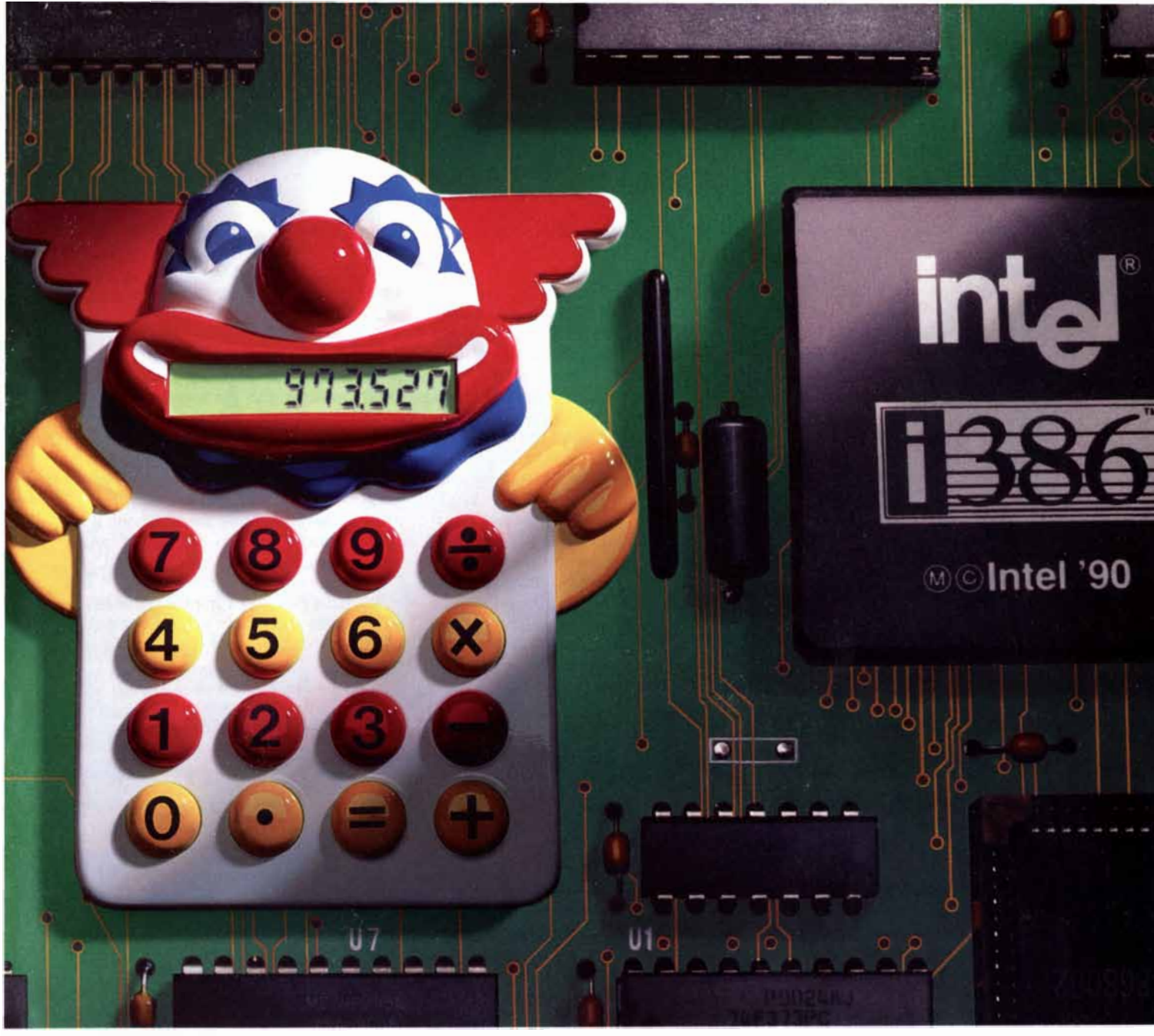

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JANUARY 1942

"Possibly veteran jumpers can describe sensations and thoughts during the brief seconds that elapse between the leap from the plane and the teeth-loosening wallop that ensues when the 'chute opens and applies sudden brakes to a headlong earthward plunge, but to a neophyte that brief passage of time remains pretty much a blank. Although the parachute harness is designed to distribute the shock to the portions of the body that are best suited to absorb it, the comeuppance you receive when the 28-foot-diametered canopy abruptly goes to work is comparable to an almost instantaneous reduction of the traveling speed to between 15 and 20 miles per hour. In an automobile, such a drastic change of pace might well be preliminary to a swan dive through the windshield; in a parachute harness, you have the fleeting sensation that your skeleton is about to slide feet-first out of your body."

"Administration of doses of 100 percent oxygen will offset the impaired sight induced by insulin, according to Dr. Ernst Gellhorn, professor of physiology at the University of Illinois. This sight impairment takes place, he points out, as a result of the close relationship between oxygen and blood sugar content. Administration of insulin in 'shock' therapy, for example, decreases excess sugar in the blood, deprives the brain of some of the sugar which it burns, and thus produces visual disturbances including loss of the ability to see 'after images.'"

"Our army's youngest, smallest, toughest baby has many pet names: jeep, peep, blitzbuggy, jitterbug, beetle-bug, iron pony, leaping Lena, panzer-killer. The names are all affectionate, for the jeep has made good. I was standing in the hot Mississippi sun while Lieutenant Patrick Summerour, of Camp Shelby, explained the jeep. In front of me was a car 11 feet long, 56 inches wide, 40 inches high—half the height of your family auto and three feet shorter. Summerour pointed to a rear towing hook. 'You pull an anti-tank gun here,' he said. 'Civilians often ask why we do not fight tanks with tanks. The answer is twofold. In the first place, a jeep costs $900; a tank $35,000. Second, these tank-destroyers, towing anti-tank guns, can swarm round old Schicklegruber's tanks and give 'em hell.'"

SCIENTIFIC AMERICAN

JANUARY 1892

"A reverse of seasons is supposed to take place upon this earth once in every 10,500 years, due to the varying inclination of the earth's axis. About 1,500 years ago we entered the epoch of a more genial winter temperature, and if nothing happens to prevent, we may expect a gradual softening of our winter climate during the next 9,000 years, when another glacial epoch will begin. What sort of country will this be in the year 11,500? Will it resemble Egypt, with remains of great buildings buried or sticking up out of the sand?"

"Inhabitants of cities indulge far too freely in meat, often badly cooked and kept too long; the poor and country population do not often get their meat fresh. Professor Verneuil considers something should be done to remedy this state of things. He points out that Reclus, the French geographer, has proved that cancer is most frequent among those branches of the human race where carnivorous habits prevail."

"We have received a number of ingenious solutions of how to so place the ten digits that their sum shall be 100:

$$0+1+\frac{3}{2}+\frac{9}{6}+4+5+87=100.$$

$$0+1+34+5+6^2+7+8+9=100.$$

$$1+3+4^2+50+6+7+8+9=100.$$

—By C. F. Erhard.

$$5+10+36+47=98+2=100.$$

—By W. Donaghy.

It is to be said, however, that the use of fractions involving division, or of exponents involving multiplication and virtually repetition of the same number, is hardly fair."

"In the specifications to one of his recent patents, Thomas A. Edison says: 'I have discovered that if sufficient elevation be obtained to overcome the curvature of the earth's surface and to reduce to the minimum the earth's absorption, electric signaling between distant points can be carried on by induction without the use of wires.'"

"There will probably be no more interesting exhibition in connection with the World's Fair than the facsimile which it is proposed to construct of the Santa Maria, the vessel in which Columbus himself sailed on his voyage of discovery. As is well known, there were three vessels in his fleet, and the appearance they presented on approaching the first land of the New World is the subject of this engraving."

DISCOVERY OF THE NEW WORLD by Columbus from the painting of Brugada, in the Naval Museum, Madrid.

"So you're testing a prototype already?" *"Yep. Mmm, lasagne."* "Patents checked?"

"Wouldn't test otherwise." "Meet industry standards?" *"It'll comply...*

...which I don't think is true of the meatloaf." "Say, where're you getting so much help, anyway?"

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Venus Revealed

Stunning maps strip the clouds from a restless planet

Like through a crack in the fence, planetary scientists have eagerly and impatiently watched the action unfold as crisp radar images from the *Magellan* spacecraft progressively unveil the surface of Venus. At the conclusion of its first year of mapping, *Magellan* has revealed a vast array of stunning and often enigmatic landscapes.

The National Aeronautics and Space Administration recently released the first global maps, vividly displaying impact craters distorted by the thick atmosphere, volcanoes shaped like pancakes, intricate networks of fractures and a mysterious lava channel that snakes 6,800 kilometers across the planet. Now the various specialized teams of scientists are stepping back "to look at how all these things interrelate, what it all means," says R. Stephen Saunders, the Magellan project scientist at the Jet Propulsion Laboratory.

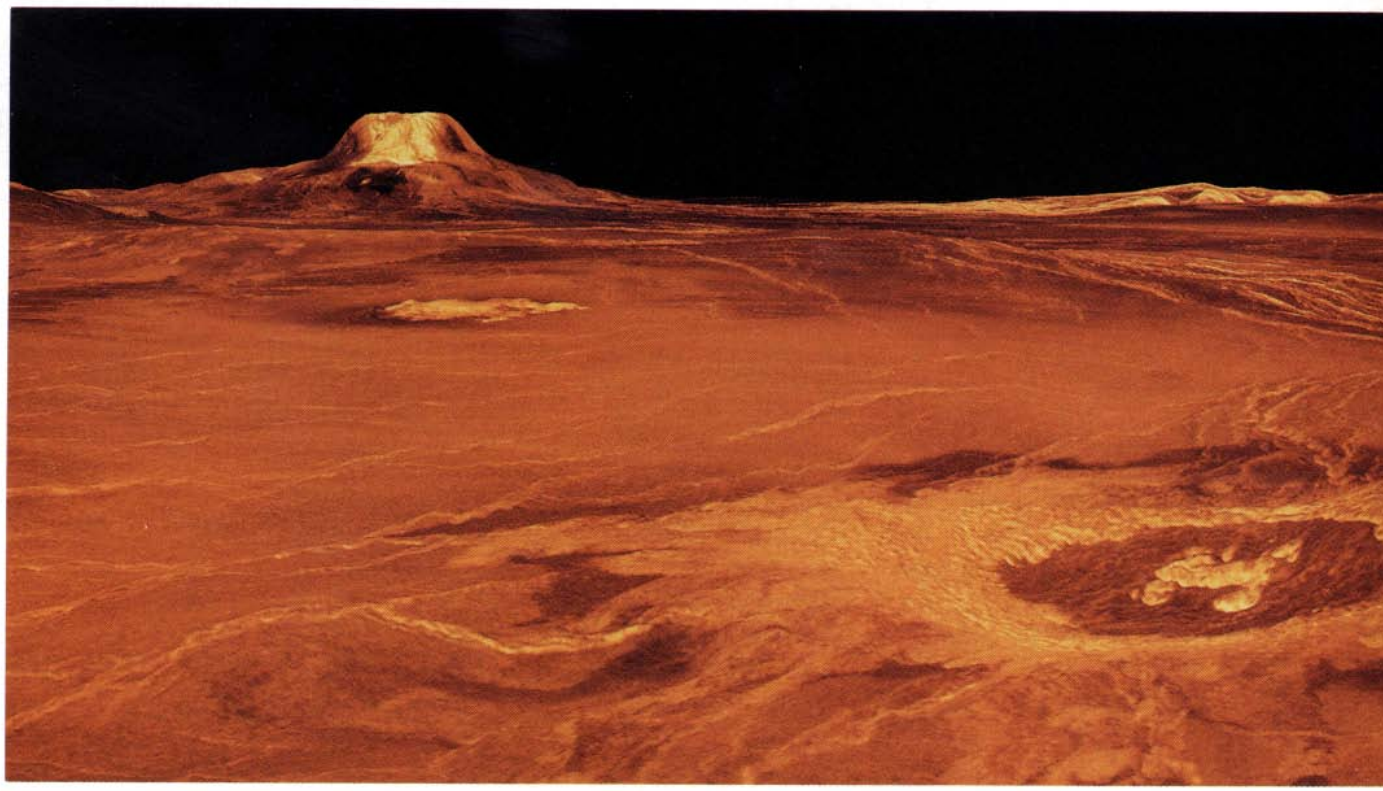
Although surface winds on Venus move no more than a few kilometers an hour, wind streaks appear around many craters. These streaks preferentially point toward the equator, giving scientists a "compass direction" of atmospheric circulation, says Gerald Schubert of the University of California at Los Angeles. Windblown dust could cause erosion or might stick to the rocks on Venus's scalding hot (475 degrees Celsius) surface. Chemical erosion also takes place, reports Raymond E. Arvidson of Washington University.

Even so, the Venusian surface is pocked with large, seemingly unaltered craters, such as the 50-kilometer-diameter Cunitz, which is named for mathematician Maria Cunitz. (All features on Venus bear the names of famous women or female mythological characters.) *Magellan* has found only about 850 craters on Venus, far fewer than on the moon or Mars. Planetary scientists speculate that small meteors disintegrate in the atmosphere; larger craters may have been buried by ancient lava flows.

One of the most spectacular volcanic features on Venus is Gula, named after an Assyrian goddess. Gula extends hundreds of kilometers across but only about three kilometers high. Early in the mission, Saunders selected Gula as a possible active volcano. But when *Magellan* got a closer look, it revealed an impact crater and bits of ejecta lying atop the lava flow around Gula and Sif, its sister volcano.

Lofty locations, such as the top of Gula, appear bright to *Magellan*'s radar. Several scientists have identified iron sulfide or iron oxide, which are efficient radar reflectors, as the likely materials crowning Venus's high mountains. Interestingly, Maat Mons, which is the second highest mountain on Venus, appears dark at the top. John A. Wood of the Smithsonian Astrophysical Observatory thinks the dark material is lava that has not yet been weathered into radar-reflective materials. Wood concludes that Maat Mons is younger than other Venusian volcanoes, although weathering occurs so slowly that the lava could be quite ancient.

Some scientists think large parts of Venus's surface were reworked during a huge volcanic episode 500 million years ago, similar to outbursts seen on Mars and the moon. Others envision a

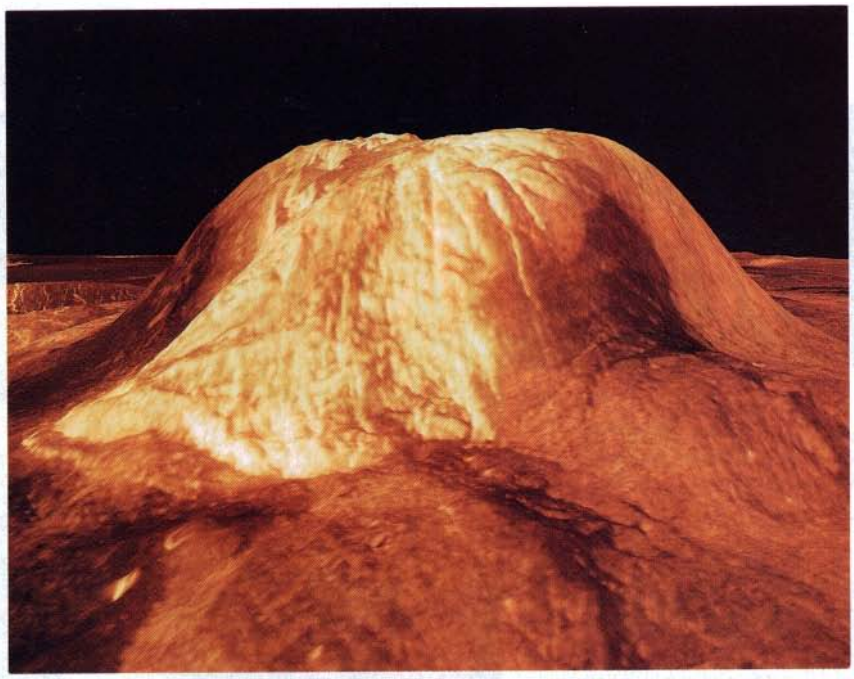


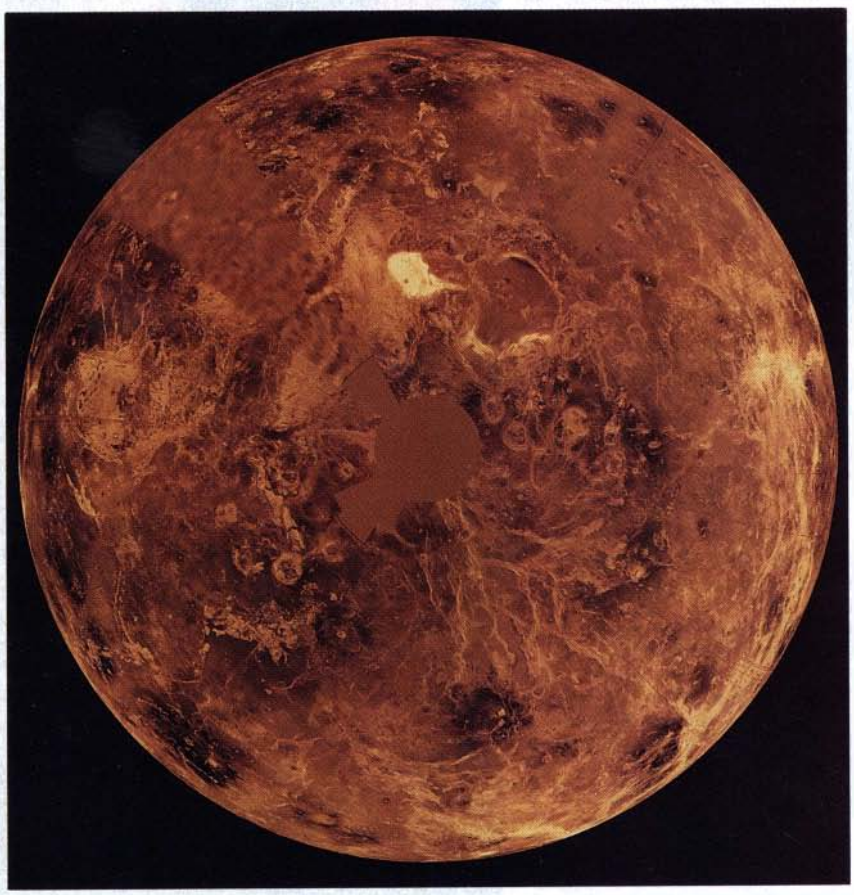
"steady state" scenario involving fairly constant volcanic activity over geologic time. Arvidson sees Venus as "a perverted earth," lacking plate tectonics but supporting ongoing volcanic activity.

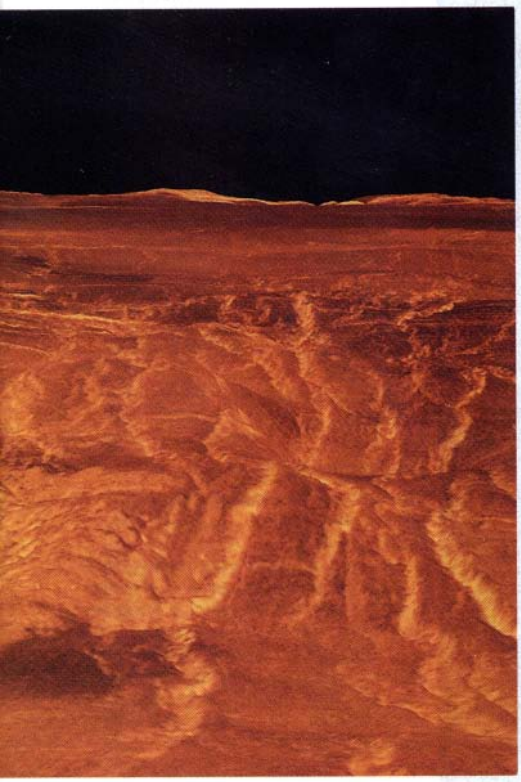
Topographic features on Venus seem to be dominated by the upwelling and downwelling of material in the planet's interior. Upwelling produces circular fractures, called coronae. What appear to be trenches at the edges of some coronae might be places where crust is subducted into the Venusian mantle, Schubert reports. A map of Venus's northern hemisphere, centered on the north pole, reveals bright, highland features, such as Maxwell (just above the pole) and Aphrodite (extending along the bottom to the right edge of the image). These elevated regions may have formed as cool material sunk into the planet's mantle, crumpling the overlying crust in the process. Gordon Pettengill of the Massachusetts Institute of Technology reports that Maxwell has sharp slopes, a surprise given the hot, deformable surface rocks.

Despite the wealth of data released, the Magellan mission is far from completed. A second round of mapping, to be completed this January 15, will fill in the gaps in the first map and allow researchers to search for surface changes.

By the time its mission ends in 1995, *Magellan* will have returned four trillion new bits of data. Planetary scientists studying Venus suddenly find themselves faced with the delicious problem of having too many new facts to explain. Want to lend a hand? Early next year, NASA will release the data from the first mapping cycle on a set of 62 optical disks. —*Corey S. Powell*







MAGELLAN *RADAR IMAGES show the Cunitz crater* (below), *Gula Mons* (top right) *and a nearly complete map of the planet's northern hemisphere* (bottom right). *Photos: NASA/JPL.*

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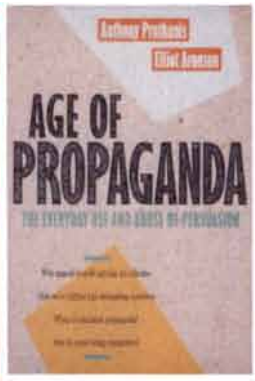

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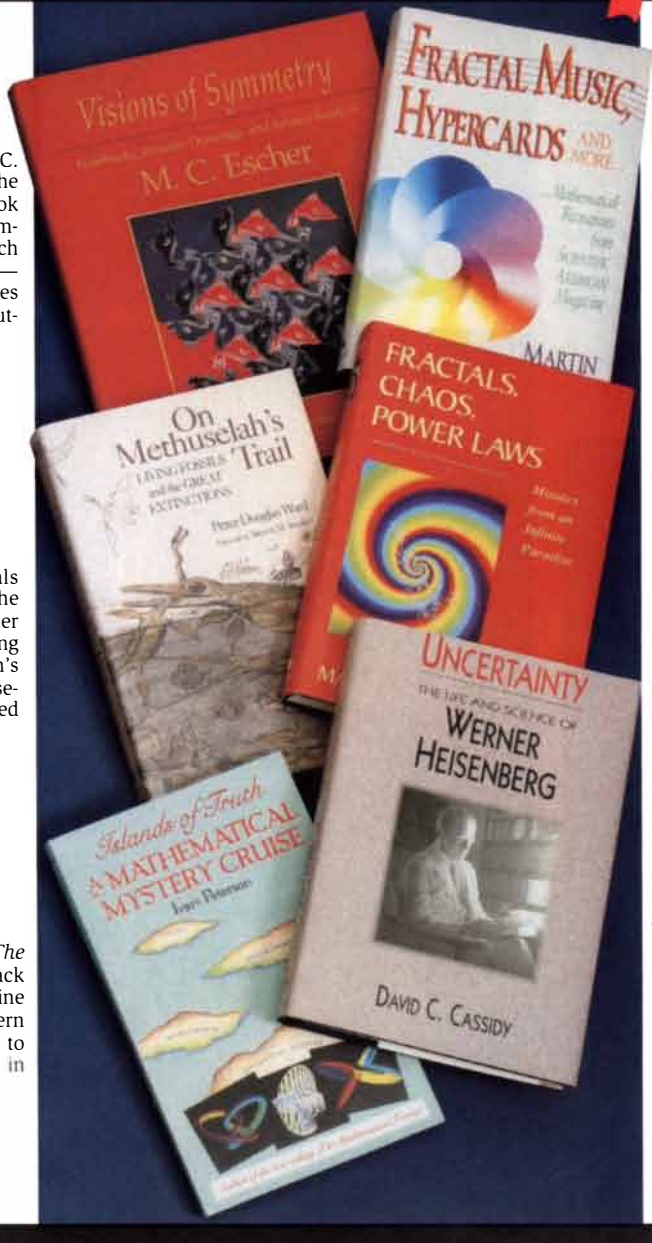

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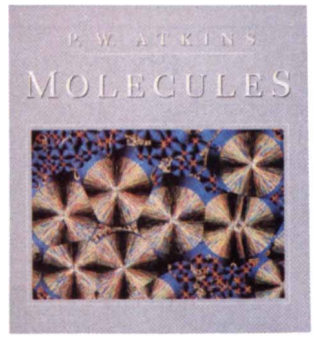

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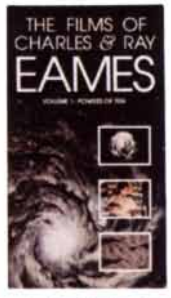

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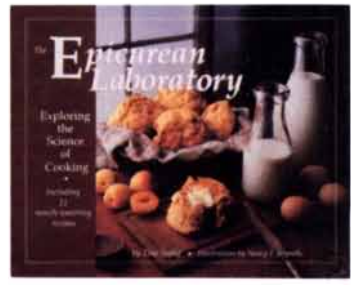

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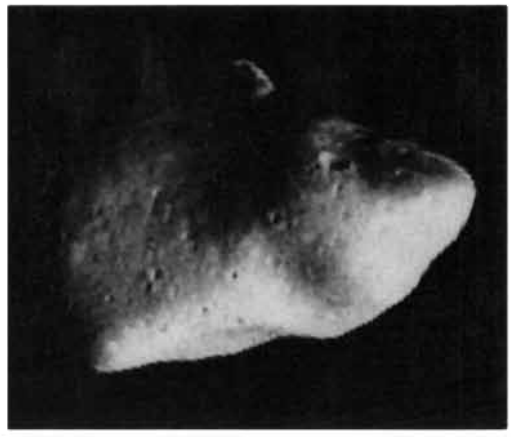
Rocky Rendezvous

They are a staple of science fiction movies, but nobody had ever seen a real asteroid up close—until now. Last October 29, on its circuitous journey to Jupiter, the National Aeronautics and Space Administration's *Galileo* spacecraft sent back a historic first image of Gaspra, a smallish (about 12 by 20 kilometers) denizen of the asteroid belt that lies between Mars and Jupiter.



Gaspra is the most common variety of asteroid, a stony S type. This diverse group probably includes both pristine leftovers from the formation of the solar system and shards from larger, more evolved bodies. Gaspra falls into the latter category, says Joseph Veverka of Cornell University. Ida, which *Galileo* will call on in 1993, seems a more primitive sort.

Its irregular shape comes as no surprise: small asteroids are likely to have suffered a few collisions over the age of the solar system, and their gravity is too weak to pull the material into a round shape. Based on the paucity of craters on Gaspra, Veverka estimates that its surface is 300 to 500 million years old, young compared with the 4.6-billion-year age of the solar system. A color image of the asteroid shows variations on the surface, perhaps where meteorites have disturbed a loose outer layer.

Because of a faulty antenna, *Galileo* will not transmit additional stored images until it approaches the earth this spring. The best of these should reveal features less than 100 meters across, three to four times the resolution seen here.

Planetary scientists are elated by their first look at Gaspra. And what about *Lost in Space* fans? Well, the early indications are that real asteroids can be plenty interesting in their own right. —*Corey S. Powell*

After the Inferno

Kuwait has stopped burning, but questions still smolder

On November 7 firefighters in Kuwait capped the last of more than 700 oil wells blown up by Iraqi troops last February. The job was completed with astonishing speed; as recently as last June, the veteran firefighter Red Adair had predicted it could take years. Nevertheless, in the wake of the catastrophe questions linger. An examination of three questions—one economic in nature, one environmental and one political—follows.

 Have Kuwait's oil reservoirs been irreparably damaged?

Last spring, some fires began spewing forth large amounts of what appeared to be steam in addition to the black soot. Oil industry experts worried that the oil reservoirs were showing signs of "coning," which occurs when a layer of water underlying the oil begins to extrude into it.

Peter V. Hobbs, an atmospheric scientist at the University of Washington who last May headed a scientific mission to the Gulf region sponsored by the National Science Foundation and the Department of Defense, said his group had found no evidence of steam in Kuwait's smoke plume. But a subsequent study by Thomas A. Cahill, a physicist at the University of California at Davis, showed that the smoke was rich in salt. The salt, Cahill asserts, indicates that "oil brine" has indeed contaminated the oil reservoir.

Before the fires were extinguished, various observers also reported a marked decrease in their height and intensity—an apparent sign of a loss of oil pressure. A permanent drop in pressure, together with water contamination, could boost Kuwait's oil production costs and, eventually, oil prices. Kuwaiti officials have declined to discuss the extent of damage to their fields.

 All scientists agree that the fires did not have a significant impact on the global climate, but did they affect weather over Asia?

Hobbs has discounted this possibility, as have workers from the British Meteorological Office who visited the Gulf region in March. But Thomas J. Sullivan, a meteorologist at the Lawrence Livermore National Laboratory, suspects otherwise.

Sullivan has tracked the smoke's path with a computer model developed to monitor the transport of plumes released by nuclear accidents. The model showed large amounts of smoke collecting in a typhoon that struck Bangladesh last April. The typhoon, which killed more than 100,000 people, was accompanied by torrential rains and record-breaking floods. Sullivan says his model also showed smoke drifting over regions of China ravaged by rain-induced floods last summer.

Salt in the smoke from Kuwait might have contributed to the heavy precipitation in Bangladesh and China, according to Cahill. Noting that salt serves as an excellent cloud-seeding agent, Cahill calls the Kuwait fires "the biggest cloud-seeding experiment in history."

 Who ordered U.S. government scientists not to talk about the environmental impact of the fires?

The censorship was imposed during the war, allegedly to protect national security, but it continued for months afterwards at such agencies as the National Oceanic and Atmospheric Administration (NOAA). A cable sent by the State Department on June 16 to diplomatic posts in the Persian Gulf region noted that predictions concerning "the risks from the oil fire smoke to human health, the environment, crop productivity and the global climate . . . should be considered as little more than guesswork." At that time, U.S. officials were publicly claiming that such risks were insignificant.

John A. Knauss, the head of NOAA, said in June that the gag order was issued by the White House "from as high a level as you can imagine." John H. Robinson, who supervised NOAA's activities in the Gulf region, attributed the order to Stephen I. Danzansky, director of the White House office of cabinet affairs. Danzansky, who took a job as chief of staff at the Department of Education last April, denied giving the order but suggested it might have come from an official on the National Security Council. Danzansky declined to reveal the official's name. In October the House Subcommittee on Oversight and Investigations began looking into the censorship issue. —*John Horgan*

Report Card

Advice about science is being heard in the administration

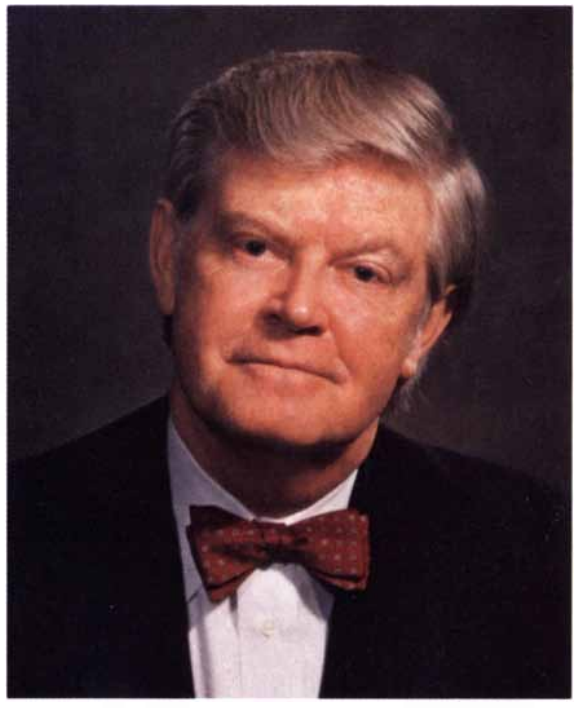
When D. Allan Bromley came to Washington three years ago as President George Bush's science adviser, his vow to provide scientific and technological insight that would inform the administration's thinking drew polite nods and knowing smiles. After all, the Office of Science and Technology Policy (OSTP) had dwindled to insignificance during the Reagan administration. White House chief of staff John H. Sununu had the president's ear for his outspoken and often contrary views on such issues as global warming. And other free-market champions in the administration—principally Michael J. Boskin, chairman of the Council of Economic Advisers and Richard G. Darman, director of the Office of Management and Budget (OMB)—strongly opposed measures that they believed would usurp the role of industry by favoring specific technologies.

"Bromley's problem is that he's working for a Republican president," jibes Lawrence J. Korb, a senior fellow at the Brookings Institution. Whether or not he has the president's attention to the extent that he hoped, Bromley has been winning passing grades for making significant headway in improving federal research planning. And the administration and Congress are cautiously inching closer together on a range of measures to improve commercial returns from the $75-billion federal research and development budget. Meanwhile the cost-conscious administration is putting pressure on other technologically developed nations to pull more weight in fundamental research.

The most visible success for Bromley occurred in 1990, when he cleared enough political hurdles to produce an official document on technology policy that acknowledges federal responsibility to support "precompetitive research on generic, enabling technologies." He has also revived a group of committees that analyze research expenditures across the executive branch and organized a research program on global environmental change. He has successfully won support for new programs in elementary teacher training, public literacy and education of technicians. "We have forgotten the middle ground," Bromley declares.

Under Bromley's leadership, the OSTP also nurtured a presidential initiative on high-performance computing. Waiting approval from the OMB are two new interagency technology initiatives: one on materials science and technology and a second on biotechnology. A proposal on advanced manufacturing technology is still in the planning stages.

Bromley is confident those programs will move forward. Much of the existing effort to encourage development of commercial technology is concentrated in the tiny advanced technology program run by the National Institute of Standards and Technology (NIST). "I anticipate that it will be significantly expanded," Bromley predicts.



PRESIDENTIAL ADVISER D. Allan Bromley is changing science and technology policy "from the bottom up."

He does not, however, foresee a dramatic change in the role of the Defense Advanced Research Projects Agency (DARPA), which has earned widespread admiration for its success in advancing military technologies. A proposal to convert DARPA to civilian operation was one of the principal recommendations of a 1991 report by the Carnegie Commission on Science, Technology and Government. Yet Bromley does not see any need for special efforts to redirect defense research in the direction of civilian applications, as some lawmakers have suggested. "The mechanisms are evolving naturally," he insists.

Nevertheless, the administration and Congress seem to be moving toward a mutual accommodation on several science and technology issues that have been sticking points. Bromley actively supported the idea of a Critical Technologies Institute to oversee research and development in crucial technologies after it was initially funded by Congress in 1990. Several agencies, including the OSTP, have since produced lists of technologies that are considered essential to the nation's future, either economically or militarily, and there is little disagreement on what those technologies are.

Bromley was ordered to kill the project when word reached Darman that it would breach the administration's prohibition against industrial policy that singles out specific technologies for development. Yet when Senator Jeff Bingaman of New Mexico, who heads a defense industry and technology subcommittee and introduced the legislation to set up the institute, met with Darman to discuss the objection, according to a Bingaman aide, "they realized they had more common ground than they thought."

As a result, the White House agreed to support the plan in exchange for more flexibility in staffing the institute. The National Science Foundation (NSF) will set up the institute, but it will be largely freestanding, patterned after the Institute for Defense Analysis and providing advice directly to the president.

Several other technology development measures Bingaman introduced into the 1992 defense authorization act were adopted by a House-Senate conference in November. Among the proposals is one that would direct DARPA, in partnership with industry consortia, to continue a new program to develop critical technologies that have civilian and military applications. The administration had proposed to terminate the program, but Congress funded it at $60 million. Congress also added $183 million to the administration's request for $97 million to support a Defense Department manufacturing technology program. "The Defense Department has an interest in the health of subtier high-technology firms," Bingaman says.

Although the authorization bill that is the vehicle for the initiatives could be vetoed by the president, Bingaman's staff believes the administration is ready to go along with most of the pro-

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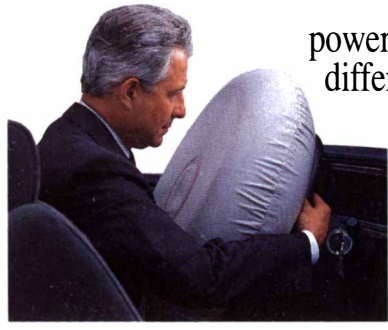

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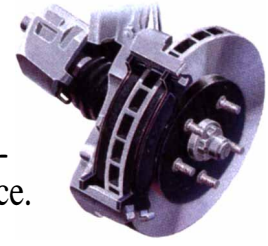

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posals. "They've got past all this picking winners and losers nonsense," one aide says. "They've realized how much we're spending on R&D, and they want to see a return."

While the competitiveness of industry seems to be getting its due, Bromley is engaging in some quiet international diplomacy to assure that basic science does not suffer as a result. With the sponsorship of the Carnegie Commission, Bromley has hosted two "very private" weekend meetings in Mount Kisco, N.Y., with his opposite numbers from several European nations, Canada, Japan and the Soviet Union. Although Bromley will not reveal the substance of the discussions, sources say he tried to drum up international collaboration in research.

Heading Bromley's list is support for the Superconducting Supercollider (SSC), the multibillion-dollar particle accelerator the administration wants to build in Texas. The administration is committed to finding support for one third of the cost of the SSC from nonfederal sources. Even after $1 billion from Texas has been counted, current estimates indicate that the SSC is still $1.8 billion short.

Bromley is putting particular pressure on Japan, which, despite its dominance in consumer technologies, has a relatively small stake in university-based fundamental research. On a recent trip to Japan, Bromley broke new diplomatic ground by proposing that the Japanese government set up a fund to support university-based research as well as take an equity holding in the SSC.

The Science Council of Japan has voted to approve the scheme, Bromley says, although whether the Japanese cabinet will welcome the advice is not yet clear. Bromley has also proposed a collaborative research program with Japan on opto-electronics, and the administration is pondering Japanese invitations to participate in joint technology development schemes in information processing and "intelligent" manufacturing.

Improved collaboration with Europe is also being examined in a number of areas, including biotechnology. "Our exchanges with Europeans have been dwindling," Bromley acknowledges. The NSF will in the future consider grant proposals from partnerships of U.S. and foreign scientists in return for similar arrangements benefiting U.S. researchers working overseas. "I have been trying to develop things from the bottom up, getting individual scientists together," Bromley says. Even if he succeeds only at that, it will be an important contribution. —*Tim Beardsley*

Under Construction

Temporary scaffolding guides nerves in the developing brain

Like most ambitious architectural projects, the developing brain seems to need scaffolding during construction. And, like the angular, skeletal framework that encases buildings, this scaffolding appears to be dismantled when construction is complete. At least that is the substance of a growing body of evidence, some of which was presented at the November 1991 Society for Neuroscience meeting.

"A theme in development is 'Here today, gone tomorrow,'" says Carla J. Shatz, professor of neurobiology at Stanford University, whose work first elucidated the function of one type of transient scaffolding in the developing brain. In the future, Shatz says, some birth defects such as cerebral palsy may be associated with these early structures. "You can't base your thinking just on what's in the adult brain," she adds. "The early brain is very different."

The existence of scaffolding could help explain how the connections from certain neurons reach their final destination—before it exists. For example, during development, the long nerve fibers that carry messages from the retina must reach into an area of the brain called the visual thalamus. From there, axons from the visual thalamus grow on to make connections with other neurons in layer four of the visual cortex, the outer, convoluted part of the brain. But, like overeager homebuyers, these axons arrive just below the cortical layer before the house—or even the street—is built.

Several years ago Shatz and her colleagues found that a group of short-lived cells serve as intermediate targets and tour guides to the incoming axons. These subplate neurons, as they are called, appear just below the visual cortex and seem to direct the thalamic axons to their final destination. "These neurons act as a temporary linkage," she says. (No one seems to know how subplate neurons get their directions.)

Although the existence of subplate neurons has long been recognized, some researchers assumed they were an evolutionary vestige—rather like the tailbones at the end of the human spinal column—or a waiting station. In a series of experiments in cats, however, Shatz and her colleagues demonstrated the pivotal role of these neurons. When Shatz removed the subplate neurons early in development, thalamic axons roamed around below the corti-

cal plate, the home of the forthcoming layer-four neurons. They never made it to the cortex.

In a recent experiment, Shatz removed the subplate neurons later in development. She found the cats did not develop what are called ocular-dominance columns, the fine-tuned structure of the visual cortex organized according to whether cells respond to stimuli from the left or right eye. Whereas some ocular dominance depends on incoming visual stimuli, the brain apparently had no means by which to develop the organization without the subplate neurons. In other words, "if we get rid of the subplate neurons early, the axons don't find the right city," Shatz observes. "If we get rid of them later, the axons don't find the right address."

Although Shatz, like many scientists studying development in the brain, focuses on the visual system, she says her laboratory has evidence that subplate neurons play the same organizational role in other areas of the cortex. Subplate neurons seem to forge the first connections between the cortex and subcortical areas early in development, when the distances to travel are small.

In normal development, the subplate neurons disappear once the subcortical axons reach the right address. The region in which they reside becomes white matter, which functions as a pathway for incoming and outgoing axons in later development. Shortly before they die, the subplate neurons lose their receptors for nerve growth factor.

The idea of transient structures in the developing brain is an old one, but "it is currently going through a useful renaissance," comments Dale Purves, professor of neurobiology at Duke University. In 1972 Pasko Rakic, professor of neuroanatomy at Yale University, reported that radial glial cells—nerve cells that surround neurons and that, until recently, were considered the wallflowers of the nervous system—support neurons as they migrate to their place of residence in the developing brain. Just like subplate neurons, radial glial cells are not present in the adult brain. Simpler nervous systems in fish and insects also have early-forming neurons that establish pathways and then die, just like subplate neurons.

But although "there are some other examples of vertebrate neurons that may appear transiently, none of those are implicated so profoundly in development as the subplate neurons," comments Corey S. Goodman, professor of neurobiology at the University of California at Berkeley. "This is a very novel discovery." —*Marguerite Holloway*

Bonus Game

A microchip that plays pinball with electrons

Most people, when confronted by a problem, roll up their sleeves and get to work. But physicists are often different. They might decide to play games—such as pinball. To gain an understanding of how electrons move through the lattice of a semiconductor under certain conditions, physicists Dieter K. Weiss of the Max Planck Institute for Solid State Physics, Michael L. Roukes of Bell Communications Research and their colleagues have created a microchip in which carefully positioned defects serve as bumpers to bounce electrons about like the balls in a pinball machine.

At issue is whether classical mechanics or quantum theory suffices to explain the behavior of rapidly moving, or high-mobility, electrons sailing through a magnetic field at low temperatures. Electrons in a magnetic field normally drift in a direction perpendicular to the flow of current. This drift, known as the Hall effect, has all the features associated with current, including voltage and resistance. If the magnetic field is reduced, the Hall resistance drops smoothly. When electrons are confined to narrow, high-mobility channels, however, researchers encounter the unexpected: the Hall resistance levels off, forming a plateaulike feature, and then drops to near zero.

At first it was thought that the phenomenon, called the quenching of the Hall effect, came from the quantum mechanical ability of electrons to behave like waves. But Christopher J. B. Ford and his colleagues at the IBM Thomas J. Watson Research Center and C. W. J. Beenakker and H. van Houten of Philips Research Laboratories in Eindhoven, the Netherlands, were not convinced. They calculated that such phenomena could be explained by classical considerations, that is, by treating electrons as billiard balls careening around in the semiconductor.

Weiss and his colleagues have confirmed the classical reasoning with their microchip. They have shown that "an electron can behave like a pinball with charge," observes Sean Washburn of the University of North Carolina at Chapel Hill. To prove the point, the researchers lithographically peppered a semiconductor with an array of indentations, equally spaced about 300 nanometers (billionths of a meter) apart. These "anti-dots," as Weiss and co-workers call them, scatter the electrons. Although

semiconductors have naturally occurring and randomly positioned defects into which the electrons collide, there are "many more little anti-dots in the system than there are relative impurities," Weiss says. So the electrons bang most often into the anti-dots.

Depending on the strength of the magnetic field, the electrons could get "hung up" on any desired number of indentations—that is, by forming perfectly circular, closed orbits around the anti-dots. Or they may simply bounce around the anti-dots, skipping their way across the semiconductor. Such classical behavior shows up as sharp peaks of increased resistance, because the hung-up electrons lower the density of charge flowing through the channel. The experimenters' measurements matched predictions made by a simple billiard-ball model of an electron, indicating that the motion obeys classical rather than quantum rules.

Investigators now think genuine quantum effects would occur if the anti-dots are about 50 nanometers apart or if the temperature is reduced by a factor of 100. The wave nature of the electrons should then dominate, leading to such possible effects as the formation of standing waves between anti-dots. "There should emerge novel features that have not been observed so far," Weiss says.

Telltale quantum signs might include very small scale oscillations and irregularities in the resistance measurements. But because the motion existing at that level is sure to be complicated and chaotic, "it would be very difficult to solve complete quantum mechanical models," Washburn observes. "In technical terms, all hell will break loose."

Although this game is designed for the fundamental physics arcade, some practical applications could be possible. Washburn thinks very sensitive detectors might be made from an anti-dot array. In principle, such a circuit could be more sensitive than conventional ones, he says. According to Weiss, a denser array of anti-dots may suppress scattering caused by phonons, or the vibrations of the crystal lattice. Less scattering means more mobile electrons. "You can fabricate a material with much higher mobility" and thus make a more efficient circuit even at room temperature, Weiss notes. *—Philip Yam*

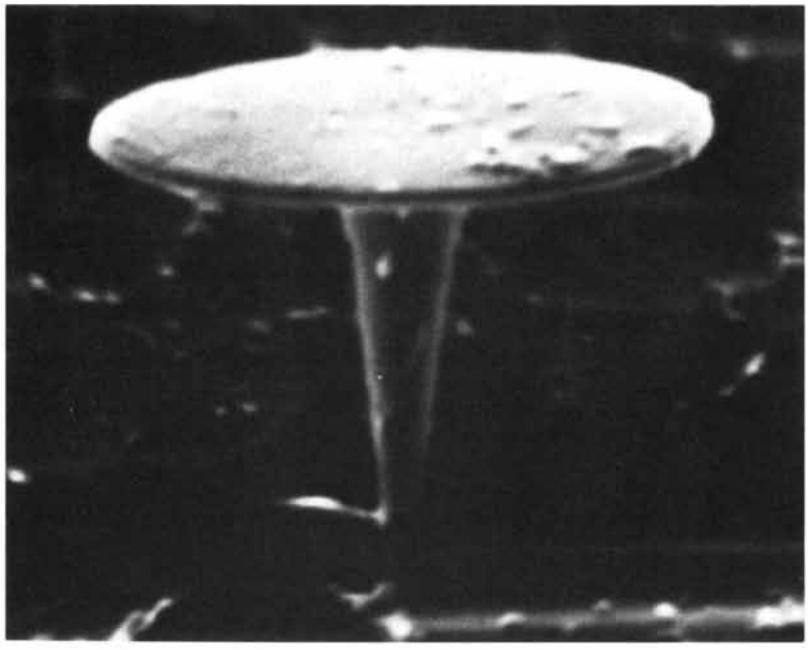
Tacky Lasers Are the Tiniest Yet

Forget about the number of angels dancing on the heads of pins. Researchers at AT&T Bell Laboratories in Murray Hill, N.J., are counting lasers. In November they announced that they had made and operated the world's tiniest lasers—so small that at least 10,000 of the curious thumbtack-shaped devices would fit on the head of a pin. The investigators hope such devices will eventually become the heart of ultrafast telecommunications switches and optical computers, which would rely on light rather than electrons to process data.

The new devices build on results that were reported almost two years ago. At that time, working in collaboration with investigators at Bell Communications Research (Bellcore), researchers at Bell Labs crafted arrays of tiny, cylindrical lasers that could emit light from their tops [see "Microlasers," by Jack L. Jewell, James P. Harbison and Axel Scherer; SCIENTIFIC AMERICAN, November 1991]. The more recent lasers, which are made of layers of indium gallium arsenide sandwiched between layers of indium gallium arsenide phosphide, can emit light from either their disklike top surfaces or from the disks' edges.

The investigators built the lasers by using chemical vapor-deposition techniques to create semiconductor layers only 400 atoms thick. They then etched away material using microlithography to produce the tack-shaped structures. So far the lasers come in three sizes, with diameters measuring two, five and 10 microns across.

Because the lasers are built from less material than earlier devices, they should have significantly lower thresholds—that is, they require less power before beginning to lase. The novel shape of the lasers also changes the way they emit light. In the cylindrical devices, for instance, light bounces back and forth between pairs of mirrors in the laser cavity, growing in intensity until it escapes (and so lases). In the tacklike devices, the intensity of light builds as photons travel around the edge of the disk.



The team of five Bell Labs researchers who built the devices still has much work ahead of it before the components can be incorporated into other systems. So far the devices must be excited optically (rather than electrically) and operate continuously only at temperatures below zero degrees Celsius.

Nevertheless, Samuel L. McCall, the Bell Labs physicist who designed the lasers, hopes to keep lowering the lasing threshold by trimming the size or the volume of the devices further. Because the active material of the laser is needed only around the edges of the disks, he proposes to carve material out of the center of each laser, "so it will look just like a washer," he says. In that case, Bell Labs researchers could call them "lasing Lifesavers." *—Elizabeth Corcoran*

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Turing Test

A computerized therapist for human passes (almost)

If Alan M. Turing could have watched the crush of media in the auditorium of the Computer Museum in Boston last November 8, the British computer pioneer just might have muttered, "Bloody strange." It was the first annual Loebner Prize Competition, in which programs vied with one another to pass a restricted form of the Turing test, a method the master proposed in 1950 for determining whether machines can think.

Elsewhere in the museum 10 human judges played musical chairs with eight terminals. Each terminal was connected with one of six competing computer programs or one of two human surrogates. In each case, typewritten conversation was the only channel of communication by which a judge could decide whether the entity at the other end of the line was a person or a program. The conversations, which appeared on large screens ringing the auditorium, elicited sporadic groans and guffaws from the audience.

The scene was not exactly the quiet, intellectual one-on-one that Turing had formulated. His proposal was the essence of British fair play: A human judge would interact with either a computer or a human and then guess which was which. Communication would take place only by teletype; the absence of a face, irritating personal habits and other human traits would provide an intellectually level playing field. Could the intelligent program fool the judge, through a period of expert questioning, into thinking that it was a person?

Robert Epstein of the Cambridge Center for Behavioral Studies, administrator of the competition, decided to restrict the topics to give today's rather unintelligent programs a fighting chance. The judges were asked to rank all eight conversational partners on a score sheet from most human to most computer-like. The judges were then supposed to draw a line between putative persons and programs.

Each of the judges in Boston discussed a different topic, from women's clothing to Shakespeare to martini making. Behind the scenes, museum officials worried that the contest might be a bust. What if the judges, for all their lack of expertise, could easily tell the programs from the human surrogates? No news would be bad news.

They needn't have worried. A few of the screens left some of the audience clearly baffled over the nature of the respondent. In the topic area of Shakespeare's plays, for example, the answers were crisp and to the point, sometimes demonstrating inhumanly detailed knowledge of the plays but at other times showing a human understanding of the intricacies of plot and character. The topic called "whimsical conversation" created even more excitement at the screen of terminal 5, as judge 9 wrangled with a somewhat evasive character on the other end of the line.

Judge: How do you define whimsical?
Terminal: A whim is a sudden, capricious and often peculiar change in behavior . . . a bit of sunlight in this grim, gray world!
Judge: Pretty pessimistic view of the world. Have you ever gotten yourself in trouble because of your whims?
Terminal: My country is the earth, and I am a citizen of the world, wouldn't you agree? You aren't really talking about me, are you?

Later, judge 9 finally became annoyed with the evasive replies.

Judge: Can't you once just answer me a direct question with a direct reply?
Terminal: A sudden, bold and unexpected question will frequently catch me by surprise! You like to think I once just answer you, don't you? Sometimes I wish I was a systems analyst.

It was the grammatical blunder ("I once just answer you") that gave the program away to most experts and near-experts watching the terminal 5 screen. It was reminiscent of the way a very early conversation program called Eliza incorrectly reflected human sentences in framing replies. But Eliza was a program that attempted therapy on humans. Program or person, the entity at the other end of terminal 5 seemed a trifle psychotic.

A few programs ended up on the human side of some score sheets. Although the whimsical conversationalist did not fool judge 9, it did fool five of the 10 judges and walked away, so to speak, with the $1,500 prize. (The money was supplied by the contest's sponsor, Hugh G. Loebner, a New York businessman.) The program, called PC Therapist, is intended to help users "let off steam," according to its creator Joseph Weintraub, who heads a firm called Thinking Software in Woodside, N.Y.

Runner-up was a program called Turing, entered by Kenneth M. Colby, a pioneer in artificial intelligence and professor emeritus of psychiatry and biobehavioral sciences at the University of

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California at Los Angeles School of Medicine. Colby's program, specializing in problems of romantic relationships, fooled two of the judges and narrowly edged out Julia, an expert in the area of small talk. The two human surrogates handled their topics with skill. But then, Shakespeare and women's clothing may lie outside computational competence for some years to come.

During the proceedings, there were a few whispers that the Turing test by itself might do nothing for artificial intelligence. Indeed, if PC Therapist represents the avant-garde of future winners, the contest might come to be regarded as more of a computer circus than an intellectual milestone. There were also some doubts about the competition's design. The randomness of whimsy, for example, springs as readily from a silicon chip as from a human mind. Could this fact have given PC Therapist an unfair advantage over its rivals? Turing might have thought so.

Such thoughts made no appearance during the euphoria of victory in the Computer Museum auditorium. As Weintraub recited the address of his company over the public-address system, one reporter nudged another. "He'll clean up on this!" Future contestants could fare still better in a planned, unrestricted Turing test, which will proffer a purse of $100,000. By then, presumably, Professor Turing will smile down on the contest and bless the silicon.

—A. K. Dewdney (the official commentator at the first annual Loebner Prize Competition)

Inside Job

Antibodies can destroy some viruses inside neurons

Immunologists have known for decades that the circulating proteins called antibodies fight infections by selectively locking onto foreign substances carried by the bloodstream. In this way, antibodies destroy viruses before they can invade cells. But viruses that had gained entrance to cells were generally considered to be safe—at least from antibodies.

Now it seems that antibodies are a more pervasive defense than was previously thought. Last fall a surprising report by a team of neurobiologists at the Johns Hopkins University School of Medicine revealed that antibodies can also eliminate viruses growing inside neurons. This overlooked immunologic mechanism seems to protect the nervous system and is conceivably at work in other tissues.

When the immune system rids the body of infected tissues, its usual methods are efficient but brutal. The white blood cells called killer *T* lymphocytes zero in on infected cells and rip them apart with destructive enzymes. The surrounding tissues then undo the damage by replacing the lost cells.

That immunologic strategy does not work in the nervous system. Mature mammalian neurons typically do not reproduce; consequently, if *T* cells exterminated sick neurons, the brain and spinal cord would soon be full of permanent holes.

To investigate how neurons cope with viruses, Diane E. Griffin and her colleagues infected a strain of mouse that lacks an immune system with a virus that multiplies in nerve cells. The mice that received no further treatment remained infected throughout the experiment. Some of the mice, however, received antibodies from normal animals exposed to the same virus. With that serum in their systems, the mice purged their nervous systems of viruses within 48 hours. In contrast, mice injected with *T* cells instead of antibodies showed no improvement.

Griffin's group concluded that the injected antibodies had somehow directly cleared the viruses from the neurons. The antibodies appeared to interfere with either the transcription or translation of the viral genes—the early stages of replication when the cell manufactures viral proteins.

Beth Levine, one member of the Johns Hopkins team, offers two alternative explanations for how the antibodies cleared the viruses. One possibility is that the antibodies entered the neural cell bodies and interacted with the replicating viral components. Studies have shown that neurons can take up antibodies near their synapses, although no one yet knows whether this absorption serves any purpose. The other possibility is that the antibodies bind with viral particles on the surface of the neuron and thereby trigger changes in the cell that stop viral replication. The researchers are currently trying to determine which of these mechanisms seems to be at work, Levine says.

As the researchers pointed out in their paper in *Science,* experimental treatments with antibodies have reportedly been successful against some neurologic infections. Those treatments were presumed to work by containing the spread of the viruses outside cells. The new observations suggest that the serums may also obliterate viruses growing in the neurons. Even so, antibodies do not provide a perfect antiviral defense for neurons. Chronic neural infections, such as those causing herpes, persist even in individuals with working immune systems.

Although antibodies may be uniquely important in neurons for clearing viruses, Levine adds, they may also inhibit viruses in other types of cells. The Johns Hopkins researchers are looking for evidence of antibody-mediated clearance of viruses in other tissues, but the major focus of their efforts is on applying their discovery to treatments for neurologic infections. *—John Rennie*

Population Pressure

Who could possibly talk about economic development and the environment without considering the effects of human population growth? Apparently, the many nations participating in the United Nations Conference on Environment and Development (UNCED), which is to be held next June in Rio de Janeiro. The developing nations feared that the discussion would draw attention from development. The U.S., sensitive to "pro-life" issues, and its allies in the Group of Seven acquiesced.

But that seemed to be a glaring omission to officials of the Royal Society of London and the National Academy of Sciences in Washington. The world population now stands at about 5.4 billion, and U.N. projections indicate that the number will at least double before stabilizing early in the 22nd century.

To make sure that population gets its due, the two academies are planning a rare joint "statement of concern" about world population growth. The statement, which is expected to be approved by February, might be followed up with an international conference in Stockholm. "We thought that to discuss world environmental problems without giving much attention to population seems rather odd," says Sir Michael Atiyah, president of the Royal Society.

Meanwhile the attempt to downplay population at the UNCED led to protests, and at a preparatory conference in August in Geneva population was formally upgraded. In exchange, developing nations got onto the agenda an assessment of unsustainable consumption patterns. A separate U.N. meeting on population is being planned for later in the decade. *—Tim Beardsley*

A Troubled Homecoming

DAVID BALTIMORE. His presidency at the Rockefeller University was strained by a stubborn controversy over scientific ethics. Photo: Quesada/Burke.

When David Baltimore was appointed president of the Rockefeller University in 1990, it was a homecoming for him. His high-ceilinged office, with its wood paneling and towering bookcases punctuated by windows that soar to 15 feet, was where he was vetted for admission to the university as a Ph.D. student in 1961. Yet sadness and conflict tinged what should have been a triumphant return. A persistent controversy over research ethics held him in its shadow, and after little more than a year in the post, he resigned in early December.

Interviewed in October before his decision to step down, Baltimore acknowledged that he was wrestling with "knotty problems." Sitting in a spacious armchair by a huge stone fireplace, Baltimore looked uncomfortable in his role as controversial leader of a most decorous and collegial university. The room's spare, contemporary interpretation of the gothic speaks volumes about the kind of place that John D. Rockefeller, Sr., envisioned when he established this unique postgraduate institution on New York City's East Side in 1901. The university was dedicated to the advancement of biomedical science, and the 19 faculty members and associates who have been awarded Nobel Prizes—including Baltimore—testify to the success of its elitist approach. Like other institutions, Rockefeller has experienced tension, but like an ancient family the university has kept such trouble behind the high fences that surround its tree-shaded enclave.

Baltimore's discomfort was matched by the unease of Rockefeller faculty toward him. Two thirds of them were opposed to his appointment in 1990. Last October, Torsten N. Wiesel, a Nobel Prize–winning neurophysiologist and chairman of the faculty Senate, reported to the Board of Trustees that opposition to Baltimore had grown, to about 85 percent. When Baltimore finally decided to stand aside, he said it was because it had been impossible to achieve "unity of purpose" within the faculty. As a result, he said, he felt unable to accomplish the goals he had agreed on with the board. Wiesel was promptly appointed as an interim president.

When the trustees first approached Baltimore in 1989, they had hoped to recruit as a new president an academic superstar who could revitalize the institution by attracting talented young scientists. And Baltimore, at 51, certainly seemed to be the ideal candidate. He had won a Nobel Prize at the age of 37 for the discovery of the enzyme reverse transcriptase and had made several other major findings in virology and molecular immunology. He became director of the Whitehead Institute for Biomedical Research in Cambridge, Mass., and led it to international recognition in the 1980s.

What the trustees—and particularly the faculty—had not bargained for was that Baltimore would continue to be embroiled in a dispute over a scientific paper that he published in 1986 in the journal *Cell* with David Weaver of Harvard Medical School, Thereza Imanishi-Kari, now at Tufts University, and others. According to a draft report of an investigation conducted by the National Institutes of Health leaked to the press last March, the paper was based in part on falsified data from Imanishi-Kari's laboratory at M.I.T.

Before the evidence in the report was revealed, Baltimore fiercely defended his colleague. He also attacked hearings into the affair held by Congressman John D. Dingell of Michigan as "a harbinger of threats to scientific communication and scientific freedom."

Events forced a retreat. When the evidence against Imanishi-Kari became public, Baltimore formally withdrew his name from the paper, saying it was up to her to defend it. In a letter published in *Nature,* he contritely acknowledged the responsibility of government to oversee the research it supports and apologized to Margot O'Toole, the whistle-blower in the case.

Yet tensions were heightened during the year by further fiery correspondence in *Nature.* In what many saw as an "unapology," Baltimore rebutted an account of the saga by O'Toole, which stated he had known since 1986 that Imanishi-Kari never did some experiments on which the paper was based. Then Paul Doty, professor emeritus of biochemistry at Harvard University, lambasted Baltimore for "egregious departure from the usual standards of carrying out and reporting research." In a seething reply, Baltimore wrote that "the data have proved more durable than the data in most papers." Anguished Rockefeller re-

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"The eyes have one language everywhere."

George Herbert

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searchers had grown weary of the almost weekly public blood-letting. "Many of those who were not opposed to Baltimore have been swayed by his extreme mishandling of the situation," says Günter Blobel, a faculty member.

The controversy has divided biologists, but it has not diminished their respect for Baltimore as a researcher and mentor. "He has an almost uncanny ability to pick the right problem," says Owen N. Witte of the University of California at Los Angeles, who worked with him in the late 1970s. Adds Naomi Rosenberg, who now does research at Tufts University: "I feel very strongly that I received excellent training in Baltimore's laboratory."

Baltimore's fascination with experimental biology showed itself as early as 1955, when he was still in high school. His mother, an experimental psychologist, had inspired in him an interest in physiology, and between his junior and senior years he took a summer biology course at the Jackson Laboratory in Bar Harbor, Me. After that, he says, there "was no looking back." At Swarthmore College, his teachers encouraged his interest in molecular biology. Then an undergraduate research scheme run by the National Science Foundation accepted him into a program at the Cold Spring Harbor Laboratory on Long Island.

In the late 1950s Cold Spring Harbor was a mecca for research on bacteriophages, viruses that infect bacteria. When he became a graduate student at M.I.T., Baltimore duly started doing experiments with bacteriophages, but then he had "a funny idea." If bacteriophages were doing so much for the understanding of bacterial molecular biology, maybe animal viruses would do the same for animal cells. He returned to Cold Spring Harbor to take a course on animal viruses, where he met Richard M. Franklin, a Rockefeller virologist who was studying how viruses induce cells to make viral instead of cellular RNA. "There it all clicked," Baltimore says.

Baltimore transferred to Rockefeller and began studying a mouse virus called mengovirus. He quickly showed how mengovirus inhibits a cellular enzyme, RNA polymerase, that the cell uses to make its own RNA.

After completing his doctorate, Baltimore moved to the Salk Institute for Biological Studies in La Jolla, Calif., to do research on poliovirus. A student under his supervision, Michael Jacobson, made the surprising discovery that when poliovirus infects a cell, it first makes a single, large protein molecule that is only later chopped up into smaller units. "That had a lot to do with my thinking about genetic systems thereafter," Baltimore observes.

Baltimore returned to M.I.T. in 1968 with his future wife, Alice S. Huang, and the couple tried to see whether the same principles operated in the vesicular stomatitis virus. They did not. The virus, they found, was a "negative strand" RNA virus—one that carries a genetic message complementary to the one needed to produce more viruses. "That suggested to me that the virus carries into the cell polymerases that copy RNA from a negative template," Baltimore recalls. He confirmed the idea, which led him "to wonder what other viruses might have polymerases."

In search of answers, he tested RNA viruses that cause tumors in animals. He detected evidence that such viruses contain an enzyme that can copy RNA to make DNA, in apparent violation of the "central dogma" of biology. That enzyme was reverse transcriptase. The feat earned Baltimore a Nobel Prize in 1975, shared with Howard M. Temin of the University of Wisconsin, who made the same discovery independently. Reverse transcriptase is now recognized as the defining feature of retroviruses, including HIV, the AIDS virus. After the Nobel, Baltimore branched out into several other areas, while still maintaining an active interest in poliovirus and continuing to elucidate the mechanics of reverse transcription.

Baltimore's gift for directing research was recognized when he was invited by industrialist Edwin C. Whitehead to become founding director of the biomedical research institution bearing Whitehead's name. Not content to limit his scope to administration, he continued to guide research in several fields and says the time was one of the most productive and exciting of his career.

One crucial advance was the identification of a protein called NF-κB that can bind to DNA and initiate its transcription into messenger RNA. Within the past two years, Baltimore and David G. Schatz, who is now at Yale University, isolated two genes, known as *RAG-1* and *RAG-2,* that seem to be responsible for rearranging antibody gene segments.

At Rockefeller, the initial crush of presidential duties curtailed Baltimore's research. He moved decisively by hiring new administrative staff, reforming the university's finances and giving untenured faculty a greater say in university affairs. Moreover, Baltimore's position was bolstered last October when David Rockefeller gave the university $20 million, saying the gift reflected his "absolute confidence" in Baltimore's leadership. The gift was the opening salvo in a campaign to raise $250 million by the end of the decade.

Faculty and trustees had hoped that Baltimore would be able to keep the money flowing in at the rate of about $20 million a year as well as rejuvenate the aging faculty. There is no shortage of space: half of the university's chairs are filled by researchers who are more than 60 years old, and a new laboratory building is nearing completion. As president, Baltimore had hoped to appoint as many as 10 new faculty members over the next two years.

Yet there were whispers that defections could offset Baltimore's recruiting efforts. Earlier this past year two prominent faculty members, Anthony Cerami and Gerald M. Edelman, announced plans to leave. Senior faculty say other academic lights are also now in negotiations with other institutions. But Baltimore continued to profess himself unworried, noting that some turnover is normal. Both Cerami and Edelman had received extremely attractive offers.

Even while discussing his plans for the future of Rockefeller, Baltimore seemed more diffident last October than he was three years ago, when he was a firebrand challenging Dingell's inquiry. When Baltimore referred to the *Cell* paper dispute, his voice became barely audible. The lack of good laboratory records was, he allowed, central to his "problems." In his apology to O'Toole last year, he publicly pledged to safeguard whistle-blowers and researchers accused of misconduct. At Rockefeller, he took steps to institute a "fair and openly recognized mechanism for handling complaints." A proposal to appoint a university ombudsman to investigate allegations of misconduct is now under review.

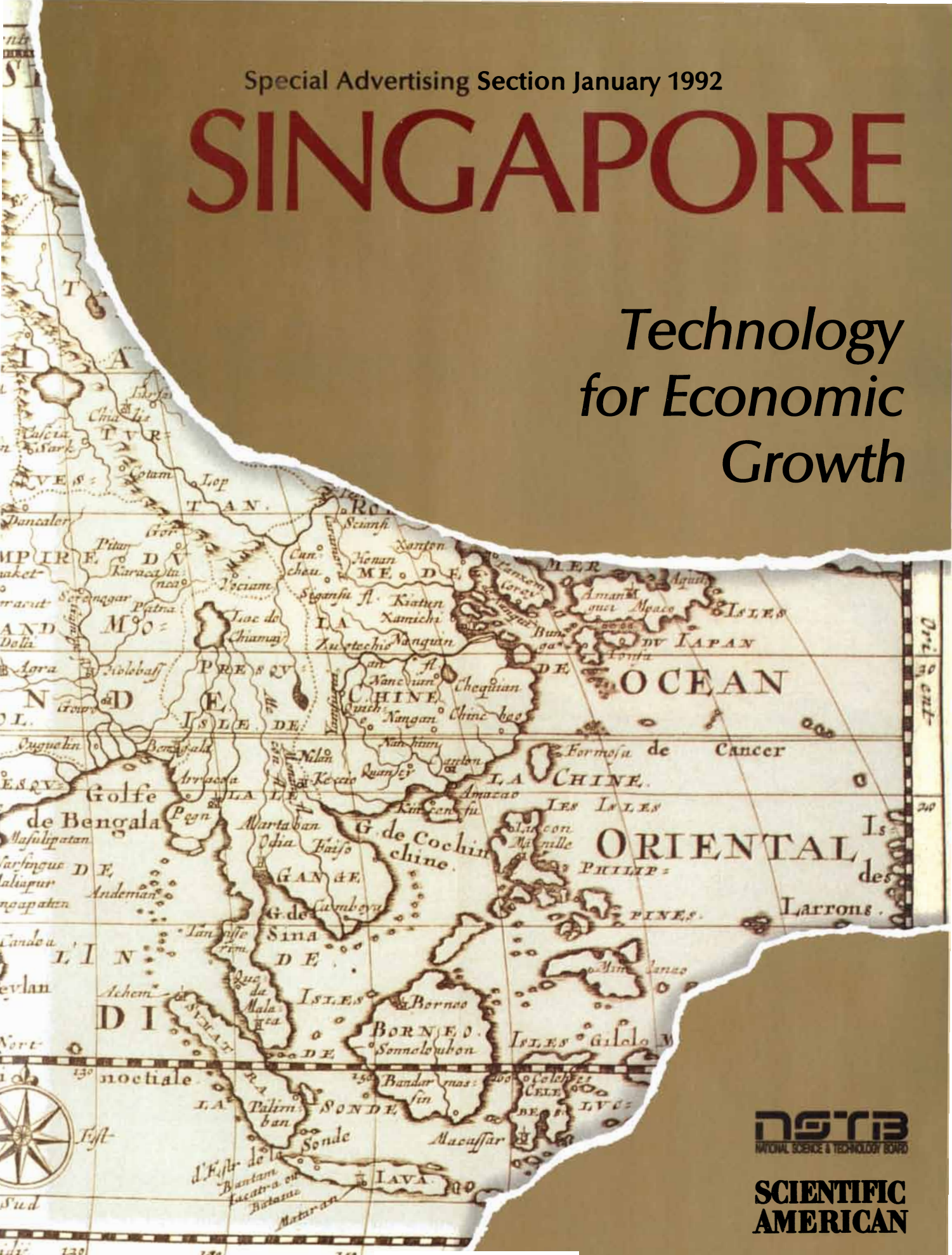
"I am beginning, I believe, to develop closer relations with some of the faculty," Baltimore said a few weeks before resigning, choosing his words with obvious care. "I trust that relations with most will become comfortable in time." His decision in December that that purpose will best be served by stepping aside as president is likely to be welcomed, if sadly, on the campus. "There is great concern on the faculty and in the country that David's troubles with the Dingell committee are not going to blow over," observes one senior faculty member, who wished not to be named.

The end of Baltimore's brief tenure as president, while a setback for him, should unleash once again his talents as a researcher. Baltimore will stay on as a faculty member, and he plans now to resume work on HIV that the pressures of the presidency had forced him to put aside. And for the troubled university, too, a distracting period of torment may now be at an end. —*Tim Beardsley*

Special Advertising Section January 1992

SINGAPORE

Technology for Economic Growth



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Singapore government commits to R&D growth

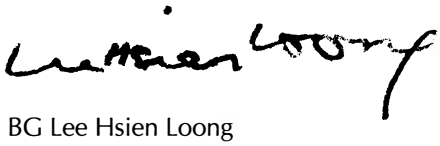
BG Lee Hsien Loong

During our short history as a nation, Singapore has undergone many changes and progressed rapidly. Thirty years ago, when the economy still depended almost entirely on commerce and entrepot trade, we embarked on an industrialization program to generate economic growth and provide our people with an alternative livelihood. For industrialization to succeed, we had to open up to the world – to export and to attract investments. Key to this strategy was to be competitive internationally.

We have transformed ourselves by building up a strong manufacturing base, and later developing as a financial and service center. Our standard of living has improved many fold. We have become a Newly Industrializing Economy. These achievements flowed from our commitment to maintain an open economy and invest in our manpower.

Singapore is now poised to embark on its next phase of development. To stay competitive, we must now move beyond manufacturing and operating machines efficiently, into more sophisticated businesses and knowledge-based activities with greater design and innovative content.

Our key assets will continue to be an open economy and an educated and skilled workforce. But the focus is now on mastering science and technology in niche areas that will contribute to our economic growth, and on building up research, development and design capabilities in these areas. Singapore intends to achieve this by working in partnership with international leaders in industry and technology, to make the most of our infrastructure and human resources. As a city-state where different cultures meet and economic opportunities are open, we welcome foreign talent and businesses which share our vision, as expressed in *Scientific American's* special report: that technology is the key to economic growth, and the strength of a nation depends on the talents and skills of its people.



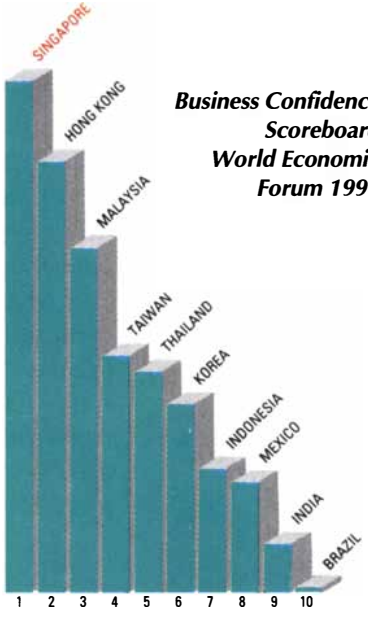
BG Lee Hsien Loong
Deputy Prime Minister
& Minister for Trade and Industry

SINGAPORE
Technology for Economic Growth

THE S$2 BILLION NATIONAL TECHNOLOGY PLAN

Thirty years ago, Singapore's economy depended almost entirely on commerce and entrepot trade. Since then, we have developed a strong capability in manufacturing and good supporting infrastructures such as telecommunications, utilities and port services.

Other countries are also rapidly industrializing and increasing their industrial competitiveness. To maintain our competitiveness, Singapore needs to move to an innovation phase of our development and promote activities with more innovative and design content. This means mastering science and technology. Singapore must increase her capacity to undertake research and development of international standard.



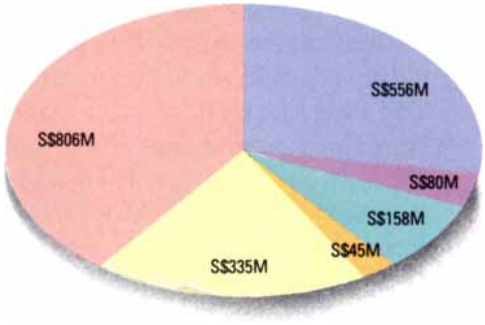
Business Confidence Scoreboard World Economic Forum 1990

The process has already begun. National expenditure on R&D increased from S$38 million or 0.2% of GDP in 1978 to S$572 million or 0.9% of GDP in 1990. Private sector spending on R&D expanded from S$26 million in 1978 to S$309 million in 1990. The private sector therefore accounts for more than half of the current total national expenditure on R&D. In 1978, we had only 1,672 people working in R&D; by 1990, this number had risen to 7,094. The number of research scientists and engineers (RSEs) as a proportion of the labor force is now 29 per 10,000.

However, Singapore is still a long way behind the world leaders or the other NIEs. Other economies like the US, Europe, Japan, Taiwan and Korea all have plans to boost science and technology. In the US, both government and industry have recently recognized the need for national strategic initiatives in R&D. In recent years, Europe has introduced large-scale pan-European collaborative programs designed to give Europe a lead in targeted technology areas. Korea, which now spends 1.8% of its GDP on R&D, has developed a detailed Plan to raise its level of R&D spending to 5% of GDP by the year 2000. Taiwan, which spends 1.3% of its GDP on R&D, plans to increase it to 2% in the 1990s.

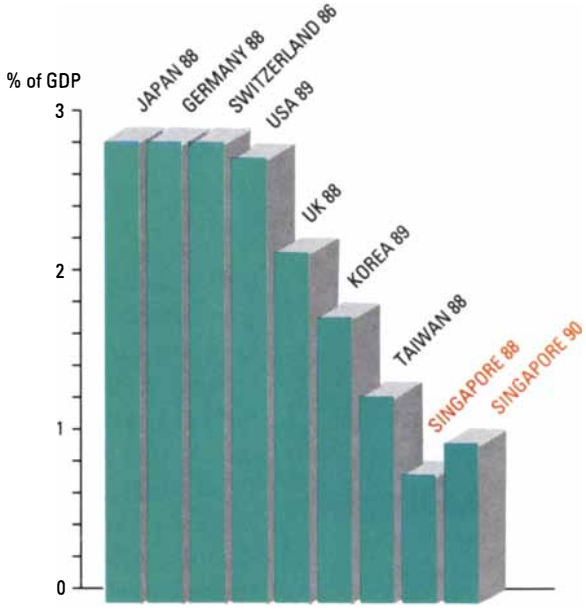
To uplift the state of our science and technology base, the Government formed the National Science and Technology Board (NSTB) in January 1991 with the mission – 'to develop Singapore into a center of excellence in selected fields of science and technology so as to enhance our national competitiveness in the industrial and services sectors.'

Indicative Allocation of Funds



- ***Technology programs***
- ***Key strategic thrust in technology; Ad-hoc projects in other areas***
- ***Research & Development Assistance Scheme***
- ***Manpower development***
- ***Technology infrastructure***
- ***Science Park development***

International Comparison of R&D spending as a percentage of Gross Domestic Product



Source: World Competitiveness Report 1991

NSTB's role is focused on the category of 'industry-driven' R&D, meaning that research that will contribute towards enhancing our competitiveness now or in the future. The private sector must undertake the bulk of these R&D activities because the best measure of the value of such R&D activities must be the willingness of profit-seeking organizations to commit funds and resources towards them. However, Government can and should play a more pro-active coordinating and facilitating role to promote these efforts. Government's role is to gauge what resources companies need in order to undertake more R&D and then to find the means of providing the support. This National Technology Plan focuses on how we can best promote and develop industry-driven R&D in Singapore.

The importance of the categories of research, for example, those conducted in the universities for academic purposes and those in hospitals for medical purposes is recognized. Separate provisions will be made for such research. The Ministries of Education and Health are studying the requirements for such research and plans will be separately submitted.

The National Technology Plan will concentrate on that part of research directed towards economic upgrading. Thus, our science and

NATIONAL SCIENCE &TECHNOLOGY BOARD

"dedicated to developing Singapore into a center of excellence in selected fields of science & technology to enhance national competitiveness in manufacturing and services"

Mr Lam Chuan Leong
Chairman

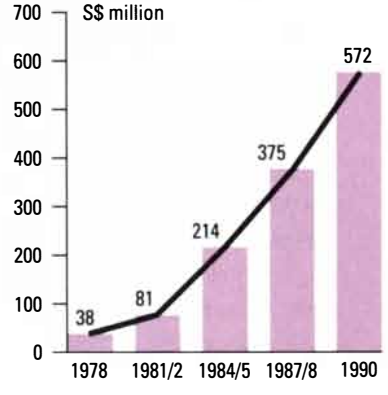
For the next phase of economic growth, Singapore needs to enhance its industrial and technology base through greater focus on Research & Development. The National Science and Technology Board (NSTB) was therefore formed to lay the foundation of a strong R&D capability in technologies that are relevant to our present and future industrial requirements. The twin strategy for this role is to promote research and development activities in Singapore and to develop the human resource capability to support such activities.

Many major multinational corporations have chosen to invest in manufacturing operations and increasingly, in regional headquarters activities here. Political stability and the ability to plan over the long-term are important pull-factors, and so is the priority placed on investing in infrastructure, with the result that today Singapore is ranked among the world leaders in telecommunications, power supply, port facilities, air transport and road networks. Our people strongly value education and self-improvement and the desire to excel.

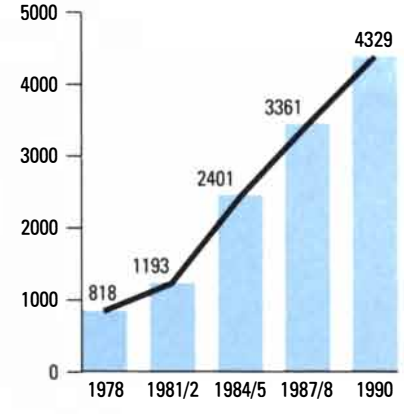
Many companies here have embarked on R&D and design activities. The private sector accounts for 54% of R&D spending in Singapore. The Singapore Government seeks to further promote such efforts through NSTB's programs of grants and fiscal incentives, training support and provision of specialized infrastructure.

Manpower is a crucial requirement for R&D. Singapore has traditionally invested heavily in advanced training and education to develop the skills and knowledge for economic development. Nearly half of the 5,500 first-degree graduates each year from local universities are from science and engineering. There are plans to increase the number of science and engineering undergraduates by some 25% by 1995. On top of that, a significant number of students obtain their degrees from universities abroad. Training for research support staff is provided in polytechnics, vocational institutes and industrial

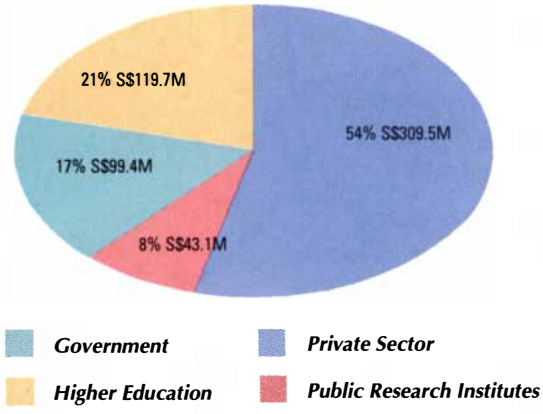
Growth in R&D expenditure



Growth in RSEs



Gross expenditure on R&D for 1990



training centers. The objective is to provide a workforce capable of supporting high technology-based industries.

NSTB, in actively promoting research and development, will assist in postgraduate training of R&D personnel. Scholarships for postgraduate courses, industrial attachments and research assistantships will be provided. The target is to increase the current number of research scientists and engineers from 29 per 10,000 labor force to 40 per 10,000 labor force by 1995.

This growth in talent pool will be achieved not only through the development of local expertise, but through a liberal foreign recruitment program. Singapore offers an English-speaking, cosmopolitan environment with the modern amenities required for a comfortable standard of living in terms of housing, healthcare, transportation and education. Yet it is an Asian society whose openness has led to an interesting mix of cultures and cosmopolitan nature. Furthermore, Singapore offers city-living without the usual urban problems of congestion, pollution and crime. For the international scientific community in particular, we offer opportunities in high-technology businesses and research.

Research institutes focusing on molecular and cell biology, information technology, computer-integrated manufacturing and systems science have been established over the past few years. Newer areas of research include microelectronics, manufacturing technology, materials science and magnetic technology. These centers and institutes for R&D will provide industry with the enabling resources of specialized manpower, knowledge, and even new products and processes developed in collaboration with the private sector.

In fact, such industry-focus is a key feature in NSTB's approach to the formulation and implementation of national science and technology policies. Together with the private sector, NSTB hopes to transform Singapore into a center of excellence for industrial innovation and research.

LAM CHUAN LEONG
Chairman
National Science & Technology Board

The Singapore Science Park...
a vibrant and conducive environment for research

THE NATIONAL TECHNOLOGY PLAN

technology research must be results-driven *i.e.* it must produce results eventually relevant to our economic competitiveness. Our target areas of excellence must be carefully selected in niches that are relevant to our strengths. Government must work in close collaboration with industry, and government's research institutes must support and complement industries' efforts in working towards a common end.

TARGETS AND KEY RECOMMENDATIONS

The targets set out in this Report are for total national expenditure on R&D to reach 2% of GDP by 1995, a minimum 50% private sector share of this total, and a ratio of the number of scientists and engineers engaged in R&D activities of 40 per 10,000 labor force by 1995.

The National Technology Plan sets out the main thrusts that Government will take in the next five years to achieve these targets, and how it intends to provide an environment that will support active and widespread R&D by companies in Singapore. The key recommendations are:


Five-year R&
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plan for
Singapore's spending
An international com
Japan
Germany

1. A S$2 billion Research & Development Fund to support industry-driven R&D over the next 5 years;
2. Provision of grants and fiscal incentives to encourage more R&D by the private sector;
3. Assistance in developing and recruiting R&D manpower;
4. Support and funding for research centers and institutes that can train the manpower or provide the technological support to enable companies to undertake their R&D; and
5. Assistance for commercialization and infrastructural support.


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blueprint aims to into the big league

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target is to attract some foreign R&Es here annual the next five years. B&T Lee noted that S pore's current ratio considerably fewer th R&Es and well beh advanced industrialis tries." NSTB's target crease this figure to per 10,000 workers to One

RESEARCH & DEVELOPMENT FUND

The S$2 billion Research and Development Fund is to provide the wherewithal to support industry-driven research. It is meant to be spent on developing key resources in technologies, manpower, and skills that industry needs but which the private sector cannot supply by itself.

The objective is to develop broad competence in selected new technologies where the future importance of these technologies is clear and where Singapore has, or could develop, a comparative advantage. Industries will be encouraged to exploit and apply new advances in these technologies as widely as possible. The funding amounts refer to public sector R&D projects, public/private collaborative projects and institutional infrastructure for research.

FISCAL INCENTIVES

A key strategic thrust of the National Technology Plan is to tap the potential of technology-based companies in Singapore. More than half of the R&D in Singapore is done by the private sector. This is an encouraging sign; the Government should not crowd out the private sector in R&D. The private sector includes both MNCs (multinational corporations) and indigenous companies. Singapore has over 1,000 MNCs, including many leaders in their respective fields. Some of them are already doing research in Singapore. We should encourage them to do more.

Companies tend to look upon R&D as an added cost and a more risky expenditure than normal business expenditure. If the Government can share part of this extra cost and risk, it will encourage more private sector R&D, and foster national competitiveness and economic vigor.

Government already offers grants to fund private sector R&D under the Research and Development Assistance Scheme (RDAS). The NSTB has proposed several ways to use tax incentives to promote R&D, *e.g.* extension of pioneer status up to an additional two years for

THE NATIONAL TECHNOLOGY PLAN

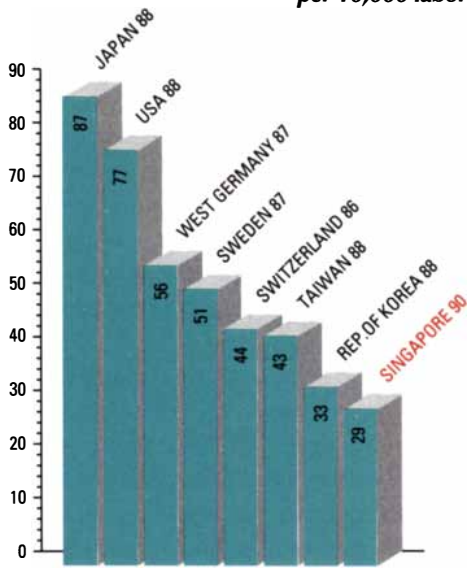
companies that are prepared to undertake specified R&D activities in Singapore, similar extension of post-pioneer concessions, double-deduction for R&D expenses, accelerated depreciation for capital expenditure incurred in acquiring approved know-how or patent rights, and tax exemptions for incremental income earned and for R&D reserves. They are not new incentives, but have been proven and refined in the last thirty years in our efforts to promote investments to Singapore. The extension of such incentives for R&D will appeal to more companies to undertake R&D here.

MANPOWER DEVELOPMENT

Singapore has about 4,000 researchers, or about 29 per 10,000 labor force. This is considerably fewer than the other NIEs and well behind the advanced industrialized countries. NSTB's target is to raise our level of manpower to 40 per 10,000 labor force by 1995.

To meet this target, we need to attract more Singaporeans into R&D and to supplement this with research talent from overseas. Internal manpower growth alone will not provide sufficient human resource for our R&D. Well qualified and experienced foreign researchers

International Comparison of Research Scientists and Engineers per 10,000 labor force



Source OECD & National Sources

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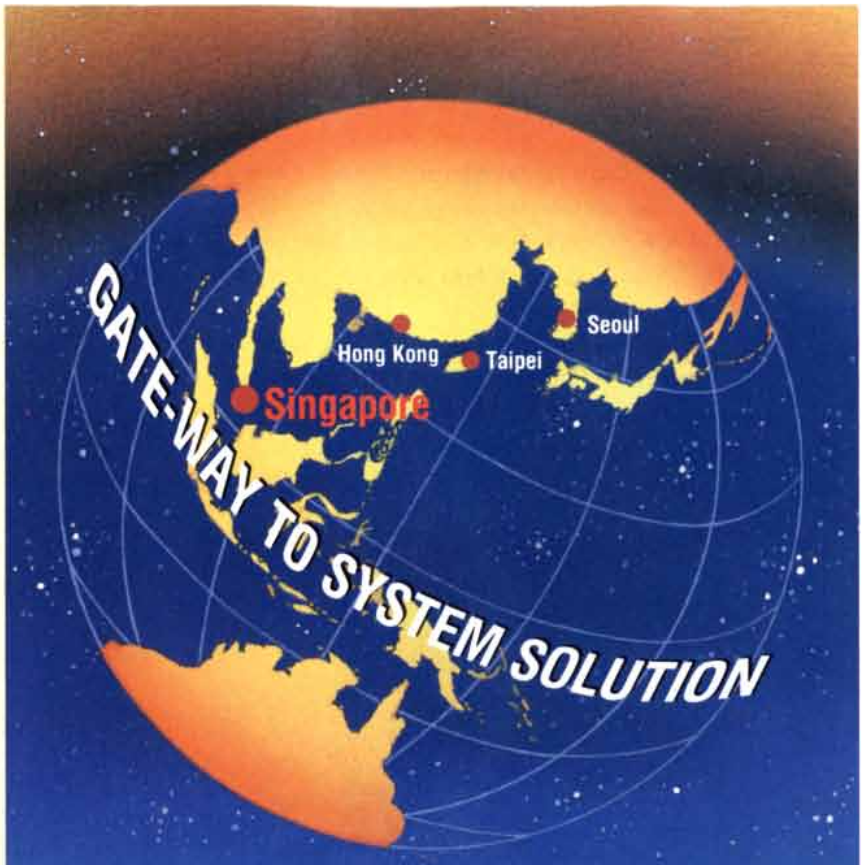
TEA, a wholly-owned subsidiary of Toshiba Corporation, was established in March 1990 to coordinate and supervise the production and marketing activities of Toshiba electronic components business in Asia and Oceania. In recognition of these activities that enhance Singapore's development in microelectronics and related fields, TEA was awarded Operational Headquarters status by the Singapore Government.

TEA plans to set up its LSI Design Center in 1992 to provide comprehensive engineering support to its customers. This will be Toshiba's fourth Design Center in Asia after Hong Kong, Taiwan and Korea.

Toshiba is also actively involved in microelectronics applied research. Mr Tsuyoshi Kawanishi, Senior Executive Vice President, Toshiba Corporation was recently appointed to the Scientific Advisory Board of IME. He is also a member of the International Advisory Panel of NSTB. Toshiba's support for IME and NSTB is consistent with the company's philosophy of working closely with the communities it serves.



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bring with them knowledge and skills that we would take years to develop if we went it alone. Local researchers would also benefit from the exposure to, and interaction with, top talent from all over the world.

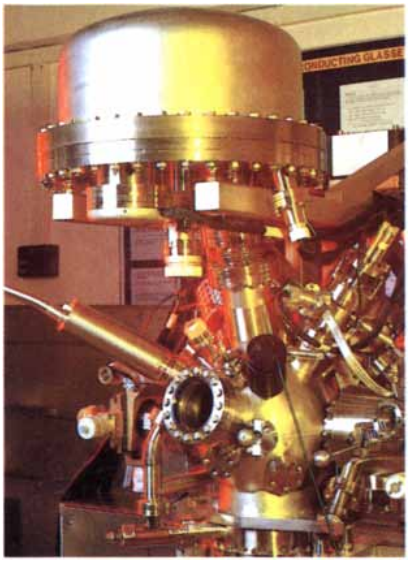
A career in R&D incurs a higher training cost because of the need to acquire post-graduate qualifications. This cost is made up of the expenditure on fees to acquire advanced degrees as well as the opportunity cost of being out of the job market for a few years. The Government can help address the imbalance by helping to defray part of the training cost. Scholarships and financial aid can be provided to those choosing to enter a research career.

View of CINTECH, the Center for Information Technology

Besides financial assistance, it is important that the right type of training be given, and the right type of graduate produced, to meet the needs of the private sector. NSTB must therefore work closely with the private sector on one hand and research centers and institutes on the other to do this. Recognition and other intangible rewards should be given to promote a more positive research culture. Career guidance and job placement services will be provided.

RESEARCH CENTERS AND INSTITUTES

Research institutes are key players in terms of providing the enabling resources of manpower, skills, technology, knowledge, and products and processes for the private sector. The missions and



X-ray Photoelectron Spectrometer

Preparation for growth of III-V compound semiconductor epitaxial layers

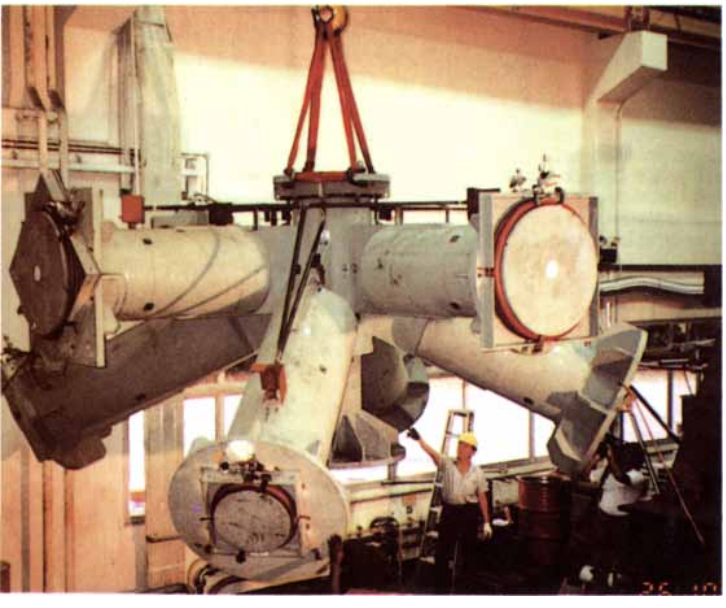
objectives of the public sector research institutes funded by NSTB must be oriented towards supporting the R&D activities undertaken by companies in Singapore.

For the first phase, the objective for these institutes is to provide trained researchers required by industry. Institutes can supplement local talent by attracting researchers from all over the world to come to Singapore to do research. This will provide us with a base of technology and a means of training students and future researchers. Provided we direct the type of re-

Plant tissue culture

search work of the institutes suitably, this program will provide both trained manpower and appropriate technology to lay the foundation for our future competitiveness.

Having laid sound foundations, the institutes and research centers need to move on to contributing more directly to our industrial competitiveness. At some point, preparatory efforts must yield dividends in a form relevant to and valued by industry. Such dividends can be in producing new processes or products for industry, solving problems for industry, or spinning off new ideas and products and even venture companies. The institutes should pay particular attention to generic pre-competitive technology which companies need but are less suited to taking up themselves, and to process R&D.



Model of a node in a roof structure being prepared for full-scale tests in a Science Park laboratory

Process R&D, as opposed to product R&D, involves improving the production process and technology, whereas product R&D focuses on coming up with a new gadget. The advantage derived from a new product often only lasts a few months before it is overtaken by the next innovation. Process R&D, on the other hand, results in more lasting benefits, because the techniques learned can be applied to produce successive generations of products. Besides, it is much easier for competitors to copy a product than to duplicate a finely tuned production process.

The institutes must work closely with the private sector, wherever possible in joint projects with a commercial angle. At the very least, the institutes should be actively aware of the commercial environment, the time pressures and fleeting windows of opportunity which technology companies must contend with, and the difficulties of converting a promising research idea into a viable, marketable product. That is the only way to bridge the gap between the research environment and the commercial world.

COMMERCIALIZATION & INFRASTRUCTURE

We have been relatively weak in our ability to commercialize R&D results. This should not be the case because many of the basic elements of success in innovation exist in Singapore and have been strengthened over the last decade. However, successful commercial exploitation of R&D requires the ability to bring together assets such as finance or capital, marketing skills, distribution muscle, and competitive manufacturing

capabilities. Start-ups typically have difficulties commercializing their research findings because they do not possess, or cannot find, all the requisite elements.

NSTB can assist start-ups by helping to bring the elements together. For example, administrative policies can be changed and institutional barriers removed to encourage greater tie-ups between the research institutes and industry. The flow of technology from academia and the centers of research to industry will be better effected if there is closer interaction between researchers and entrepreneurs, financiers and managers. If finance or managerial expertise are lacking, NSTB can also assist in match-making these with R&D start-ups through strategic partnerships, joint ventures, or direct equity investments in the start-ups.

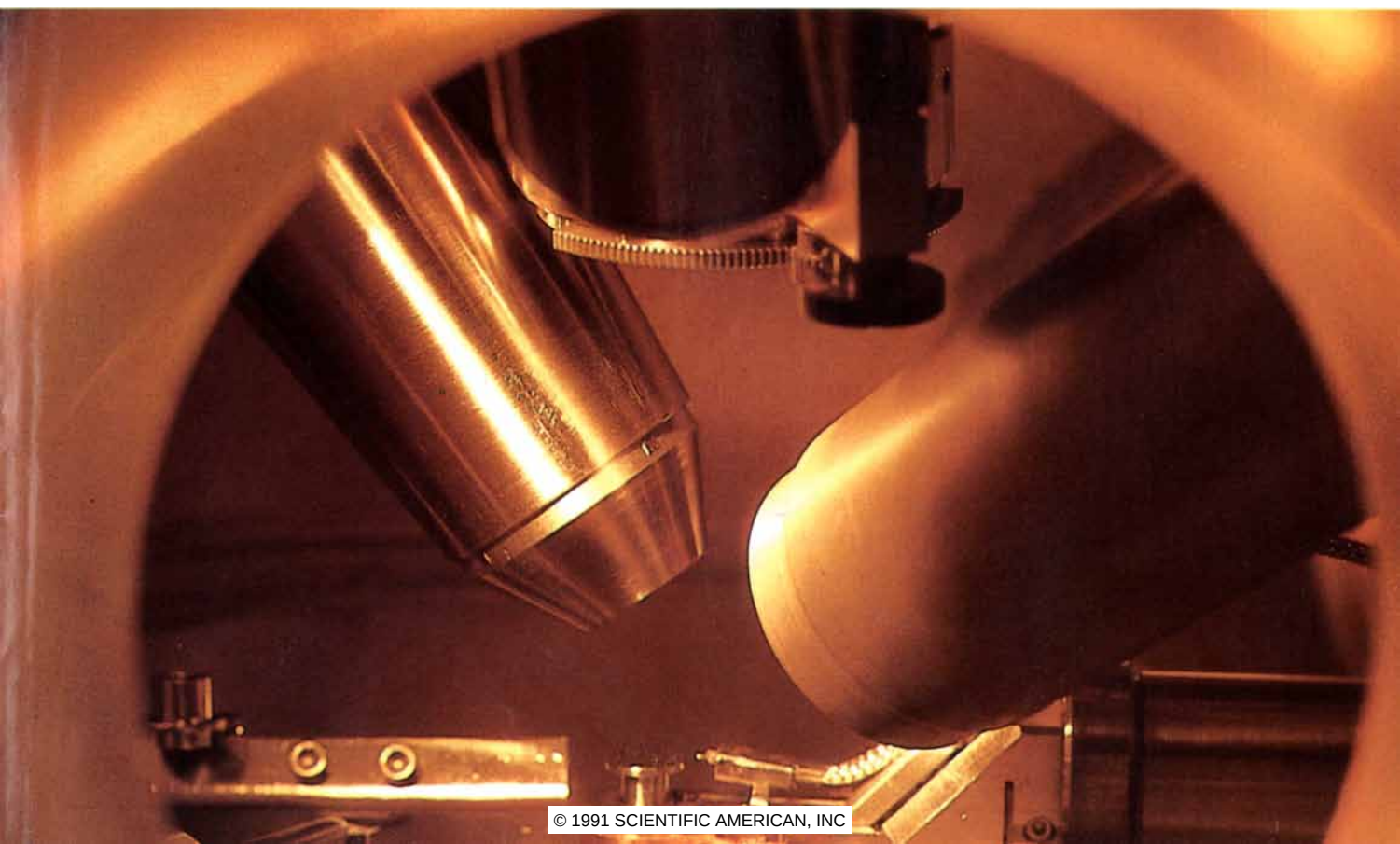
Highly-skilled personnel at the Probe Station characterizing device performance

NSTB should be developed into a "one-stop Technology Assistance Center" covering the entire life cycle of R&D. For example, it will provide guidance on subjects related to commercializing R&D, application for patents, and availability of fiscal incentives for R&D.

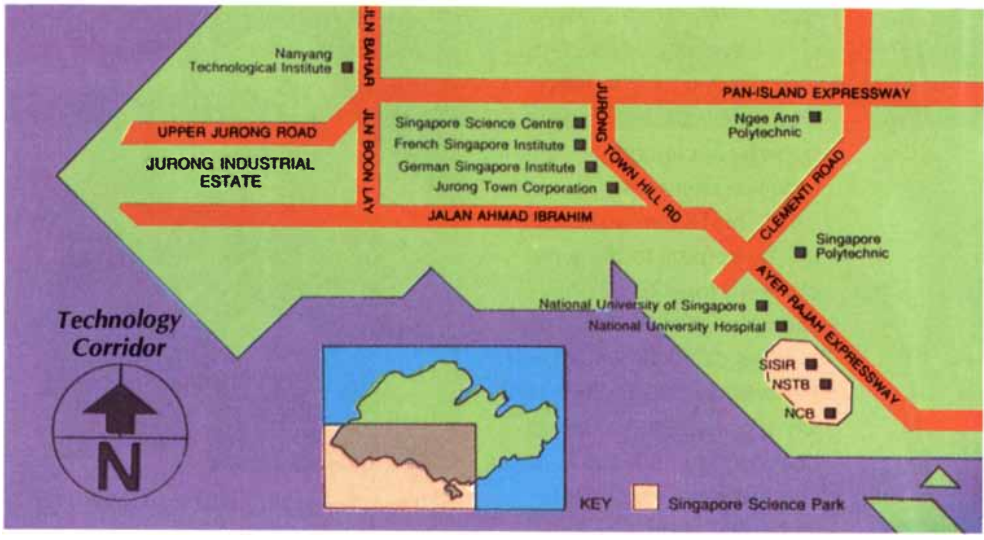
The key objective of a "science city" or "technopolis" is to create an attractive living environment that will attract and retain scientific talent because of its physical attributes and because it fosters innovation through intimate and informal interaction amongst the research community.

A suitable site for a technopolis is the area that runs from Nanyang Technological University to the Science Park at Kent Ridge. This Technology

Scanning Electron Microscope Chamber



Corridor has a concentration of tertiary educational institutions and research institutions, high-tech business activities, housing, social and recreational amenities, and good communications access to other parts of the island. Another potential Technology Corridor is alongside the northeastern part of the island.



CONCLUSION

Our mission for the next phase of our economic growth is to seek a more innovation-driven industrial program. Our basic approach will still be to maintain an open economy to attract high quality world class businesses to Singapore. We will refine this approach to encourage more developmental and research work in Singapore. Our aim is to make Singapore a center of excellence in science and technology in fields that are properly chosen and suited to our capabilities.

SCIENTIFIC AMERICAN wishes to thank Professor C.C. Hang (Deputy Chairman), Dr S.K. Chou (Executive Director) and Mrs Rosa Tan (Head, Administration and Public Relations) for their invaluable assistance in realizing this project.

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Mr Phillip Melchior, Managing Director, ***Reuters Singapore***

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SINGAPORE TECHNOLOGIES

Your Partner in Innovation

Singapore Technologies

Singapore Technologies is the largest diversified industrial and high-technology group in the nation. Under its umbrella are 60 companies with a skilled workforce of 13,000. In 1990, the group profitably achieved US$ 1 billion in sales.

Structurally, Singapore Technologies operates as five primary business sectors, with some of its companies already listed on the Singapore Stock Exchange.

CHARTERED INDUSTRIES OF SINGAPORE (CIS)

CIS, the defense business sector of Singapore Technologies, comprises nine main subsidiaries sharing complementary capabilities in design, engineering, production and ordnance-related services.

The company invests substantially in research and development. Equipped with specialized environmental testing facilities and sophisticated equipment for metallurgical and chemical analyses, CIS specializes in designing, developing and manufacturing assault rifles, machine guns, mortars, artillery guns, howitzers and anti-aircraft gun systems. Its range of infantry weapons includes the SR 88 A assault rifle, Ultimax 100 light machine gun, 0.5" heavy machine gun and 40mm automatic grenade launcher. The FH-88 155mm field howitzer stands out among its artillery weapons.

Its ammunition division produces a range of enhanced performance extended range ammunition, 2.75" air-to-ground rockets and pyrotechnic products.

CIS also has capabilities for the design, development, overhaul and rebuilding of all classes of military vehicles including the upgraded AMX-13 SM1 light battle tanks, trucks, field hospitals and armored personnel carriers.

SINGAPORE AEROSPACE (SAe)

SAe, a premier aerospace engineering company, offers its customers worldwide a comprehensive range of engineering services and products for both military and civil aircraft. The successful re-engining and avionics upgrade of the A-4 Skyhawk ground support aircraft and the F-5 Tiger air defense aircraft attest to its strong engineering capability, backed by an advanced avionics laboratory, CAD/CAM and test flight facilities.

Renowned for its depot-level maintenance and upgrading of military aircraft, SAe is the leading regional specialist in the overhaul of C-130 transport aircraft. For over a decade, the US Navy's fleet of C-130 in the Asia-Pacific region has been overhauled by SAe.

Building on its experience in military aircraft engineering, SAe has reached out to the commercial aviation market, to undertake maintenance and modification work on wide-bodied commercial aircraft in 1990. With a strong thrust to go international, a second center, Mobile Aerospace Engineering, was established in Alabama, USA, for the North and South American market. SAe manufactures airframe parts and engine sub-assemblies for international customers like British Aerospace, Aerospatiale, Rohr and Pratt & Whitney.

In its international partnership, SAe is collaborating with Aerospatiale of France and the China-National-Aero-Technology Import & Export Company (CATIC) of the PRC on the new P-120L light helicopter, incorporating state-of-the-art technologies in helicopter design and advanced materials.

SINGAPORE TECHNOLOGIES INDUSTRIAL CORPORATION (STIC)

The principal activities of STIC are electronics, precision engineering and industrial services. In electronics and information technology, STIC offers a broad spectrum of electronic products and services such as systems integration, building automation systems, communication & radar equipment and software development.

STIC owns the largest computer software house in Southeast Asia (outside Japan). It also operates a Supercomputer Center with an NEC SX-1A supercomputer and IBM 3090 with vector processor, facilities which are timeshared by institutions and organizations involved in higher education and R&D projects. In software development, STIC is employing object-oriented technology to develop the next generation of business applications and software development tool products for the international market using its internally developed interactive C++ language.

In precision engineering, STIC operates Singapore's national mint, manufactures semiconductor leadframes, acts as OEM supplier for the stitcher/binder module of the Xerox 5090 photocopier and binder and fabricates super-alloy components for the aerospace industry.

STIC's industrial services activities include automation consultancy providing solutions to manufacturing problems – from plant design to fully automated flexible manufacturing systems with financing.

In infrastructure construction and development, STIC is instrumental in building and operating a 500-hectare industrial park on the Indonesian island of Batam. This park will employ at least 20,000 workers in electronics manufacturing for the world market. STIC is also involved in developing the Bintan Beach International Resort and the Bintan Industrial Estate on the Indonesian island of Bintan, next to Batam.

SINGAPORE SHIPBUILDING AND ENGINEERING (SSE)

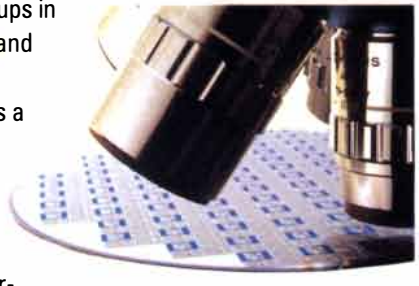
SSE is one of the world's leading shipbuilders, ship repairers, military equipment fabricators and technical management service specialists. Its specialized shipyard has an array of state-of-the-art facilities including the latest CAD/CAM design system and underwater CNC plasma plate cutting machine.

The pinnacle of the company's military effort has been the design and construction of six 62-meter Missile Corvettes. These high-speed vessels incorporate cutting-edge electronics with systems integration of weapon systems to deliver a potent force.

SSE also builds a wide range of commercial vessels including offshore supply, LPG carriers, catamaran ferries and container ships.

SINGAPORE TECHNOLOGIES VENTURES (STV)

STV is the venture and development arm of Singapore Technologies. Its mission is to nurture and develop technology-based businesses, both organic as well as through partnership, to address the international market.



STV has a number of startups in the semiconductor, electronics and precision engineering sectors.

In semiconductor, STV has a world-class CMOS foundry providing independent fabrication services with 0.8 to 3.0 micron capability. Advanced R&D efforts are underway in sub-micron manufacturing processes.

In advanced materials, STV has developed an innovative metal injection moulding process using carbon steel and stainless steel materials.

Anticipating the needs of tomorrow's users, STV is working with international partners to develop a range of innovative integrated intelligent electronic-based products for the home and office.

YOUR PARTNER IN INNOVATION

New markets and new business opportunities are what Singapore Technologies is seeking. We have a strong need and desire to form partnerships, as part of our vigorous globalization program, to establish a firm and progressive position in the international market place.

SINGAPORE CHANGI AIRPORT. LIKE NO OTHER ON EARTH.

Lush vegetation surrounding a tranquil pond, home to a school of lazily cruising golden carp, is hardly the sort of scene one expects to discover in a bustling international airport.

Equally unexpected are the hundred shops that grace the halls of Singapore Changi Airport, though they are merely the beginning of a seemingly endless parade of diversions.

There are 20 restaurants waiting to tempt you with the cuisines of 8 different countries, and a Skytrain waiting to whisk you between terminals in just one minute.

If you're between flights and feel like a snooze, you can take a room in the transit hotel. Or shake off the cobwebs with a visit to one of the 2 gymnasiums and saunas.

These are just some of the ways Singapore's Changi Airport is changing even the most experienced traveller's perception of what an airport should be.

Changi Airport – global hub that's a destination in itself..

CAAS

SINGAPORE TOURIST PROMOTION BOARD

CAA13/9

SINGAPORE CHANGI AIRPORT

Changes the Face of Air Travel

CAAS

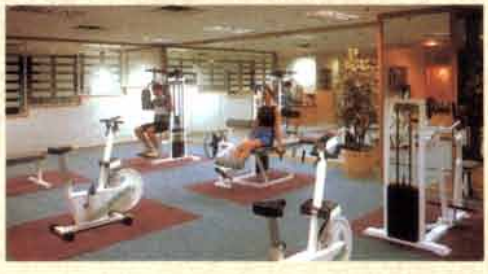
In Singapore, the world meets at Singapore Changi Airport, a unique "city within an airport" where travellers are almost lost in luxury.

Built largely on land reclaimed from the sea, Singapore Changi epitomizes the Singapore success story, demonstrating high technology and human endeavor at their potent best.

Throughout the airport, the accent is on speed, efficiency, top class service and comfort – a formula that resulted this year in business travellers from both the USA and UK/Europe voting Changi the world's best airport.

This was a remarkable achievement, considering the airport was still adjusting from single to multi-terminal operations following the opening last November of a second passenger terminal.

The award recognizes how Changi has added an exciting new dimension to international travel. Among its facilities are 100 shops and boutiques, 20 restaurants, 75 luxurious dayrooms for travellers, gymnasia and saunas, hairdressing salons, medical center, banks, exhibition center, theater, and even a Science Discovery Corner for children.



Singapore Changi Airport is run by the Civil Aviation Authority of Singapore (CAAS), a government statutory board. Set up in 1984, CAAS capitalizes on Singapore's strategic location at the vortex of air routes that link the US, Europe and Japan with the rest of Asia, Australia and the Pacific.

Its relentless efforts to get foreign airlines to fly to Changi have made Singapore one of the world's top air junctions, with direct links to 110 cities in 53 countries through more than 2,000 scheduled flights a week.

The opening of Terminal 2 has already increased the airport's passenger handling capacity to 24 million, the highest of any airport in the Asia-Pacific region. With an airport working community of some 17,000 people, there is heavy emphasis on staff development and training at Changi to maintain its high standards of service and efficiency.

However, much of the credit for the airport's outstanding success lies in its highly advanced systems which ensure speedy service for travellers.

The installation of sophisticated baggage handling sub-systems to speed up baggage processing includes a semi-automated system in Terminal 2 capable of sorting 10,700 bags per hour.

An inter-terminal baggage handling system enables baggage to be transferred between Terminals 1 and 2 within three minutes. This consists of computerized high-speed carts running on

a network of rails in underground tunnels.

For passengers, an automated transit system known as the Changi Skytrain cuts out a 15-minute walk between the two terminals. Instead, passengers travel the 600 meters in air conditioned comfort in just one minute.

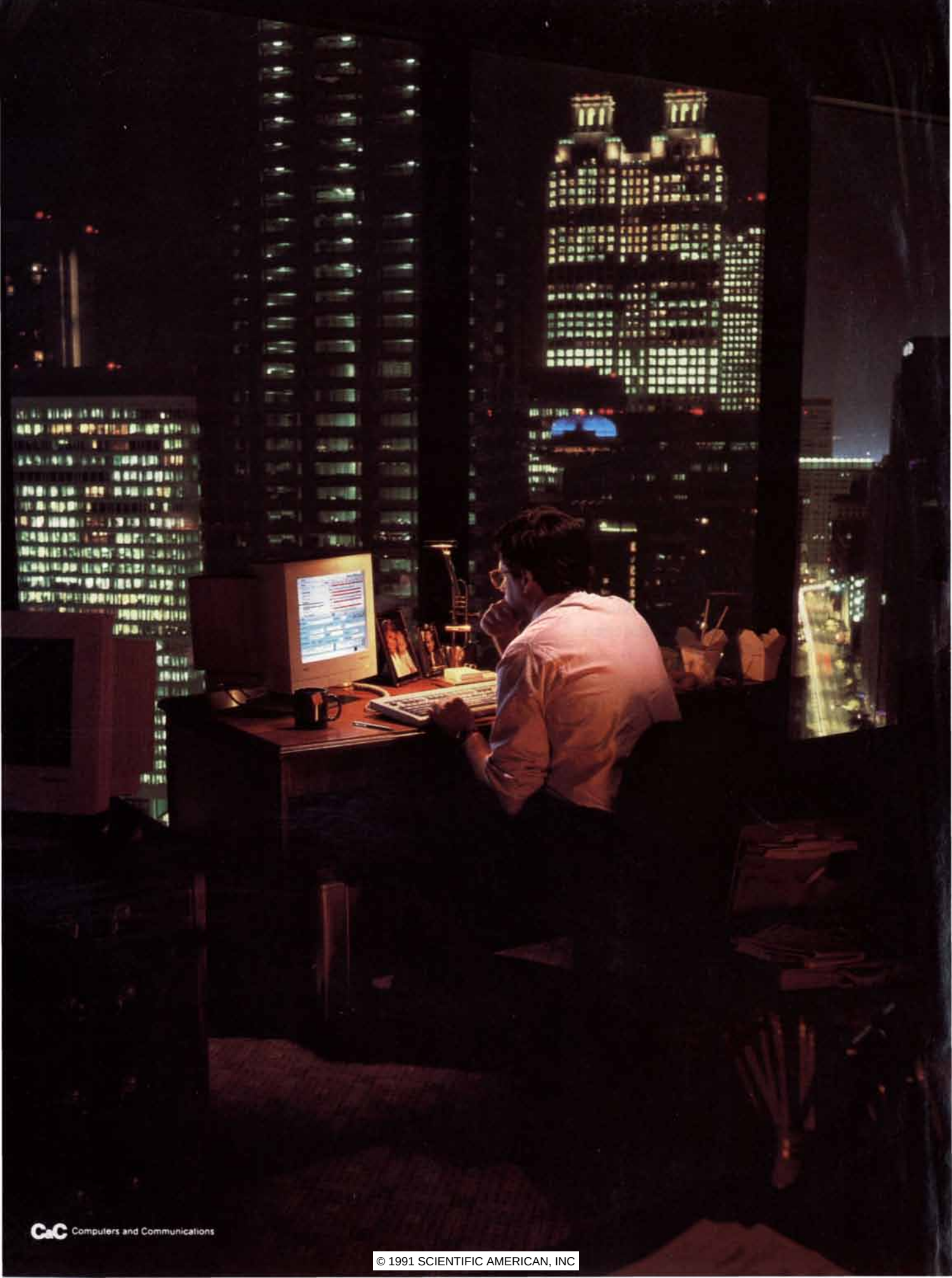
With both the Skytrain for passengers and the inter-terminal baggage handling system for luggage, Singapore Changi is well able to maintain its minimum connecting time to one hour for transfer passengers. The opening of Terminal 2, besides increasing passenger comfort, heralded the introduction of major sophisticated electronic and telecommunications systems.

The Philips Flight Information Display System (FIDS) comprises 330 26-inch color TV monitors which display flight information, using high resolution graphics with a combination of up to eight colors.

The FIDS is linked to several other ergonomically designed peripherals such as public flight information indication flapboards, LCD boards and keyboard display terminals. It also provides external communications through links with other information networks such as Teletext, Teleview, the baggage handling system and hotel data services.

Among other recent introductions is a computerized Telephone Flight Information Enquiry System (TELEFIQS), which is interfaced with the FIDS.

With these state-of-the-art systems, this tiny republic's ambition of becoming the airhub for Asia-Pacific is fast becoming a reality.



C&C Computers and Communications

9:27 PM

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NEC: AN R&D COMMITMENT

In 1991, the Republic of Singapore began issuing credit card-sized identity cards (ICs) for all its citizens. It was NEC Singapore Pte Ltd (called NECSIN) which was chosen by the Government to implement this card program, using an NEC mainframe and specialized software. Within the year, the Singapore Police Force's Criminal Investigation Department was using the high-tech NEC Automated Fingerprint Identification System. It is but one example, but tells the tale of NECSIN as a constructive partner in Singapore's progress.

Such front-line projects implementing world-class technologies are only a start. NECSIN deploys about 150 software engineers in an R&D group, men and women linked to a series of institutions throughout Singapore. Working with allies and partners at the National University of Singapore, the Institute of System Science and the Japan-Singapore Artificial Intelligence Center, NECSIN people are developing software systems in knowledge engineering, artificial intelligence expert systems, neural networking software and image processing.

NECSIN's Software Development Center

It was NECSIN which scored the first of bringing into Singapore the NEC supercomputer, the standard-setter in Southeast Asia. This focal hardware and its software are at the service of the nation's Meteorological Center, the Nanyang Technological University, the National Computer Board, the National University of Singapore and Information Technology Institute.

Such projects are consistent with the Government's vision for Singapore's high-tech future, embodied in the programs of "IT 2000". NECSIN supports and joins in the Singapore Government's objective for making the nation a model of information technology, something fundamental to its international competitive advantage. Singapore's IT aspirations are also in line with NECSIN's own plans to promote R&D.

NECSIN recruits engineers around the world, offering careers and training for software engineers and specialists. Noel Hon, NECSIN's Managing Director, underlines the company's commitment to quality IT technology in the region: "While NEC Singapore is an aggressive, locally incorporated sales company, we believe a key factor to our success lies in the reinvestment we make in the people we employ and in the community where we work. For this reason, we emphasize both training in Singapore and long-term assignments for our people in Japan, where we are headquartered."

In response to the Government's call for software development "made in Singapore", NECSIN established its Software Development Center (SDC) in 1985. Since then, SDC has embarked on development projects in a wide range of fields. For example, in image processing, a Signature Inquiry System developed for a leading bank enables a client's signature to be easily retrieved on screen, for matching. In artificial intelligence, NECSIN is currently at work to develop a knowledge engineering "expert shell" for diagnosis/classification. Noel Hon explains: "About 90% of our software system engineers now work in customer support or development at our SDC. We view our joint programs with the universities and public sector to be fundamental for development beyond the prototype stage."

NECSIN utilizes the high language proficiency of Singaporeans for its software conversion programs. Japanese software is translated and con-

NEC's Supercomputer from the SX-Series

verted for regional and local use, allowing SDC to accept development assignments from the Asian region, including development of a word processing application in Arabic.

Daniel Cheng, SDC's Assistant Division Manager, explains SDC's plans for propelling NEC to the forefront of software development: "We shall invest time and personnel in developing both operating systems and application software here. Our ultimate objective is to position ourselves as not only a company with an internal software development capacity, but also as one of the prime NEC software development points within our global network."

To this end, NECSIN has initiated "INtelliVEST", a joint undertaking with the National University of Singapore and the Institute of Systems Science. It is a project using NEC's SX-1A supercomputer in Singapore to develop neural network models for use in the financial sector. It aims to use the multi-layer perceptron type of neural networking to develop forecasting models for the securities and foreign exchange markets. Development of a mathematical library, to solve large-scale mathematical problems, is also being undertaken.

Samuel Neo, Senior Specialist (Software), views the future this way: "We are increasingly concentrating on applications. In our economic, financial and foreign exchange forecasting, we have reached accuracy as high as 99% in certain areas. This is a strategic technology we must develop."

Because Singapore is sited as a strategic regional hub, NECSIN established a Regional Support Center for all NEC products and services in Southeast Asia. NEC hardware is serviced from here – computers, peripherals, home electronics and communications equipment.

Singapore's global communications linkages were enhanced by installation of four NEC earth stations between 1971 and 1982. NECSIN works to provide linkages between communication hardware OAI (Open Application Interface) and computers.

NEC's presence is consolidated through three subsidiaries: electronics (established 1976), regional marketing (1977) and a business coordination center (1991) which also enjoys the status of Operational Headquarters in Singapore. Each of these subsidiaries adds its own flavor, helping NEC strengthen her regional presence. This diversification enhances NEC's commitment to be a good corporate citizen. Sports programs, musical events, charitable undertakings and educational programs for youth all manifest NECSIN's commitment to the future of the Singaporean people. The company's policy is to work in every way to realize the goal of making Singapore an "Intelligent Island" through information technology.

And NECSIN's future? Noel Hon sees the right path to be through increasing collaboration and coordination: "given the cost of R&D, no one party in Singapore can act alone. It is the combination of overseas technology, government encouragement, academia and local commercial interests acting in concert that is needed. Only then can that R&D environment come about that leads to product development for commercial success."

NEC

JURONG TOWN CORPORATION

From Industrial Parks to Science Parks

Technology Parks

Yeo Seng Teck
Chairman of JTC & Technology Parks Pte Ltd

Singapore started life, twenty-six years ago, with her main thrust on developing manufacturing industries to support economic growth. The country has now commenced the next phase of its industrial development and that means shifting into high technology and scientific development. The Jurong Town Corporation (JTC), the key State agency for industrial infrastructure – having produced the facilities to support manufacturing activities (and brilliantly so, as more than 3000 multinationals call Singapore home) – is now committed to support the National Science and Technology Board (NSTB) in the further upgrading process.

JTC's Chairman Yeo Seng Teck says, "To reach our shared goals and in a focused way, JTC has formed a subsidiary company – Technology Parks Pte Ltd – whose mission is to plan, build and manage science parks. We have already developed a most successful Science Park covering 29 hectares (72 acres), located in what we call the Technology Corridor of Singapore. This first phase development of the Singapore Science Park has seen an extremely high tenancy rate, and by occupants of global stature. To name a few: Du Pont, AT&T, Sony, Exxon Chemicals. Our tenants, who bring to Singapore the best of their work, are active in research in cutting-edge technology ranging from biomedical to robotics to materials engineering.

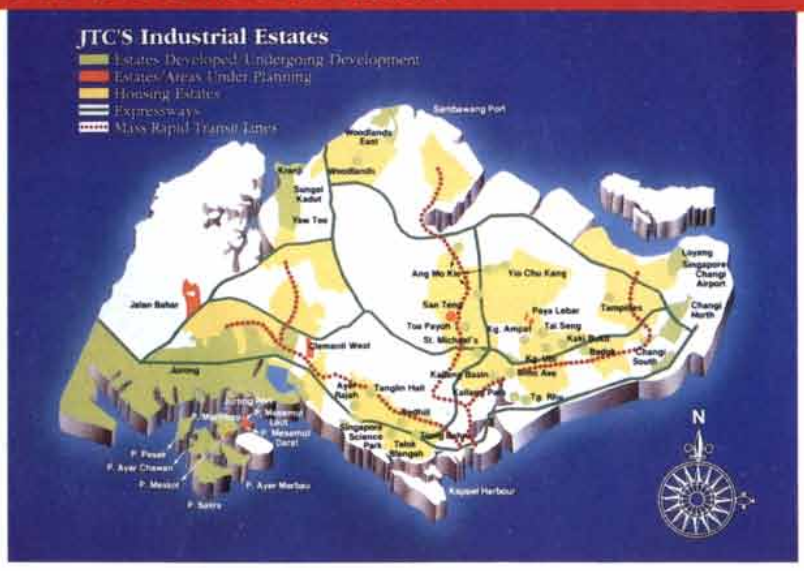
From 1992, Technology Parks will be proceeding with Phase 2: another 20 hectares (49 acres) of land area, making available to our tenants some 120,000 square meters (1.3 million square feet) of usable space. This is suitable for up to one hundred different entities, the number we serve in Phase 1."

The Science Park is located halfway between the city center and JTC's Jurong Industrial Estate, and right next to the National University of Singapore and various other research institutions. This area is a planned 'green zone', slated to have ever more high quality housing and recreational facilities. Yeo: "We want not only to provide the best facilities in terms of design and practical usage, but also do so in a timely fashion, because we know companies and investors want to move fast. Our strategy is to have the facilities ready for them to move in quickly. We do this in two ways. First, we have land that is fully prepared for companies to build their own specialized buildings. Second, we provide ready-built R&D buildings, (named after famous scientists, like Curie, Pasteur, Maxwell, Mendel) with units of varying sizes and at various degrees of fitting-out. For example, some units are fitted with air-conditioning, carpets and lighting. Start-up time is reduced when such units are taken up.

JTC and Technology Parks are committed to Singapore's economic growth through the provision of the best facilities for top-of-the-line tenants. Our goal is not simply to fill space but to bring into the Science Park and our newly planned business parks, that sort of tenant who contributes to our nation's objectives: the upgrading of Singapore as a technology and R&D center."

With the close link between Technology Parks' and JTC's facilities, a smooth transition is possible from R&D premises to industrial space. When they are ready to do so, companies from the Science Park can move into manufacturing facilities built and maintained by JTC who is Singapore's principal

Cintech III at the Singapore Science Park will be completed in 1993. This building is designed specifically for companies engaged in computer software R&D, information processing and data technology.



developer and manager of industrial estates.

JTC operates thirty industrial estates. And if that is not what is called for, a company can settle into one of the world-class business parks currently being developed by JTC.

"In the past," explains JTC's Yeo, "service activities of manufacturing companies – technical, engineering and software services – used to have to pay high rents in the central business district. So we created business parks for them to consolidate their operations in one convenient location."

A new business park is being constructed at Jurong East. Its first building has a floor area of 43,000 square meters (464,400 square feet). Eventually, more than twenty buildings will be spread over a landscaped 40 hectares (100 acres) providing working area for the full range of high-tech manufacturing and service companies. This business park is in very close proximity to one of Singapore's excellent mass rapid transit stations. In addition, it is served by two superhighways and is only a fifteen minute drive from the center of the city.

According to Yeo, "We design our business parks on a simple formula – optimize land use as well as blend our buildings into the natural foliage and greenery. Tenants will enjoy the lush tropical landscape and yet are only minutes from the heart of one of the world's busiest cities.

What we want to do is to make the Science Park, and the industrial parks/business parks, together one of the key nodes of the global R&D-based industrial system. To do that, we have committed to linking ourselves with the world, connecting people into the international scientific industrial community."

In the industrial parks, JTC offers one of the best telecommunications and transport grids in Singapore. Singapore is a place where the business and scientific communities are fully in synch, through an integrated electronic data interchange (EDI) network, allowing for paperless transactions and information exchange. Tenants in the industrial parks benefit from this high level of information integration.

In the Singapore Science Park, optic fiber will link Singapore-based researchers to the world. Already in place is Technet (linked to the international Internet and Bitnet), a global networking system which is a big boost to the local R&D community. Local researchers can access up-to-date information at their fingertips and enjoy close interaction with the international scientific community, helping them to keep at the forefront of technological change and allow them to compete better globally.

EXAMPLES OF CURRENT R&D ACTIVITIES IN THE SCIENCE PARK

Allied-Signal	R&D center & lab for new product development & applications development for performance additives (chemicals)
AT&T Microelectronics	R&D of application specific integrated circuits
Bayer Polysar Asia Pacific Pte Ltd	R&D of rubbers as additives to plastics for the improvement of flex life, impact strength & low temperature properties
Exxon Chemical (S) Pte Ltd	Research & product development of fuel additives & of flow improvers for middle distillates & heavy fuels
Rhone Merieux Asia Pacific Pte Ltd	R&D on disease control & pharmaceuticals for regional farming industries
Seagate Technology International	R&D on hard disk drives and design of micro-code
Silicon Graphics Pte Ltd	R&D of software packages for communication interface between superworkstation, supermini & mainframe computers
Sony Precision Engineering Centre (S) Pte Ltd	R&D and designing of software for factory automation, robotics, machine vision system & CAD/CAM/CAE systems
Union Carbide Asia Pacific Inc	R&D of solvents and polymeric coating resins
Xerox (S) Software Center	R&D of software applications such as laser printers & CIM

It may be immodest to call the Singapore worker the best in the world. But after 25 years of investing in the education, skills, productivity and quality of our people, it's about time they were given recognition.

The U.S. based Business Environment Risk Intelligence (BERI) report has already done this, rating the Singapore worker number one for each of the last ten years.

In addition, the 1991 World Competitiveness Report ranked Singapore the best newly industrialised economy in human resources and industrial efficiency.

Hire the best worker in the world.

The productivity and quality of our workforce has encouraged more than 3,000 multi-national companies to establish operations in our island Republic. A track record that makes our nation one of your best bets. Now and in the future. Because we realise that to stay at the top, we have to be the best that we can be.

NATIONAL PRODUCTIVITY BOARD SINGAPORE

SCIENTIFIC AMERICAN

Plant Life in a CO_2-Rich World

Even without considerations of global warming, increasing atmospheric levels of carbon dioxide may greatly alter the structure and function of ecosystems. These changes will not necessarily benefit plants

by Fakhri A. Bazzaz and Eric D. Fajer

Plants are the green cornerstone of terrestrial life. The abundance and productivity of trees and grasses, herbs, shrubs, crops and weeds shape how ecosystems circulate gases and nutrients, cleanse water, build soils and provide sustenance for a variety of other life-forms. Any significant variation in the productivity and composition of plant life would precipitate a cascade of changes affecting herbivores, carnivores and omnivores alike.

One such change may be under way. Fuel combustion and deforestation are rapidly altering the nature of the earth's atmosphere. Perhaps the most important atmospheric component affected by human activity is carbon dioxide (CO_2). Since the dawn of the industrial age, the concentrations of this gas have increased from 280 to 350 parts per million—the highest level in the past 160,000 years for which a CO_2 record can be found in ice core samples. Measurements at the Mauna Loa observatory in Hawaii have documented about a 20 percent increase in CO_2 levels between 1957 and the present. Although estimates vary, experts anticipate that global concentrations of CO_2 will double by the middle to the end of the 21st century.

At first glance, elevated carbon dioxide levels might seem an agricultural blessing. Initial studies suggested that a high CO_2 environment would enhance plant growth. This CO_2 fertilization effect, as it is called, is expected to be particularly pronounced if plants have plentiful supplies of nutrients, light and water.

The CO_2 fertilization effect also promises to provide a buffer for concerns about global warming. Plants growing larger in such an environment could be counted on to draw more CO_2 from the atmosphere. Thus, the level of this greenhouse gas—which traps energy from the sun that is reradiated as heat from the earth's surface—would be lower than expected. Indeed, the fertilization effect has been considered in atmospheric models that predict how much of the CO_2 produced by industrial and land-use activities would be absorbed by terrestrial vegetation.

Our experiments, conducted at Harvard University, and work done by our colleagues at other institutions suggest that such assumptions about the benefits of a world replete with CO_2 may be overstated. Studies have shown that an isolated case of a plant's positive response to increased CO_2 levels does not necessarily translate into increased growth for entire plant communities. Even the notion that plants will serve as sinks to absorb ever mounting levels of carbon dioxide is questionable.

Considerations of the benefits of a high CO_2 world are rooted in the details of photosynthesis. During this fundamental chemical process, plants capture CO_2 molecules and, using energy from visible light, build carbohydrates. Carbon dioxide from the atmosphere diffuses into the plant through stomata, pores in the outer layer of leaf cells. The gas ultimately arrives at the chloroplasts—organelles in which photosynthesis takes place.

One way increasing concentrations of CO_2 could enhance photosynthetic rates, and therefore plant growth, is by curbing water loss. Normally, the entrance of CO_2 entails a cost to the plant. For every molecule of carbon dioxide that enters the stomata, between 100 and 400 molecules of water are lost.

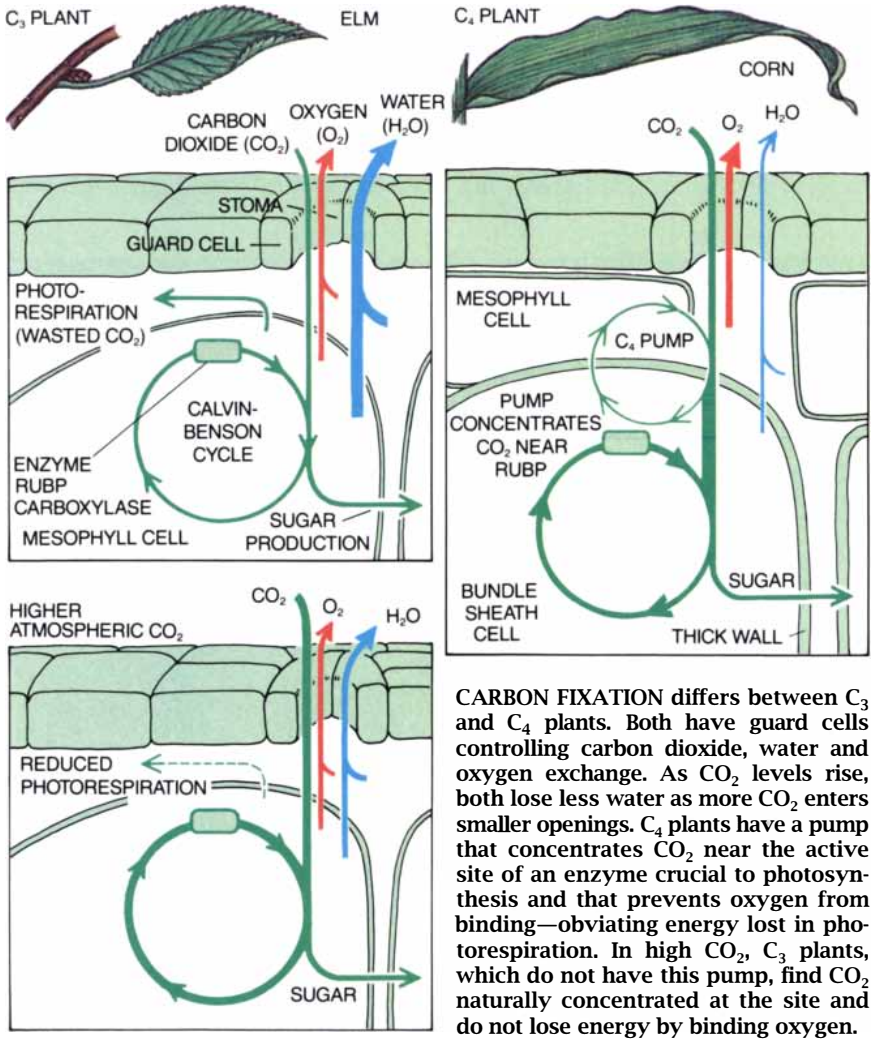
In a CO_2-rich atmosphere, a higher concentration gradient would exist between the exterior and the interior of the leaves. Equivalent amounts of carbon dioxide would therefore diffuse through the stomatal openings even if the guard cells, which regulate these openings, kept them small. Reduced stomatal openings would curtail water loss, and so plants would require less

FAKHRI A. BAZZAZ and ERIC D. FAJER have studied various aspects of the complex role of atmospheric carbon dioxide in ecosystems. Bazzaz is the H. H. Timken Professor of Science at Harvard University and for the past two decades has researched how rising CO_2 levels will alter plant life. He received his Ph.D. from the University of Illinois in 1963. Fajer recently completed his Ph.D. at Harvard, where he examined the impact of high CO_2 levels on plants and herbivorous insects. He is a postdoctoral researcher at the Center for Science and International Affairs at the John F. Kennedy School of Government. The authors gratefully acknowledge the support of the U.S. Department of Energy.

TOWER IN HARVARD FOREST is instrumented to measure CO_2 exchange between trees and the atmosphere in an effort to quantify the role of forests in the global carbon cycle. The round shields keep water out of gas intake tubes.

water to grow to the same size. In addition, smaller stomatal openings could improve the health of certain plants by limiting the entrance of air pollutants, such as sulfur dioxide, thereby reducing injury to those plants.

Beyond promoting water conservation, a CO_2-rich environment could allow some plants to waste less energy during photosynthesis. In particular, a group of plants designated C_3 stands to benefit from such an atmospheric change. Virtually all forest tree species are C_3 plants, as are many major crops, including rice, wheat, potatoes and beans. During the initial carbon dioxide fixation step, C_3 plants bind the gas to a five-carbon sugar called ribulose bisphosphate (RUBP) in the presence of the enzyme RUBP carboxylase, producing an unstable six-carbon compound.



CARBON FIXATION differs between C_3 and C_4 plants. Both have guard cells controlling carbon dioxide, water and oxygen exchange. As CO_2 levels rise, both lose less water as more CO_2 enters smaller openings. C_4 plants have a pump that concentrates CO_2 near the active site of an enzyme crucial to photosynthesis and that prevents oxygen from binding—obviating energy lost in photorespiration. In high CO_2, C_3 plants, which do not have this pump, find CO_2 naturally concentrated at the site and do not lose energy by binding oxygen.

This short-lived compound then breaks into two three-carbon derivatives, hence the carbon three, or C_3, name of the plants. The derivatives proceed through a series of reactions, called the Calvin-Benson cycle, that culminates in the production of sugars.

Under ambient atmospheric conditions, oxygen competes with CO_2 for the active site of RUBP carboxylase. If oxygen outcompetes CO_2, the plant loses energy because it fixes less carbon dioxide as it processes the oxygen. In this case, oxygen combines with RUBP carboxylase to form a three-carbon sugar and a two-carbon compound, which is then recycled in an energy-expending process known as photorespiration.

As its concentration increases, CO_2 would be more likely than oxygen to bind to the active site of RUBP carboxylase because more CO_2 molecules would be present there. Indeed, in some experiments, photorespiration was found to be reduced by 50 percent when carbon dioxide levels were established at 600 parts per million. Limiting photorespiration means that plants can use more of their energy to build tissues.

Despite these physiological and biochemical considerations, photosynthetic rates are not always greater in CO_2-rich environments. Often plants growing under such conditions initially show increased photosynthesis, but over time this rate falls and approaches that of plants growing under today's carbon dioxide levels. The reasons for this decline are unclear, but several mechanisms have been proposed.

The first idea suggests that increased photosynthesis results in the excess accumulation of starch in the chloroplasts, thereby hindering the organelles' ability to function. Second, in the presence of greater amounts of CO_2, a plant's ability to produce carbohydrates initially exceeds its ability to move the starch by-products to actively growing parts. In this circumstance, a biochemical feedback may slow down photosynthesis. A third hypothesis involves the nutrient phosphorus, necessary to the transport of accumulated carbohydrates: perhaps phosphorus recycling does not keep pace as photosynthesis increases. And finally, there may be a reduction in both the amount and activity of RUBP carboxylase.

Even if photosynthetic rates did rise as levels of CO_2 increased, plants might not grow faster, larger or become more plentiful. Studies have shown that the relation between photosynthetic rate per unit area and growth is not always positive. Plant growth is also greatly affected by such factors as the amount of leaf area available to intercept light as well as how plants partition their resources between roots and aboveground stems, leaves, flowers and seeds. It is therefore important to examine how plants allocate resources to their different structures and functions under high CO_2 conditions.

Evidence indicates that habitat fertility and water availability are important limitations to ecosystem productivity. When nutrient, water or light levels are low, many plants show only a slight CO_2 fertilization effect. Our laboratory, for instance, used a model system of six annual plant species—including ragweed and foxtail—that dominate abandoned farmlands in the Midwest to study the importance of carbon dioxide relative to other environmental resources. We found that plant growth was most dramatically influenced by the amount of light and nutrients provided. Compared with these inputs, elevated levels of CO_2 had only a slight effect. Indeed, when given little light or few nutrients, the plants did not exhibit any enhanced growth as CO_2 levels increased.

Other controlled studies have found similar results. Walter C. Oechel and his colleagues at San Diego State University showed that doubling the concentration of atmospheric CO_2 did little to improve tundra grassland productivity, presumably because most nutrients, frozen in the permafrost soil, were not accessible to plants. These C_3 grasses also exhibited photosynthetic decline over time in such an atmosphere.

In contrast, habitats replete with nutrients may demonstrate increased growth in a high CO_2 world. The estuarine marshland of the Chesapeake Bay is unusual because it has an unlimited water supply and ample nutrients. An important component of the estuary vegetation is a C_3 sedge, *Scirpus olneyi*. Bert G. Drake and his associates at the Smithsonian Environmental Research Center in Edgewater, Md., exposed plants in this habitat to different concentrations of carbon dioxide. As expected, plots containing *Scirpus* grew larger and more densely in an atmosphere of 700 parts per million CO_2.

Studies of forests have yielded insight into another factor determining the health of future ecosystems: competition. Because forest trees are C_3 species, researchers might predict that the trees would exhibit a large CO_2 fertilization effect, especially if light, nutrients and water are plentiful. Indeed, when raised individually, tree seedlings from the temperate forests of New England and the southeastern U.S., as well as some neotropical species, do grow better in an enriched CO_2 environment.

Yet in the few studies performed so far, competition diminished the CO_2 enhancement. Experiments in two deciduous temperate forests and one Mexican rain forest showed that tree seedling communities were not more productive in a CO_2-rich atmosphere when different species were grown together. The reasons for these findings are not fully understood. Conceivably, competition for scarce resources could constrain the plants' response to higher levels of atmospheric carbon dioxide.

Even within the same plant community, certain species will grow better than others. For instance, when several species of Mexican rain forest trees were grown together in high CO_2, seedlings of two species—*Piper auritum* and *Trichospermum mexicana*—thrived while seedlings of another C_3 species, *Senna multijuga,* declined.

An atmosphere rich in CO_2 may also put another category of plants at a comparative disadvantage. The C_4s, which include many grasses in hot, dry tropical and subtropical areas as well as important crops such as maize, sorghum and sugarcane, already possess the biochemical and structural means to reduce photorespiration. C_4 plants use a unique chemical pump that concentrates carbon dioxide near the chloroplasts, greatly reducing the likelihood that oxygen rather than CO_2 will bind the active site of RUBP carboxylase. Because they lose substantially less energy to photorespiration, these plants have higher photosynthetic efficiencies than C_3 plants.

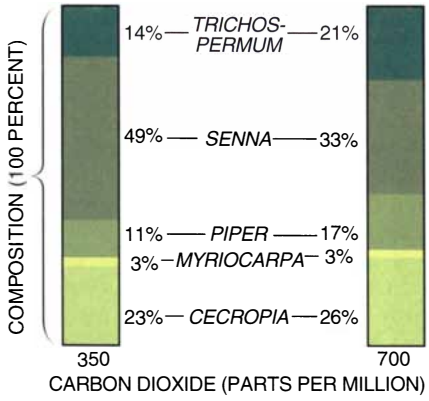
As CO_2 levels rise, however, C_4 plants may lose this edge. Reduced photorespiration and water loss in C_3 species would disproportionately improve their performance compared with that of C_4 plants. Indeed, Boyd R. Strain and his associates at Duke University found that in a high CO_2 environment, *Aster pilosus,* a C_3 perennial herb common to abandoned fields, grew better than *Andropogon virginicus,* a C_4 grass. When the plants were grown together under dry, CO_2-rich conditions, *Aster* dominated *Andropogon.* Another study, conducted by Douglas R. Carter and Kim M. Peterson of Clemson University, also demonstrated the dominance of C_3 over C_4 species in such an environment. When grown together in competition, *Festuca elatior,* a C_3 grass, outgrew *Sorghum halepense,* a C_4 plant.

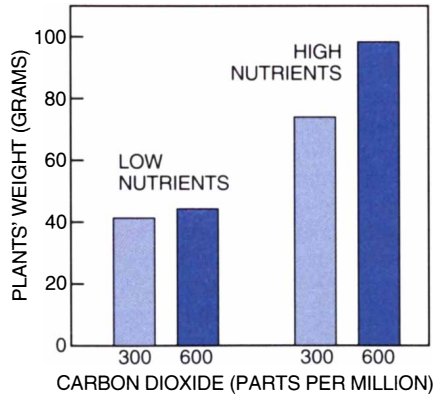
Competitive interference and limited nutrients will influence not only natural ecosystems such as meadows and forests but also man-made ecosystems such as farms. For this reason, we do not expect that agricultural yields will necessarily improve in a CO_2-rich future. Again, at first glance, harvests do seem to benefit from such an atmosphere: Bruce A. Kimball of the U.S. Department of Agriculture reviewed more than 700 agronomic studies and found that, on average, grain production increased 34 percent in high CO_2 conditions. But on closer examination, it becomes clear that such yields were dependent on the presence of fertilizers and water—resources often well supplied only on farms in the developed world.

Although such bounty would be most welcome if we hope to feed, clothe and shelter the eight to 10 billion human beings expected to inhabit the planet within the next 40 to 100 years, the costs of these harvests may be prohibitive. Large quantities of fertilizers, biocides and water from irrigation projects must be added to crops for them to be productive in a CO_2-rich environment. But of course today water is a limited and expensive resource. We fear that the costs of these inputs, in dollars and in environmental quality, may be too great. Poorer, underdeveloped countries will be at a disadvantage.

Farming will also be adversely affected by the differential response of C_3 and C_4 plants. David T. Patterson of the USDA and Elizabeth P. Flint of Duke University have shown that the relative productivity of *S. halepense,* a C_4 agricultural weed, decreased in the presence of higher levels of CO_2 when grown with soybean, a C_3 crop. In other words, in a high CO_2 world, C_3 soybeans did better in comparison to a C_4 weed when the two were grown together. In contrast, whereas C_3 crops may benefit in environments where their major weeds are C_4 species, important C_4 crops, such as maize and sugarcane, may experience yield reductions because of the increased performance of C_3 weeds.

Other organisms that depend on threatened plant species for food, shelter or mating sites may also become endangered. A dramatic reduction of species diversity would, in turn, undermine the integrity of natural ecosystems. Because individ-





PLANT COMMUNITY COMPOSITION will change as levels of carbon dioxide increase. Even among plants that may benefit from this change, some species will do better than others. As the chart on the left shows, rain forest seedlings were grown in ambient and enriched CO_2 conditions. After 120 days, only the biomass of *Cecropia* (*canopy shown in photograph*), *Trichospermum* and *Piper* increased.

CO_2 FERTILIZATION EFFECT depends on the supply of nutrients to the ecosystem. The biomass of a group of plants did not increase in high CO_2 levels unless sufficient nutrients were added.

ESTUARINE MARSHLAND of the Chesapeake Bay is one of few natural areas used to study how an atmosphere rich in CO_2 alters ecosystems. Grasses grow in open-topped chambers in high (about 700 parts per million) or ambient (about 350 parts per million) CO_2 levels. A monitoring station stands in the background.

ual plants and animal species supply a wealth of essential industrial, agricultural and medicinal products, the loss of diversity will have pervasive environmental and economic consequences.

As already noted, C_3 species tend to outperform C_4 species in a CO_2-rich atmosphere; such a change could have extensive ramifications. Plant species that respond less positively than their neighbors to an enriched CO_2 atmosphere may become rare, rendering them vulnerable to extinction. Indeed, certain C_4 plants found in ecosystems dominated by C_3 plants might disappear without adequate protection.

Even if plant extinction rates are not accelerated by increased concentrations of carbon dioxide, the changing character of plant communities will alter ecosystem stability as well as nutrient cycling. Within the rangelands of the Great Basin, for example, Strain of Duke, Stanley D. Smith of the University of Nevada at Las Vegas and Tom D. Sharkey of the University of Wisconsin found that *Bromus tectorum,* a weedy grass, grew much better with plentiful CO_2 than did three other grasses. Because *Bromus* predisposes land to burning, its potential increase in future rangeland communities may lead to greater numbers of wildfires in this region, as well as to more severe fires.

Nutrient cycling could also be dramatically altered if atmospheric CO_2 levels surged. For instance, if the abundance of legumes—members of the pea family—were to change, so would the amount of nitrogen in the soil. Legumes convert atmospheric nitrogen into nitrate and ammonium, forms that are also accessible to other plants. Reductions in the numbers of legumes would modify soil fertility and potentially the types of plant species that could thrive there.

The relation of dead plant material such as fallen leaves and twigs to soil microorganisms may shift as well. The work of Richard J. Norby of Oak Ridge National Laboratory, John Pastor of the University of Minnesota and Jerry M. Melillo of the Ecosystem Center in Woods Hole, Mass., suggests that if plant litter has less nitrogen, the rate of decomposition will decrease. This process would be limited because the growth of soil bacteria and fungi is constrained by lack of nitrogen. Many studies have shown that litter from plants grown in a CO_2-rich environment has less nitrogen in comparison to carbon. It appears that in response to high levels of atmospheric CO_2, most plants, unaccountably, reduce the nitrogen concentrations in their leaves. Such an atmosphere may lessen soil fertility and nutrient cycling because many nutrients, trapped in litter, would be inaccessible to the plants.

Changes in the nutritional quality of plant leaves could lower herbivore and predator populations within their habitats. The amount of nitrogen and, hence, protein in plant leaves determines the growth and fecundity of insect herbivores. Lower concentrations of leaf protein determine the amount that an insect eats and the number of offspring it produces. So, although the quantity of plant tissue may increase in a world replete with carbon dioxide, the palatability of this tissue from an insect herbivore's perspective declines.

To compensate for the lower nutritional quality of these plants, insects consume more leaves. David E. Lincoln and Robert H. Johnson of the University of South Carolina have shown that grasshoppers and caterpillars from several moth species eat substantially more than do those feeding on plants grown in ambient CO_2 levels. Taken alone, such augmented consumption by insects could negate any benefit gained from the hypothesized crop yield boon in a CO_2-rich environment.

Research in our laboratory suggests that insect herbivore performance and subsequent population size also may be decreased on such a diet. When fed on plantain grown in a high CO_2 environment, larvae of the buckeye butterfly, *Junonia coenia,* did not develop as rapidly and died more frequently. Slower larval growth can mean that fewer individuals reach adulthood, because caterpillars remain vulnerable to attack from predators and parasites for a more extensive time. In addition, fewer caterpillars may complete development before dry or cold seasons begin. Consequently, it is likely that butterfly populations will decline.

If insect herbivores suffer population reductions in a world abundant with carbon dioxide, many predators will have less prey. Some predatory insects, for example, feast on other insect pests that damage certain crops. And a variety of other ecological interactions could be reconfigured. Researchers have discovered that plant development and flowering times are often altered unpredictably by elevated CO_2. Shifting

flowering times might, in turn, disrupt pollination as an asynchrony ensues between peak flowering times and peak pollinator abundance.

Although ecosystem-wide changes resulting from a CO_2-rich environment could be negative, there appears to be at least one exception. The association between plants and root symbionts, such as nitrogen-fixing bacteria and mycorrhizal fungi, may be enhanced in the future. More carbohydrates may be produced in the presence of higher concentrations of CO_2, and these can be used to promote the growth of root symbionts. A greater association with root symbionts could enable plants to expand their ranges into habitats formerly too infertile for growth.

Yet other factors related to the atmospheric change could undercut this benefit. Work by Margaret B. Davis of the University of Minnesota, Thompson Webb of Brown University and several European researchers has shown that when the massive glacial ice sheets receded and average global temperatures rose, most trees migrated slowly northward. Similar climate changes induced by anthropogenic sources, however, would probably occur 10 to 100 times faster than the postglacial warming did.

Furthermore, modern habitats are interrupted by man-made barriers to migration such as roads and buildings. Thus, despite the potentiating effect of greater numbers and competence of root symbionts, many tree species might not be able to migrate rapidly enough to stay with appropriate climates. Many forests may die off and be replaced by weedy herbaceous plants.

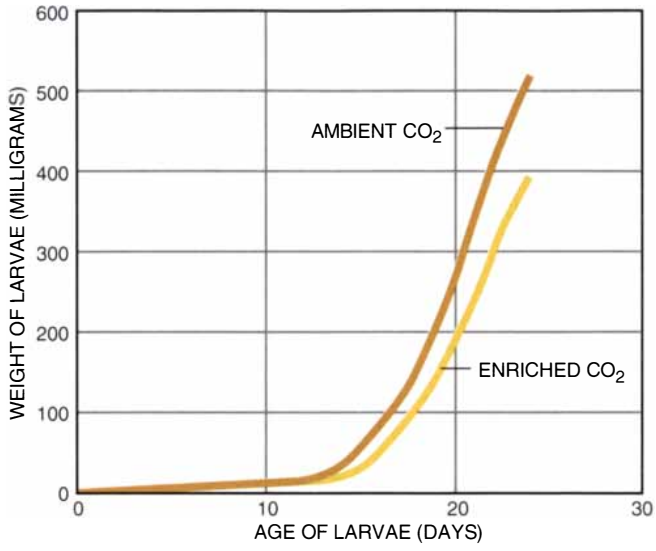
It is clear that high CO_2 levels will have wide-ranging consequences for the natural world. And it is clear that the CO_2 fertilization effect does not guarantee a lush, green future of agricultural abundance. But what about the potential for plant life to serve as a CO_2 repository? Could plant processes mitigate the future greenhouse effect by drawing more carbon dioxide out of the air than at present?

The rate and severity of potential global climatic change corresponds to the rate at which anthropogenic CO_2 accumulates in the atmosphere. Scientists such as George M. Woodwell and Richard A. Houghton of the Woods Hole Research Center estimate that burning fossil fuel contributes about five billion metric tons of CO_2 to the atmosphere annually and that deforestation contributes an additional one to two billion metric tons of carbon dioxide every year. The net annual increase of CO_2 in the atmosphere, however, is only some three billion metric tons.

Several hypotheses have been proposed to account for the missing three billion tons of carbon. Researchers first suspected that ocean processes—algal photosynthesis or direct solubility in salt water—removed the balance. The role of terrestrial vegetation in absorbing these significant amounts of CO_2 was questioned because ecological studies differed in their determination of whether the terrestrial biosphere was a net CO_2 source or a sink. If rates of terrestrial photosynthesis exceed those of terrestrial respiration, then the biosphere would be a CO_2 sink.

Recent calculations by Pieter P. Tans of the National Oceanic and Atmospheric Administration, Inez Y. Fung of The National Aeronautics and Space Administration's Goddard Institute for Space Studies and Taro Takahashi of Columbia University suggest that as much as 3.4 billion metric tons of carbon are absorbed by terrestrial ecosystems in northern temperate regions. These conclusions were drawn by comparing observed CO_2 concentrations in the atmo-

HIGH CO_2 ENVIRONMENT speeds up growth and flowering as well as senescence in some plants. The plants on the left were grown for about two months in near ambient CO_2 conditions, the equivalent of 300 parts per million. The plants on the right were grown in a high CO_2 environment of 900 parts per million. In contrast to the plants grown in a near normal atmosphere, the leaves of the tall plants in the back row (*Abutilon*) have already turned yellow in the high CO_2 environment, and the plants in the middle (*Datura*) and the front (*Phlox*) have also flowered more fully.



BUCKEYE BUTTERFLY is one of the herbivorous insects that could be adversely affected in a high CO_2 atmosphere. As shown by the graph on the right, Buckeye (*Junonia coenia*) caterpillars grow less rapidly when feeding on plantain grown in a CO_2-rich environment (*yellow*) as opposed to plantain grown in ambient CO_2 conditions (*orange*). This effect could lower future populations and reduce the food source of animals that prey on the insects.

sphere and partial pressures of the gas in the surface water of the oceans.

If rates of photosynthesis and carbon storage are enhanced under enriched CO_2 conditions, certain ecosystems may limit the increase of atmospheric CO_2 concentrations, thereby slowing the rate of potential climatic change. We are just beginning to understand how terrestrial ecosystems, especially the forests that store most of the biosphere's carbon, will change in an enriched CO_2 atmosphere. Despite our incomplete knowledge, some studies suggest that the complexity of the carbon dioxide cycle and the changes accompanying the greenhouse effect will not improve the ability of terrestrial ecosystems to absorb CO_2.

W. Dwight Billings of Duke showed by simulating greenhouse effect conditions in wet tundra grasslands that less CO_2 was absorbed. Plant growth did increase under these conditions because of warmer temperatures, increased CO_2 levels and additional nutrients freed when the depth of tundra soil increased. But as the permafrost melted, more peat (accumulated dead plant material) was exposed to decomposers. This process in turn liberated more carbon dioxide to the atmosphere. Billings estimated that if summer temperatures rose four degrees Celsius, the tundra would liberate an additional 50 percent of its CO_2—despite increased plant growth.

Indeed, in a warmer world, increased plant growth, which could absorb CO_2 from the atmosphere, would not compensate for the rapid increase in decomposition rates. This observation is particularly important because high-latitude habitats such as the tundra are expected to experience the greatest temperature increase.

Based on more than a decade of research, it is obvious that the CO_2-rich atmosphere of our future will have direct and dramatic effects on the composition and operation of ecosystems. According to the best scientific evidence, we see no reason to be sanguine about the response of these habitats to our changing environment. Such an atmosphere will not help lessen the planet's environmental and demographic woes. This atmosphere may induce climatic modifications that could undermine the integrity of the biological systems on which all *Homo sapiens* depend.

To reduce the risk associated with increased levels of atmospheric CO_2, society must limit the rate of anthropogenic emissions. Scientists must also elucidate how human-induced global changes will affect the atmosphere, oceans and terrestrial landscapes. The Ecological Society of America, the Intergovernmental Panel on Climate Change and the International Geosphere-Biosphere Program have provided a research template for these investigations.

The ecological aspect of this research must include an accurate assessment of how a CO_2-rich atmosphere will alter community structure and ecosystem productivity. Furthermore, we must study how plant communities, herbivores and pollinators respond to the combination of higher levels of CO_2 and elevated temperatures, acid rain and increasing concentrations of pollutants. These research efforts will help anticipate any insidious synergistic surprises that may emerge as our atmosphere transforms.

If we hope to formulate effective social and economic policies for adapting to environmental changes, we must better understand how man-made and natural ecosystems will be transformed by increased levels of atmospheric CO_2. Reveries about future fertile, moist habitats—the presumed greening of planet Earth—should not obscure the scientific realities of life inside our CO_2-rich and, perhaps warming, atmosphere.

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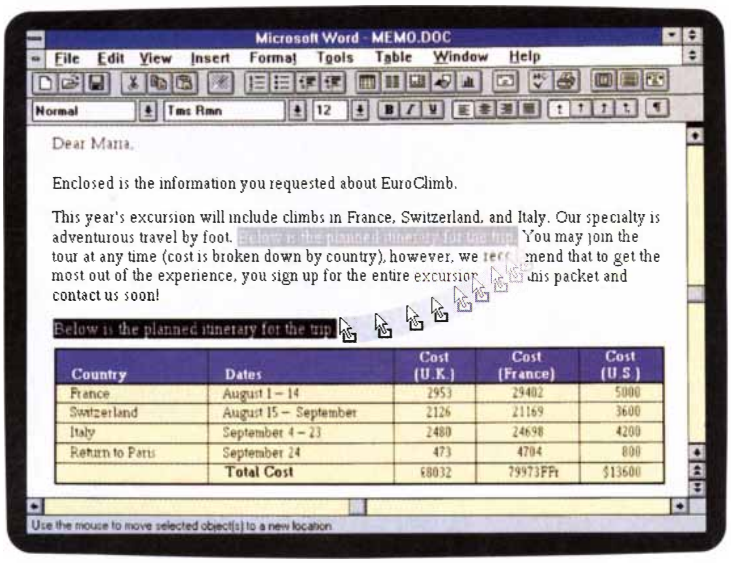

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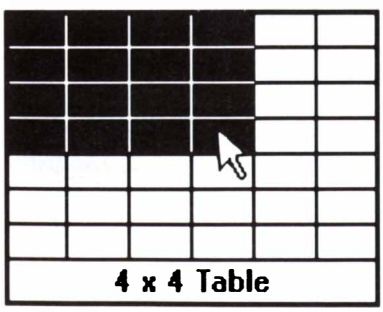

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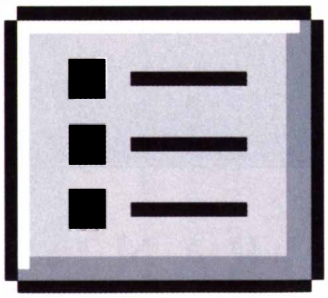

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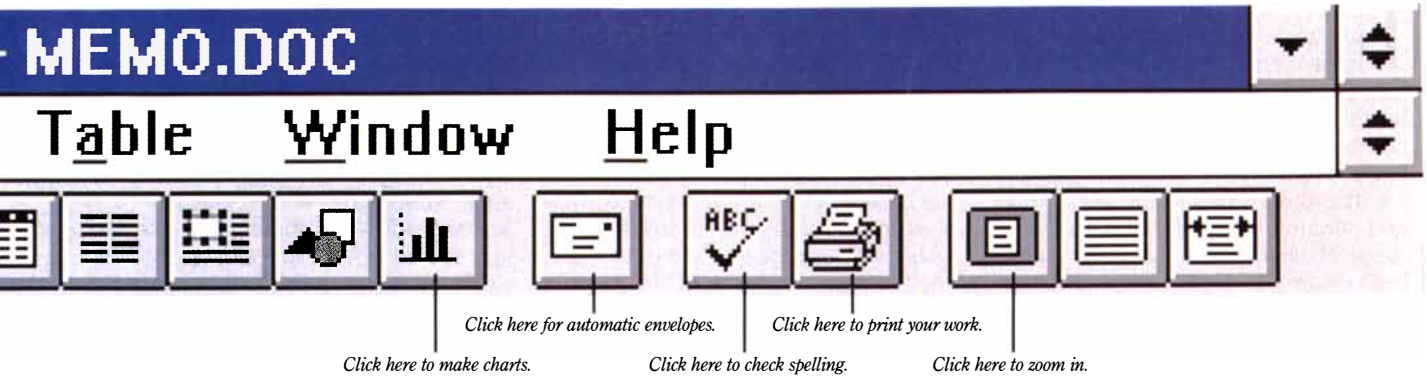

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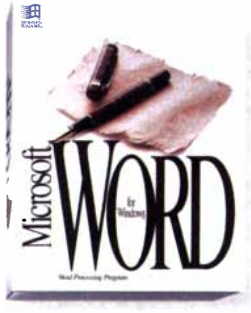

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Quantum Chaos

Does chaos lurk in the smooth, wavelike quantum world? Recent work shows that the answer is yes—symptoms of chaos enter even into the wave patterns associated with atomic energy levels

by Martin C. Gutzwiller

In 1917 Albert Einstein wrote a paper that was completely ignored for 40 years. In it he raised a question that physicists have only recently begun asking themselves: What would classical chaos, which lurks everywhere in our world, do to quantum mechanics, the theory describing the atomic and subatomic worlds? The effects of classical chaos, of course, have long been observed—Kepler knew about the irregular motion of the moon around the earth, and Newton complained bitterly about the phenomenon. At the end of the 19th century, the American astronomer George William Hill demonstrated that the irregularity is the result entirely of the gravitational pull of the sun. Shortly thereafter, the great French mathematician-astronomer-physicist Henri Poincaré surmised that the moon's motion is only a mild case of a congenital disease affecting nearly everything. In the long run, Poincaré realized, most dynamic systems show no discernible regularity or repetitive pattern. The behavior of even a simple system can depend so sensitively on its initial conditions that the final outcome is uncertain [see "The Amateur Scientist," page 144].

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At about the time of Poincaré's seminal work on classical chaos, Max Planck started another revolution, which would lead to the modern theory of quantum mechanics. The simple systems that Newton had studied were investigated again, but this time on the atomic scale. The quantum analogue of the humble pendulum is the laser; the flying cannonballs of the atomic world consist of beams of protons or electrons, and the rotating wheel is the spinning electron (the basis of magnetic tapes). Even the solar system itself is mirrored in each of the atoms found in the periodic table of the elements.

Perhaps the single most outstanding feature of the quantum world is its smooth and wavelike nature. This feature leads to the question of how chaos makes itself felt when moving from the classical world to the quantum world. How can the extremely irregular character of classical chaos be reconciled with the smooth and wavelike nature of phenomena on the atomic scale? Does chaos exist in the quantum world?

Preliminary work seems to show that it does. Chaos is found in the distribution of energy levels of certain atomic systems; it even appears to sneak into the wave patterns associated with those levels. Chaos is also found when electrons scatter from small molecules. I must emphasize, however, that the term "quantum chaos" serves more to describe a conundrum than to define a well-posed problem.

Considering the following interpretation of the bigger picture may be helpful in coming to grips with quantum chaos. All our theoretical discussions of mechanics can be somewhat artificially divided into three compartments [*see illustration on page 80*]—although nature recognizes none of these divisions.

Elementary classical mechanics falls in the first compartment. This box contains all the nice, clean systems exhibiting simple and regular behavior, and so I shall call it R, for regular. Also contained in R is an elaborate mathematical tool called perturbation theory, which is used to calculate the effects of small interactions and extraneous disturbances, such as the influence of the sun on the moon's motion around the earth. With the help of perturbation theory, a large part of physics is understood nowadays as making relatively mild modifications of regular systems. Reality, though, is much more complicated; chaotic systems lie outside the range of perturbation theory, and they constitute the second compartment.

Since the first detailed analyses of the systems of the second compartment were done by Poincaré, I shall name this box P in his honor. It is stuffed with the chaotic dynamic systems that are the bread and butter of science [see "Chaos," by James P. Crutchfield, J. Doyne Farmer, Norman H. Packard and Robert S. Shaw; SCIENTIFIC AMERICAN, December 1986]. Among these systems are all the fundamental problems of mechanics, starting with three, rather than only two, bodies interacting with one another, such as the earth, moon and sun, or the three atoms in the water molecule, or the three quarks in the proton.

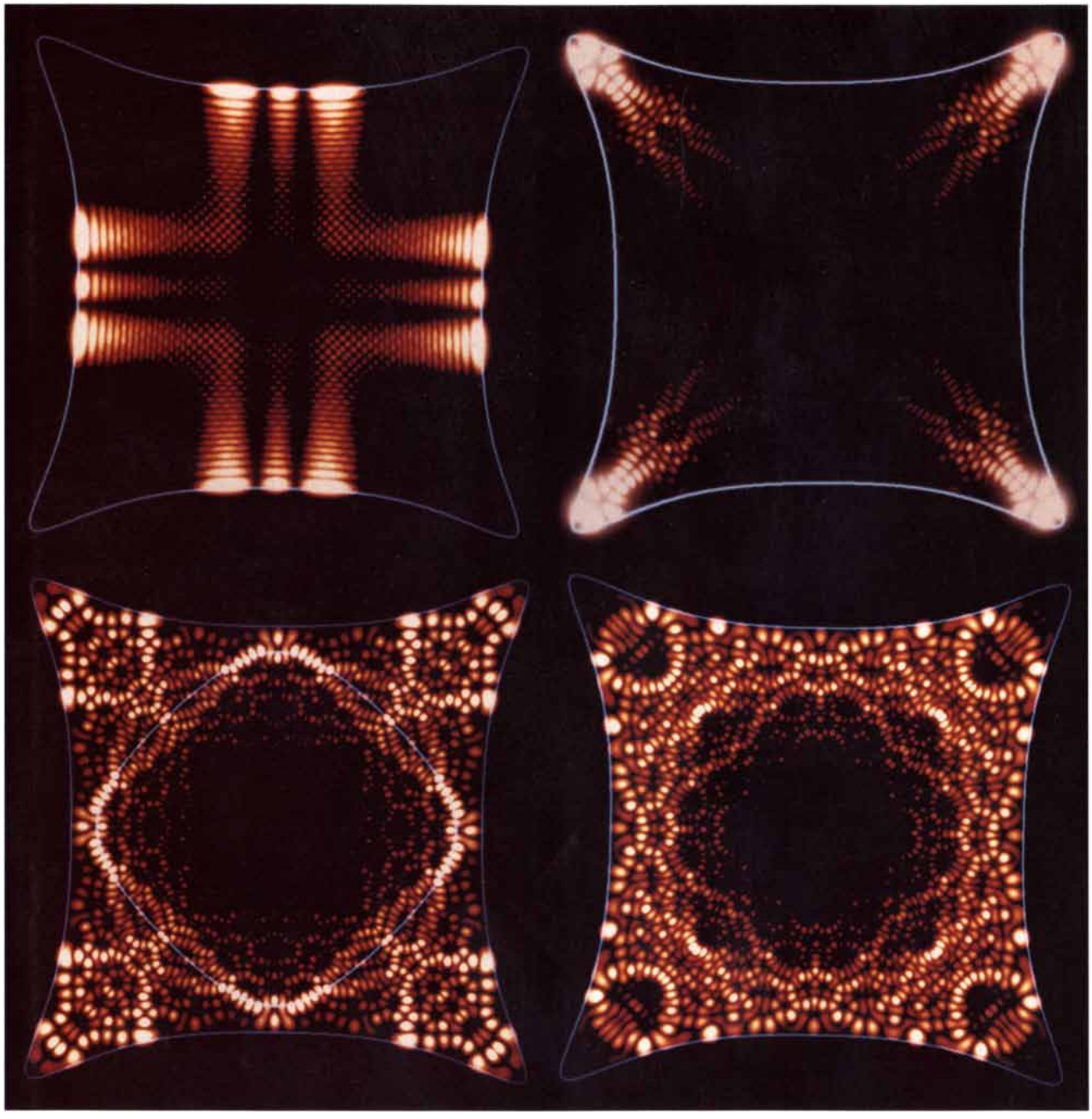
Quantum mechanics, as it has been practiced for about 90 years, belongs in the third compartment, called Q. After the pioneering work of Planck, Einstein and Niels Bohr, quantum mechanics was given its definitive form in four short years, starting in 1924. The seminal work of Louis de Broglie, Werner Heisenberg, Erwin Schrödinger, Max Born, Wolfgang Pauli and Paul Dirac has stood the test of the laboratory without the slightest lapse. Miraculously, it provides physics with a mathematical framework that, according to Dirac, has yielded a deep understanding of "most of physics and all of chemistry." Nevertheless, even though most

physicists and chemists have learned how to solve special problems in quantum mechanics, they have yet to come to terms with the incredible subtleties of the field. These subtleties are quite separate from the difficult, conceptual issues having to do with the interpretation of quantum mechanics.

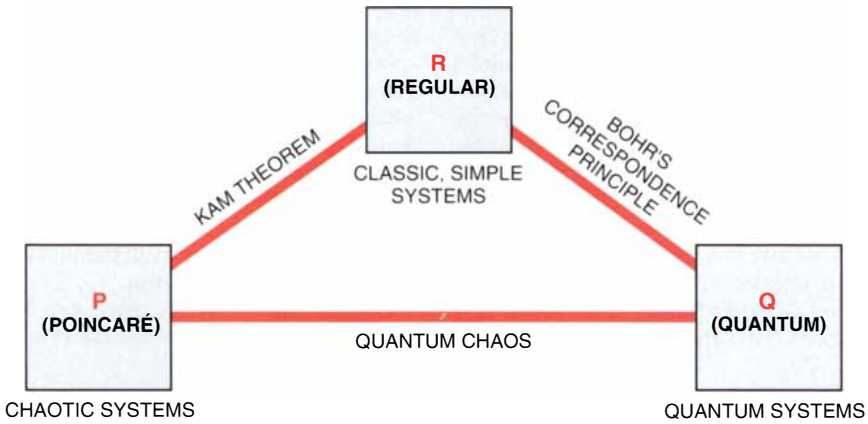
The three boxes R (classic, simple systems), P (classic chaotic systems) and Q (quantum systems) are linked by several connections. The connection between R and Q is known as Bohr's correspondence principle. The correspondence principle claims, quite reasonably, that classical mechanics must be contained in quantum mechanics in the limit where objects become much larger than the size of atoms. The main connection between R and P is the Kolmogorov-Arnold-Moser (KAM) theorem. The KAM theorem provides a powerful tool for calculating how much of the structure of a regular system survives when a small perturbation is introduced, and the theorem can thus identify perturbations that will cause a regular system to undergo chaotic behavior.

Quantum chaos is concerned with establishing the relation between boxes P (chaotic systems) and Q (quantum systems). In establishing this relation, it is useful to introduce a concept called phase space. Quite amazingly, this concept, which is now so widely exploited by experts in the field of dynamic systems, dates back to Newton.

The notion of phase space can be found in Newton's *Mathematical Princi-*



STATIONARY STATES, or wave patterns, associated with the energy levels of a Rydberg atom (a highly excited hydrogen atom) in a strong magnetic field can exhibit chaotic qualities. The states shown in the top two images seem regular; the bottom two are chaotic. At the bottom left, the state lies mostly along a periodic orbit; at the bottom right, it does not and is difficult to interpret, except for the four mirror symmetries with respect to the vertical, horizontal and two diagonal lines.



MECHANICS is traditionally (and artificially) divided into the three compartments depicted here, which are linked together by several connections. Quantum chaos is concerned with establishing the relation between boxes P and Q.

ples of Natural Philosophy, published in 1687. In the second definition of the first chapter, entitled "Definitions," Newton states (as translated from the original Latin in 1729): "The quantity of motion is the measure of the same, arising from the velocity and quantity of matter conjointly." In modern English, this means that for every object there is a quantity, called momentum, which is the product of the mass and velocity of the object.

Newton gives his laws of motion in the second chapter, entitled "Axioms, or Laws of Motion." The second law says that the change of motion is proportional to the motive force impressed. Newton relates the force to the change of momentum (not to the acceleration, as most textbooks do).

Momentum is actually one of two quantities that, taken together, yield the complete information about a dynamic system at any instant. The other quantity is simply position, which determines the strength and direction of the force. Newton's insight into the dual nature of momentum and position was put on firmer ground some 150 years later by two mathematicians, William Rowan Hamilton and Karl Gustav Jacob Jacobi. The pairing of momentum and position is no longer viewed in the good old Euclidean space of three dimensions; instead it is viewed in phase space, which has six dimensions, three dimensions for position and three for momentum.

The introduction of phase space was a wonderful step from a mathematical point of view, but it represents a serious setback from the standpoint of human intuition. Who can visualize six dimensions? In some cases, fortunately, the phase space can be reduced to three or, even better, two dimensions.

Such a reduction is possible in examining the behavior of a hydrogen atom in a strong magnetic field. The hydrogen atom has long been a highly desirable system because of its simplicity: a lone electron moves around a lone proton. And yet the classical motion of the electron becomes chaotic when the magnetic field is turned on. How can we claim to understand physics if we cannot explain this basic problem?

Under normal conditions, the electron of a hydrogen atom is tightly bound to the proton. The behavior of the atom is governed by quantum mechanics. The atom is not free to take on any arbitrary energy; it can take on only discrete, or quantized, energies. At low energies, the allowed values are spread relatively far apart. As the energy of the atom is increased, the atom grows bigger, because the electron moves farther from the proton, and the allowed energies get closer together. At high enough energies (but not too high, or the atom will be stripped of its electron!), the allowed energies get very close together into what is effectively a continuum, and it now becomes fair to apply the rules of classical mechanics.

Such a highly excited atom is called a Rydberg atom [see "Highly Excited Atoms," by Daniel Kleppner, Michael G. Littman and Myron L. Zimmerman; SCIENTIFIC AMERICAN, May 1981]. Rydberg atoms inhabit the middle ground between the quantum and the classical worlds, and they are therefore ideal candidates for exploring Bohr's correspondence principle, which connects boxes Q (quantum phenomena) and R (classic phenomena). If a Rydberg atom could be made to exhibit chaotic behavior in the classical sense, it might provide a clue as to the nature of quantum chaos and thereby shed light on the middle ground between boxes Q and P (chaotic phenomena).

A Rydberg atom exhibits chaotic behavior in a strong magnetic field, but to see this behavior we must reduce the dimension of the phase space. The first step is to note that the applied magnetic field defines an axis of symmetry through the atom. The motion of the electron takes place effectively in a two-dimensional plane, and the motion around the axis can be separated out; only the distances along the axis and from the axis matter. The symmetry of motion reduces the dimension of the phase space from six to four.

Additional help comes from the fact that no outside force does any work on the electron. As a consequence, the total energy does not change with time. By focusing attention on a particular value of the energy, one can take a three-dimensional slice—called an energy shell—out of the four-dimensional phase space. The energy shell allows one to watch the twists and turns of the electron, and one can actually see something resembling a tangled wire sculpture. The resulting picture can be simplified even further through a simple idea that occurred to Poincaré. He suggested taking a fixed two-dimensional plane (called a Poincaré section, or a surface of section) through the energy shell and watching the points at which the trajectory intersects the surface. The Poincaré section reduces the tangled wire sculpture to a sequence of points in an ordinary plane.

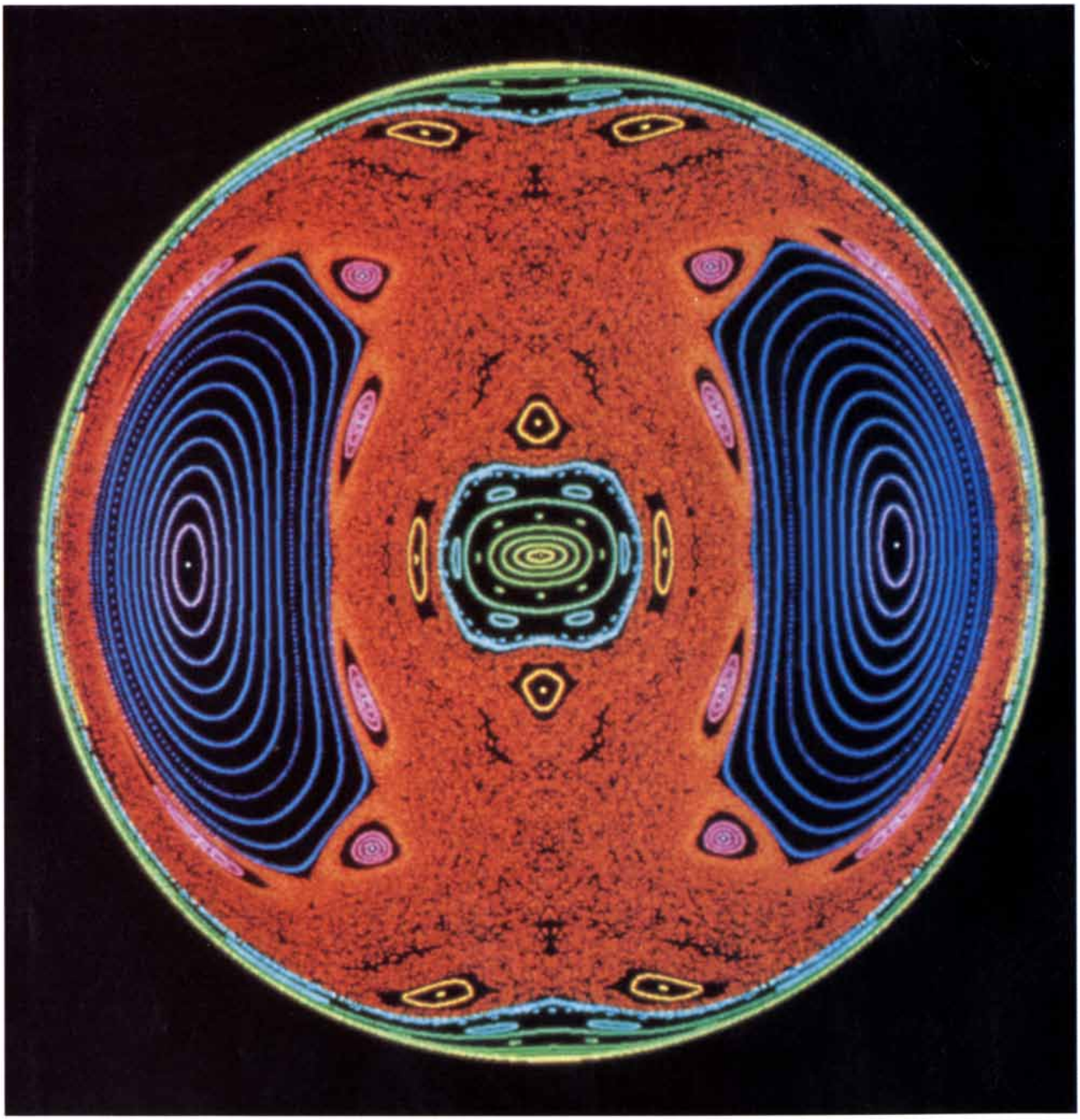
A Poincaré section for a highly excited hydrogen atom in a strong magnetic field is shown on the opposite page. The regions of the phase space where the points are badly scattered indicate chaotic behavior. Such scattering is a clear symptom of classical chaos, and it allows one to separate systems into either box P or box R.

What does the Rydberg atom reveal about the relation between boxes P and Q? I have mentioned that one of the trademarks of a quantum mechanical system is its quantized energy levels, and in fact the energy levels are the first place to look for quantum chaos. Chaos does not make itself felt at any particular energy level, however; rather its presence is seen in the spectrum, or distribution, of the levels. Perhaps somewhat paradoxically, in a nonchaotic quantum system the energy levels are distributed randomly and without correlation, whereas the energy levels of a chaotic quantum system exhibit strong correlations [*see top illustration on page 82*]. The levels of the regular system are of-

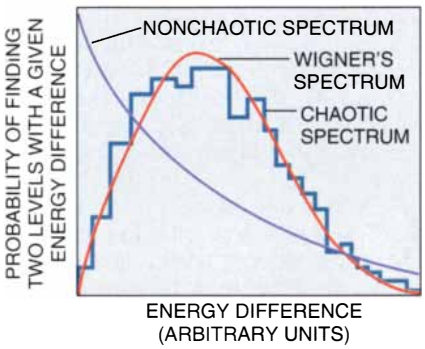
ten close to one another, because a regular system is composed of smaller subsystems that are completely decoupled. The energy levels of the chaotic system, however, almost seem to be aware of one another and try to keep a safe distance. A chaotic system cannot be decomposed; the motion along one coordinate axis is always coupled to what happens along the other axis.

The spectrum of a chaotic quantum system was first suggested by Eugene P. Wigner, another early master of quantum mechanics. Wigner observed, as had many others, that nuclear physics does not possess the safe underpinnings of atomic and molecular physics; the origin of the nuclear force is still not clearly understood. He therefore asked whether the statistical properties of nuclear spectra could be derived from the assumption that many parameters in the problem have definite, but unknown, values. This rather vague starting point allowed him to find the most probable formula for the distribution. Oriol Bohigas and Marie-Joya Giannoni of the Institute of Nuclear Physics in Orsay, France, first pointed out that Wigner's distribution happens to be exactly what is found for the spectrum of a chaotic dynamic system.

Chaos does not seem to limit itself to the distribution of quantum energy levels, however; it even appears to work its way into the wavelike nature of the quantum world. The position of the electron in the hy-



POINCARÉ SECTION OF A HYDROGEN ATOM in a strong magnetic field has regions (*orange*) where the points of the electron's trajectory scatter wildly, indicating chaotic behavior. The section is a slice out of phase space, an abstract six-dimensional space: the usual three for the position of a particle and an additional three for the particle's momentum.



ENERGY SPECTRUM, or distribution of energy levels, differs markedly between chaotic and nonchaotic quantum systems. For a nonchaotic system, such as a molecular hydrogen ion (H_2^+), the probability of finding two energy levels close to each other is quite high. In the case of a chaotic system such as a Rydberg atom in a strong magnetic field, the probability is low. The chaotic spectrum closely matches the typical nuclear spectrum derived many years ago by Eugene P. Wigner.

drogen atom is described by a wave pattern. The electron cannot be pinpointed in space; it is a cloudlike smear hovering near the proton. Associated with each allowed energy level is a stationary state, which is a wave pattern that does not change with time. A stationary state corresponds quite closely to the vibrational pattern of a membrane that is stretched over a rigid frame, such as a drum.

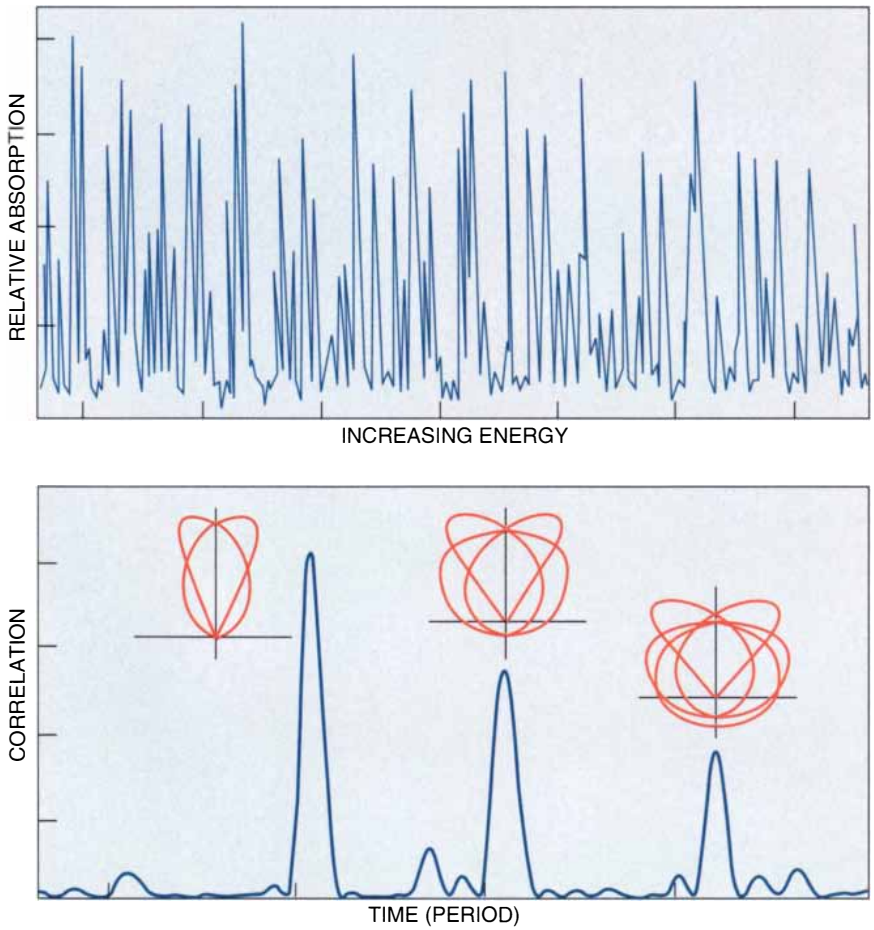
The stationary states of a chaotic system have surprisingly interesting structure, as demonstrated in the early 1980s by Eric Heller of the University of Washington. He and his students calculated a series of stationary states for a two-dimensional cavity in the shape of a stadium. The corresponding problem in classical mechanics was known to be chaotic, for a typical trajectory quickly covers most of the available ground quite evenly. Such behavior suggests that the stationary states might also look random, as if they had been designed without rhyme or reason. In contrast, Heller discovered that most stationary states are concentrated around narrow channels that form simple shapes inside the stadium, and he called these channels "scars" [*see illustration on opposite page*]. Similar structure can also be found in the stationary states of a hydrogen atom in a strong magnetic field [*see illustration on page 79*]. The smoothness of the quantum wave forms is preserved from point to point, but when one steps back to view the whole picture, the fingerprint of chaos emerges.

It is possible to connect the chaotic signature of the energy spectrum to ordinary classical mechanics. A clue to the prescription is provided in Einstein's 1917 paper. He examined the phase space of a regular system from box R and described it geometrically as filled with surfaces in the shape of a donut; the motion of the system corresponds to the trajectory of a point over the surface of a particular donut. The trajectory winds its way around the surface of the donut in a regular manner, but it does not necessarily close on itself.

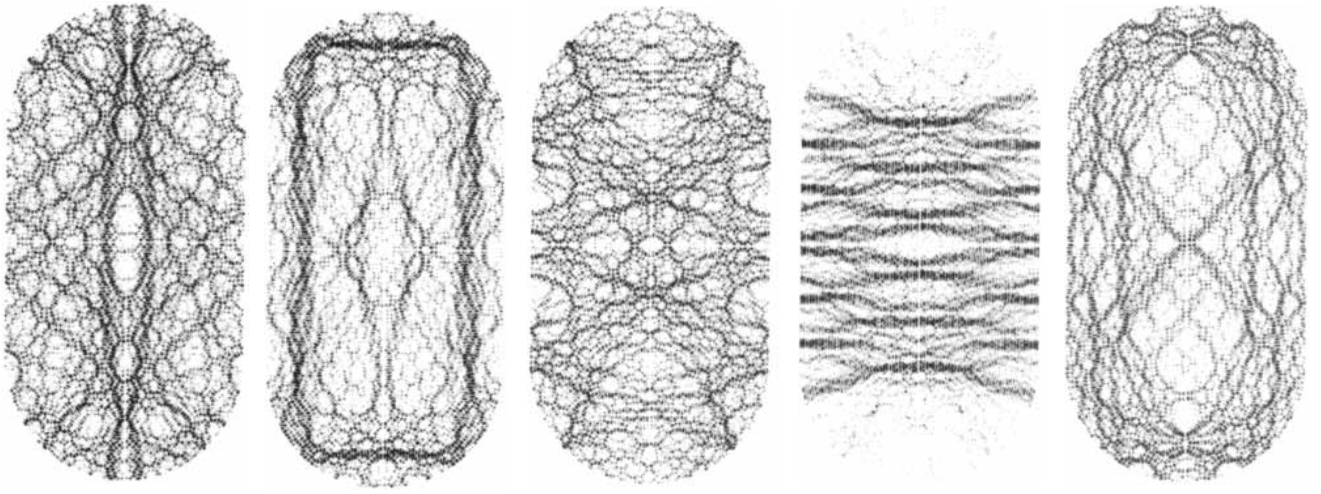
In Einstein's picture, the application of Bohr's correspondence principle to find the energy levels of the analogous quantum mechanical system is simple. The only trajectories that can occur in nature are those in which the cross section of the donut encloses an area equal to an integral multiple of Planck's constant, h (2π times the fundamental quantum of angular momentum, having the units of momentum multiplied by length). It turns out that the integral multiple is precisely the number that specifies the corresponding energy level in the quantum system.

Unfortunately, as Einstein clearly saw, his method cannot be applied if the system is chaotic, for the trajectory does not lie on a donut, and there is no natural area to enclose an integral multiple of Planck's constant. A new approach must be sought to explain the distribution of quantum mechanical energy levels in terms of the chaotic orbits of classical mechanics.

Which features of the trajectory of classical mechanics help us to understand quantum chaos? Hill's discussion of the moon's irregular orbit because of the presence of the sun provides a clue. His work represented the first instance where a particular periodic orbit is found to be at the bottom of a difficult mechanical problem. (A periodic orbit is like a closed track on which the system is made to run; there are many of them, although they are isolated and unstable.) Inspiration can also be drawn from Poincaré, who emphasized the



ABSORPTION OF LIGHT by a hydrogen atom in a strong magnetic field appears to vary randomly as a function of energy (*top*), but when the data are analyzed according to the mathematical procedure called Fourier analysis, a distinct pattern emerges (*bottom*). Each peak in the bottom panel has associated with it a specific classical periodic orbit (*red figures next to peaks*).



PARTICLE IN A STADIUM-SHAPED BOX has chaotic stationary states with associated wave patterns that look less random than one might expect. Most of the states are concentrated around narrow channels that form simple shapes, called scars.

general importance of periodic orbits. In the beginning of his three-volume work, *The New Methods of Celestial Mechanics,* which appeared in 1892, he expresses the belief that periodic orbits "offer the only opening through which we might penetrate into the fortress that has the reputation of being impregnable." Phase space for a chaotic system can be organized, at least partially, around periodic orbits, even though they are sometimes quite difficult to find.

In 1970 I discovered a very general way to extract information about the quantum mechanical spectrum from a complete enumeration of the classical periodic orbits. The mathematics of the approach is too difficult to delve into here, but the main result of the method is a relatively simple expression called a trace formula. The approach has now been used by a number of investigators, including Michael V. Berry of the University of Bristol, who has used the formula to derive the statistical properties of the spectrum.

I have applied the trace formula to compute the lowest two dozen energy levels for an electron in a semiconductor lattice, near one of the carefully controlled impurities. (The semiconductor, of course, is the basis of the marvelous devices on which modern life depends; because of its impurities, the electrical conductivity of the material is halfway between that of an insulator, such as plastic, and that of a conductor, such as copper.) The trajectory of the electron can be uniquely characterized by a string of symbols, which has a straightforward interpretation. The string is produced by defining an axis through the semiconductor and simply noting when the trajectory crosses the axis. A crossing to the "positive" side of the axis gets the symbol +, and a crossing to the "negative" side gets the symbol –.

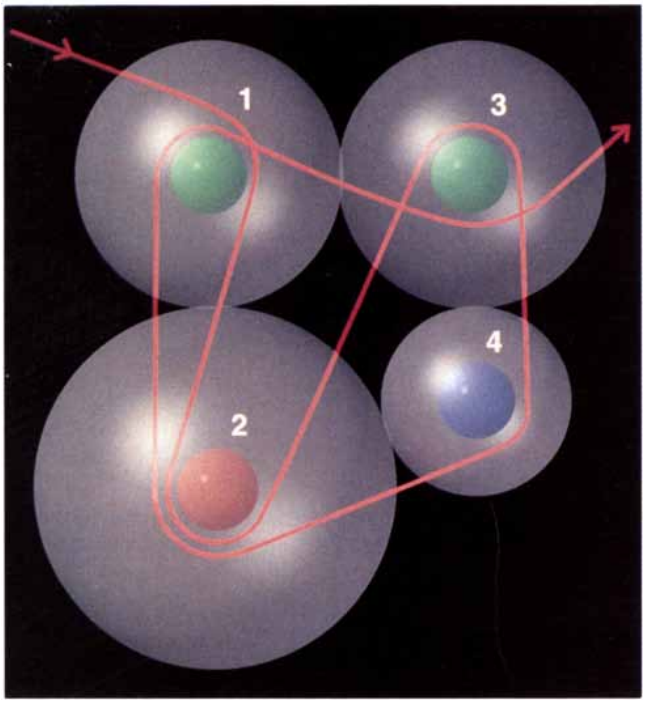
A trajectory then looks exactly like the record of a coin toss. Even if the past is known in all detail—even if all the crossings have been recorded—the future is still wide open. The sequence of crossings can be chosen arbitrarily. Now, a periodic orbit consists of a binary sequence that repeats itself; the simplest such sequence is (+ –), the next is (+ + –), and so on. (Two crossings in a row having the same sign indicate that the electron has been trapped temporarily.) All periodic orbits are thereby enumerated, and it is possible to calculate an approximate spectrum with the help of the trace formula. In other words, the quantum mechanical energy levels are obtained in an approximation that relies on quantities from classical mechanics only.

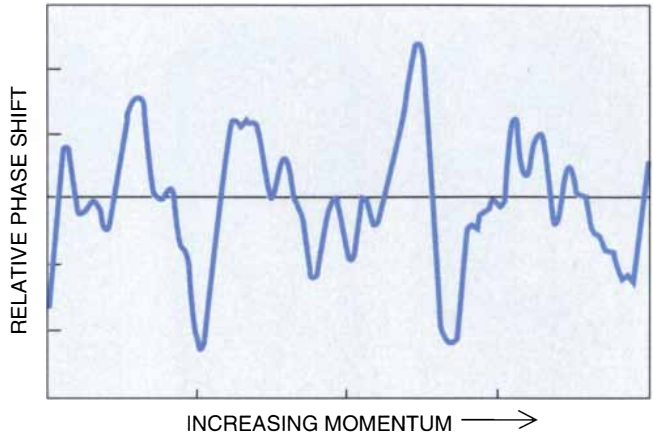
The classical periodic orbits and the quantum mechanical spectrum are closely bound together through the mathematical process called Fourier analysis [see "The Fourier Transform," by Ronald N. Bracewell; SCIENTIFIC AMERICAN, June 1989]. The hidden regularities in one set, and the frequency with which they show up, are exactly given by the other set. This idea was used by John B. Delos of the College of William and Mary and Dieter Wintgen of the Max Planck Institute for Nuclear Physics in Heidelberg to interpret the spectrum of the hydrogen atom in a strong magnetic field.

Experimental work on such spectra has been done by Karl H. Welge and his colleagues at the University of Bielefeld, who have excited hydrogen atoms nearly to the point of ionization, where the electron tears itself free of the proton. The energies at which the atoms absorb radiation appear to be quite random [*see upper part of bottom illustration on opposite page*], but a Fourier analysis converts the jumble of peaks into a set of well-separated peaks [*see lower part of bottom illustration on opposite page*]. The important feature here is that each of the well-separated peaks corresponds precisely to one of several standard classical periodic orbits. Poincaré's insistence on the importance of periodic orbits now takes on a new meaning. Not only does the classical organization of phase space depend critically on the classical periodic orbits, but so too does the understanding of a chaotic quantum spectrum.

So far I have talked only about quantum systems in which an electron is trapped or spatially confined. Chaotic effects are also present in atomic systems where an electron can roam freely, as it does when it is scattered from the atoms in a molecule. Here energy is no longer quantized, and the electron can take on any value, but the effectiveness of the scattering depends on the energy.

Chaos shows up in quantum scattering as variations in the amount of time the electron is temporarily caught inside the molecule during the scattering process. For simplicity, the problem can be examined in two dimensions. To the electron, a molecule consisting of four atoms looks like a small maze. When the electron approaches one of the atoms, it has two choices: it can turn left or right. Each possible trajectory of the electron through the molecule can be recorded as a series of left and right turns around the atoms, until the particle finally emerges. All of the trajectories are unstable: even a





TRAJECTORY OF AN ELECTRON through a molecule during scattering can be recorded as a series of left and right turns around the atoms making up the molecule (*left*). Chaotic variation (*above*) characterizes the time it takes for a scattered electron of known momentum to reach a fixed monitoring station. Arrival time varies as a function of the electron's momentum. The variation is smooth when changes in the momentum are small but exhibits a complex chaotic pattern when the changes are large. The quantity shown on the vertical axis, the phase shift, is a measure of the time delay.

minute change in the energy or the initial direction of the approach will cause a large change in the direction in which the electron eventually leaves the molecule.

The chaos in the scattering process comes from the fact that the number of possible trajectories increases rapidly with path length. Only an interpretation from the quantum mechanical point of view gives reasonable results; a purely classical calculation yields nonsensical results. In quantum mechanics, each classical trajectory of the electron is used to define a little wavelet that winds its way through the molecule. The quantum mechanical result follows from simply adding up all such wavelets.

Recently I have done a calculation of the scattering process for a special case in which the sum of the wavelets is exact. An electron of known momentum hits a molecule and emerges with the same momentum. The arrival time for the electron to reach a fixed monitoring station varies as a function of the momentum, and the way in which it varies is what is so fascinating about this problem. The arrival time fluctuates smoothly over small changes in the momentum, but over large changes a chaotic imprint emerges, which never settles down to any simple pattern [*see right part of illustration above*].

A particularly tantalizing aspect of the chaotic scattering process is that it may connect the mysteries of quantum chaos with the mysteries of number theory. The calculation of the time delay leads straight into what is probably the most enigmatic object in mathematics, Riemann's zeta function. Actually, it was first employed by Leonhard Euler in the middle of the 18th century to show the existence of an infinite number of prime numbers (integers that cannot be divided by any smaller integer other than one). About a century later Bernhard Riemann, one of the founders of modern mathematics, employed the function to delve into the distribution of the primes. In his only paper on the subject, he called the function by the Greek letter zeta.

The zeta function is a function of two variables, x and y (which exist in the complex plane). To understand the distribution of prime numbers, Riemann needed to know when the zeta function has the value of zero. Without giving a valid argument, he stated that it is zero only when x is set equal to $\frac{1}{2}$. Vast calculations have shown that he was right without exception for the first billion zeros, but no mathematician has come even close to providing a proof. If Riemann's conjecture is correct, all kinds of interesting properties of prime numbers could be proved.

The values of y for which the zeta function is zero form a set of numbers that is much like the spectrum of energies of an atom. Just as one can study the distribution of energy levels in the spectrum, so can one study the distribution of zeros for the zeta function. Here the prime numbers play the same role as the classical closed orbits of the hydrogen atom in a magnetic field: the primes indicate some of the hidden correlations among the zeros of the zeta function.

In the scattering problem the zeros of the zeta function give the values of the momentum where the time delay changes strongly. The chaos of the Riemann zeta function is particularly apparent in a theorem that has only recently been proved: the zeta function fits locally any smooth function. The theorem suggests that the function may describe all the chaotic behavior a quantum system can exhibit. If the mathematics of quantum mechanics could be handled more skillfully, many examples of locally smooth, yet globally chaotic, phenomena might be found.

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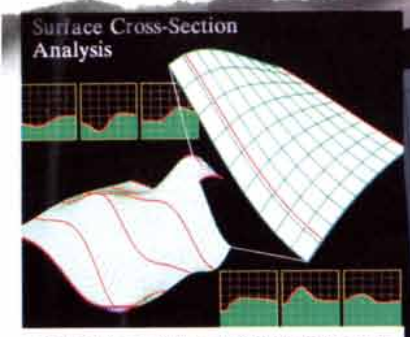

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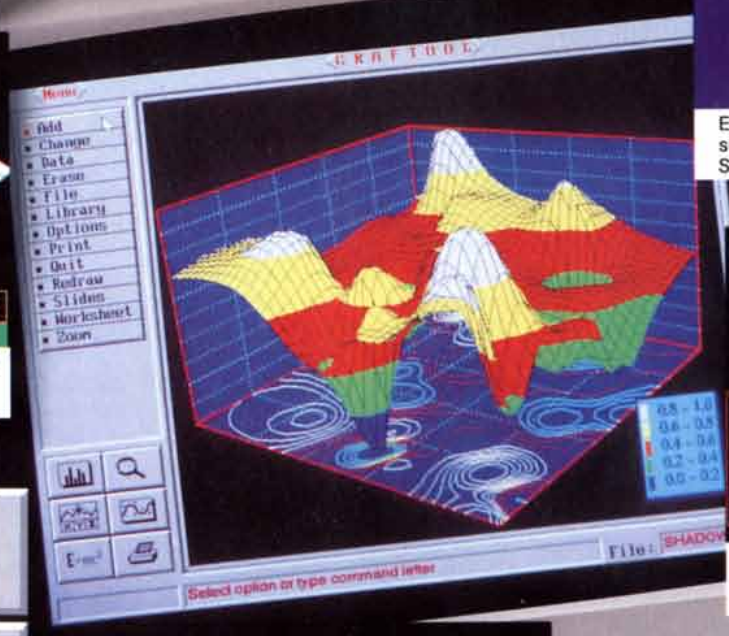

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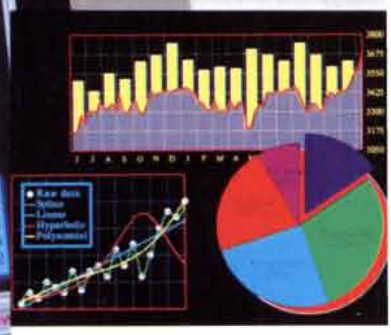

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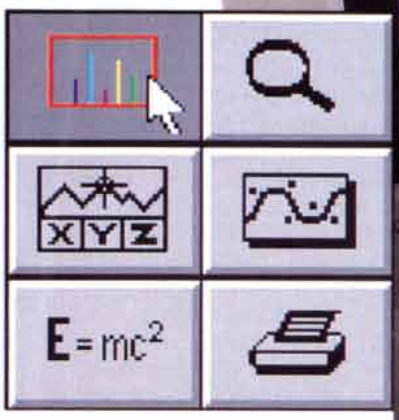

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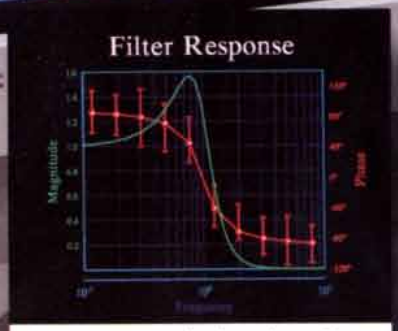

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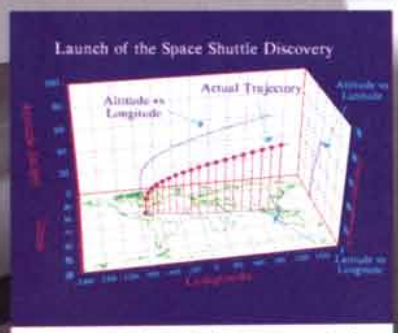

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How Cells Absorb Glucose

Glucose, a crucial nutrient, must enter cells with the aid of a special transporter. Recent research elucidates the structure and function of the transporter and how insulin regulates it

by Gustav E. Lienhard, Jan W. Slot, David E. James and Mike M. Mueckler

Glucose is the common currency of metabolism. Absorbed in the intestine or produced by the liver, the sugar travels in the blood to all the tissues of the body. There it serves as a source of energy and as a primordial precursor for other carbon-containing compounds. Yet the passage of glucose into a cell is quite intricate. It must be ferried inside by a special protein embedded in the membrane of the cell. Over the past decade, studies in several laboratories, including our own, have greatly clarified the structure of the protein and the remarkable way in which it works. Five molecular forms of the transporter have been discovered so far, each adapted to the metabolic needs of the tissue in which it is found.

The events that these vital molecules mediate begin when one eats carbohydrates. The intestine digests the carbohydrates into glucose, which it transfers to the bloodstream. The resulting rise in blood glucose stimulates the beta cells of the pancreas to release insulin. Insulin clears glucose from the blood in two ways: it prevents the liver from releasing additional glucose, and it causes muscle and fat cells to absorb more of the sugar. Muscle cells convert the glucose into glycogen, a polymerized carbohydrate that can be quickly reconverted into glucose. Fat cells convert glucose into droplets of fat for long-term storage. As blood glucose levels drop, the beta cells stop secreting insulin, and the body's metabolism returns to the basal state.

Too much insulin lowers blood sugar, producing hypoglycemia. Because this condition starves the brain, an organ that lives chiefly on glucose, it can mean death. On the other hand, when there is too little insulin—or when muscle and fat cells resist its effect—blood sugar rises, producing hyperglycemia. The high concentration of sugar molecules creates an osmotic imbalance, so the blood draws water from the tissues and the kidneys excrete the water in the urine, along with an excess of salts. Dehydration and salt loss brought on by severe hyperglycemia can lead to coma and death. Milder hyperglycemia probably contributes to such long-term complications of diabetes mellitus as heart attacks, strokes, blindness, kidney failure and gangrene of the extremities.

A lack of insulin causes insulin-dependent diabetes mellitus (IDDM), or type I diabetes. It generally develops in children or adolescents when an autoimmune reaction destroys beta cells in the pancreas [see "What Causes Diabetes?" by Mark A. Atkinson and Noel K. Maclaren; SCIENTIFIC AMERICAN, July 1990]. Non-insulin-dependent diabetes (NIDDM), or type II, usually appears later in life and is by far the more prevalent form, afflicting about 5 percent of the U.S. population who are more than 40 years old. Early in the disease some NIDDM patients do not lack insulin, and so the disease may come from an insufficient hormonal effect in muscle, fat and liver cells.

The absorption of glucose is more complex than might be supposed. A cell can survive only by preventing its interior from mixing with the watery environment outside. Such isolation is provided by the cell membrane, a double sheet of lipid molecules that repels water and those substances—such as glucose—that readily dissolve in water. (Lipids are thus said to be hydrophobic, whereas glucose is hydrophilic.) Because of this arrangement, the cell cannot absorb glucose by simple diffusion. It must instead employ a special protein: the transporter molecule.

The first glucose transporter was isolated in 1977 from human erythrocytes (red blood cells) by Michihiro Kasahara and Peter C. Hinkle of Cornell University. Eight years later a collaborative project, led by one of us (Mueckler) and Harvey F. Lodish of the Whitehead Institute for Biomedical Research, elucidated the transporter's amino acid sequence. The investigators worked backward, in this case the easiest strategy, by isolating the DNA that encodes the protein and determining the sequence of its nucleic acid bases. They then applied the genetic code to translate this sequence into a sequence of amino acids.

The protein described by this method consists of a chain of 492 amino acids that can be viewed as being organized into 25 segments. Thirteen segments are largely hydrophilic and so are likely to prefer the aqueous extracellular and intracellular environments. They alternate with 12 primarily hydrophobic segments that are likely to prefer the lipid environment of the cell membrane. This arrangement, together with some direct chemical information about those parts of the protein that face in and out of the erythrocyte, suggests that the protein weaves back and forth across the membrane 12 times [*see top illustration on page 88*].

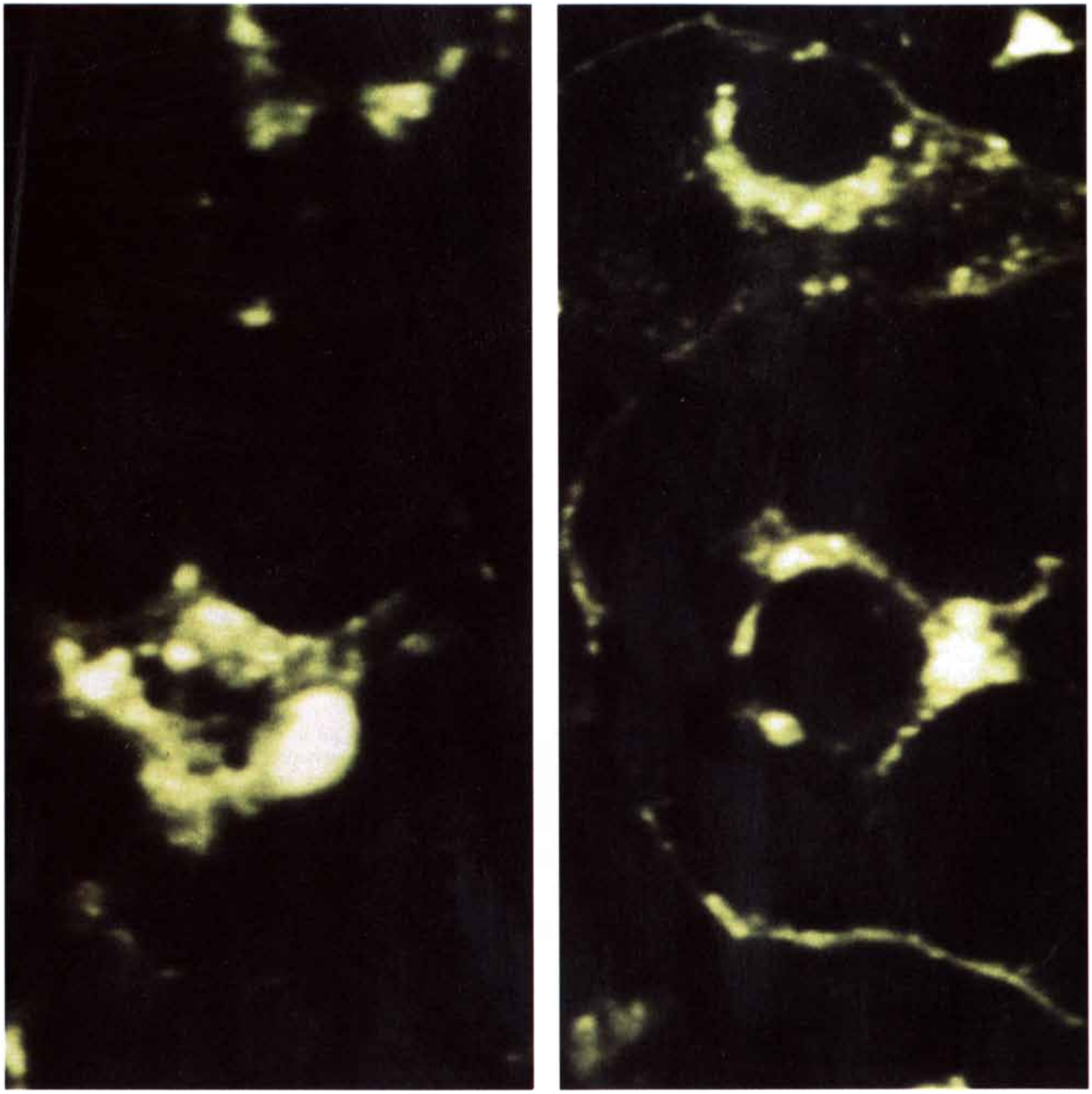
How might such a structure convey glucose into the cell? It must somehow create a pore through the membrane. The architecture of such a pore is sug-

GUSTAV E. LIENHARD, JAN W. SLOT, DAVID E. JAMES and MIKE M. MUECKLER share an interest in the regulation of glucose transport by insulin and have worked together on several projects. Lienhard has been professor of biochemistry at Dartmouth Medical School since 1975. His current research focuses on the pathways by which the insulin receptor regulates cellular processes. Slot is in the department of cell biology at the Medical School of the University of Utrecht, the Netherlands. He locates individual protein molecules in the cell by electron microscopy and uses this technique to investigate the trafficking of membrane proteins. James and Mueckler hold appointments in the department of cell biology and physiology at Washington University School of Medicine. Together they were the first to clone the complementary DNA encoding the glucose transporter GluT4, which figures prominently in this article.

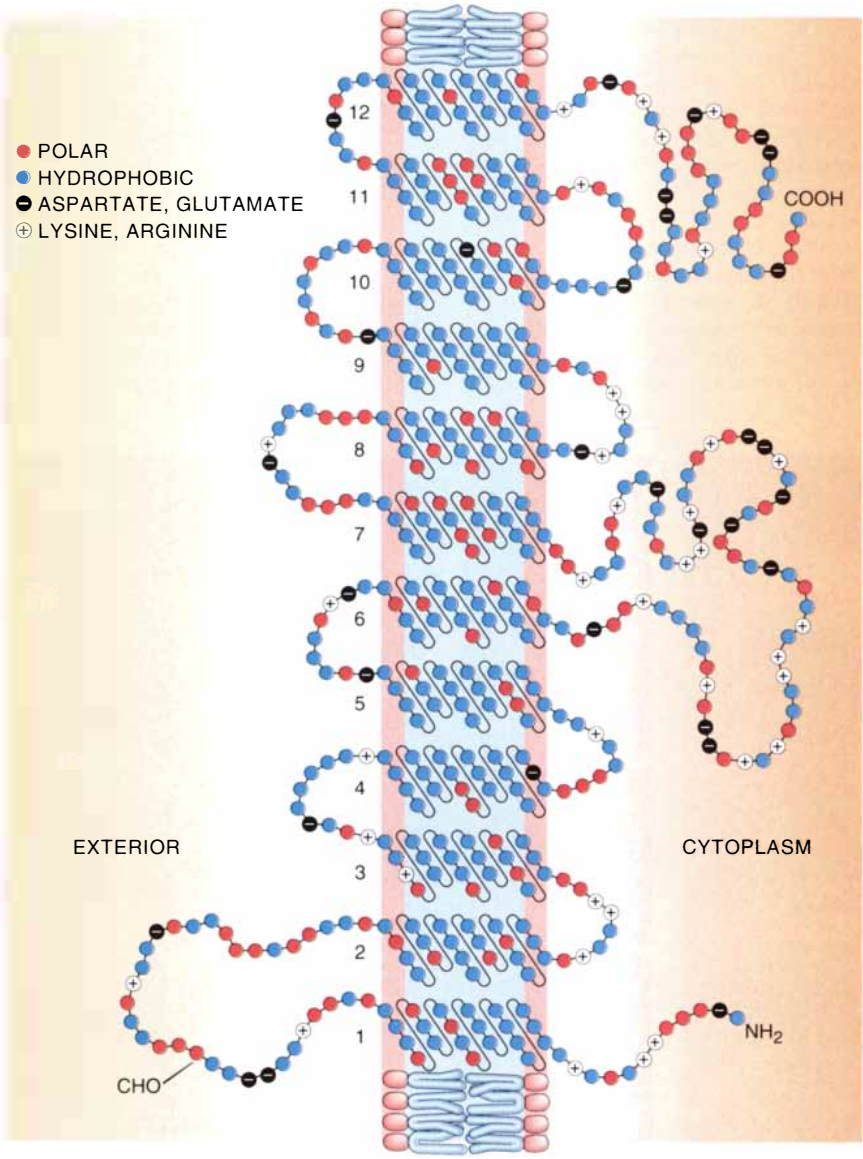
gested by the folding arrangement of the polypeptide chain and by the pattern of amino acids in the transmembrane segments. Spectroscopic evidence implies that each segment is coiled into a helix—indeed, up to 80 percent of the entire polypeptide chain appears to be helical. Because a helix takes the overall shape of a cylinder, the chemically reactive groups of the amino acids will be arrayed periodically along the surface. It turns out that in five transmembrane segments—numbers 3, 5, 7, 8 and 11—the groups are hydrophilic on one side of the cylinder and hydrophobic on the other. Bound together with their hydrophobic sides facing away from their common axis—toward the remaining transmembrane segments and the lipid environment of the membrane—the five segments would form a pore whose inner surface could bind glucose [*see bottom illustration on next page*].

We emphasize that this model for the three-dimensional structure of the glucose transporter is speculative. To determine the real structure, X-ray crystallographers will have to learn how to make the transporters into well-ordered crystals. So far, however, the lipid-loving nature of these proteins has made them resist all such efforts.

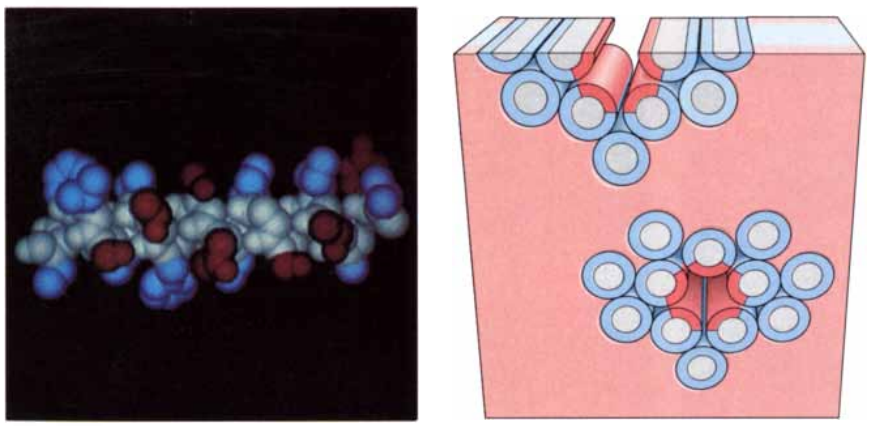
We therefore modeled the transporter in part on the examples furnished by the handful of membrane proteins that lend themselves to crystallization and have thus been imaged [see "The Structure of Proteins in Biological Membranes," by Nigel Unwin and Richard Henderson; SCIENTIFIC AMERICAN, February 1984]. One of them, called the bacterial photosynthetic reaction center,



GREENISH GLOW tracks the deployment of glucose transporters from the interior of a fat cell to its surface. The transporters, called GluT4s, were tagged with an antibody linked to a fluorescent chemical. Before exposure to insulin, they form clusters near the cell's nucleus (*left*). After exposure, some move to the surface—now defined by a halo of light (*right*).



PROPOSED STRUCTURE of the transporter's 492 amino acids is depicted as a folded chain that traverses the lipid membrane in 12 segments. Amino acids having charged groups appear as (+) or (–). Because such groups are more stable in water than in lipid, most have been located outside the membrane rather than in it.



PENTAGONAL PORE is postulated to consist of five helical segments of the transporter molecule, such as segment number 8 (*left*). If the helices were to face their lipid-loving sides (*blue*) toward the membrane and their glucose-binding sides (*red*) inward, they would create a channel that could accommodate a glucose molecule.

incorporates three separate protein chains, two crossing the membrane five times and another crossing it once. Each of the 11 transmembrane segments has a helical structure resembling the one we propose for the glucose transporter.

The detailed molecular events that bring glucose into the cell are even more complicated than our structural description suggests. The transporter is believed to manipulate glucose by holding it in weak, and therefore transient, hydrogen bonds. Such a bond stretches a hydrogen atom between an atom of nitrogen or oxygen in one compound and the unpaired electrons on an oxygen or nitrogen atom of another compound. Transmembrane segments 3, 5, 7, 8 and 11 contain many amino acids having hydroxyl (OH) and carbamido ($CONH_2$) groups that can participate in hydrogen bonding with the many hydroxyl groups on glucose. Moreover, the transporter protein takes two shapes: one binds glucose on the extracellular side of the membrane; the other binds it on the intracellular side.

Considerable experimental evidence suggests that a glucose molecule enters the cell in four steps. First, it occupies the outward-facing binding site. Second, the complex of transporter and glucose changes conformation, so that the glucose now occupies the binding site that faces into the cell. Third, the transporter releases the glucose into the cytoplasm of the cell. Fourth, the unoccupied transporter changes to the conformation in which the binding site for glucose faces outward. This final step returns the transporter to its initial shape, enabling it to transport another molecule of glucose.

The structures of the two conformations are not known, but it seems likely that in each conformation the pore is open at one end and constricted at the other and that glucose binds in the pocket at the open end. Glucose would then move as the open end closes behind it and the constricted end opens in front of it.

We thus envision the transporter as a conformational oscillator that shifts the binding pocket for glucose between opposite sides of the membrane. Kinetic studies, including several performed at Dartmouth Medical School by James R. Appleman and one of us (Lienhard), indicate that such oscillation is extraordinarily rapid. When glucose is not present, each transporter molecule in the membrane of an erythrocyte converts between the two states about 100 times per second at 20 degrees Celsius. When

glucose is bound to the transporter, the rate is even greater, about 900 times per second. Glucose speeds the oscillation by lowering the energy barrier between the two conformations.

The question arises why the glucose transporter works in such a complicated way. One can imagine simpler strategies. The transporter protein might have maintained a permanently open pore, or it might have fluctuated between such a conformation and another in which the pore is closed.

The explanation probably lies in the cell's need to maintain chemical imbalances with respect to the extracellular medium. Sodium ions, for example, are typically 10 times more concentrated outside than inside a cell. Because a glucose molecule is of comparable size, a permanent pore for glucose might allow sodium ions to leak in. Of course, a sodium ion may occasionally hitch a ride into the cell on the transporter. But such leakage would be insignificant: cells have special transmembrane channels that, when open, pass about 10 million sodium ions a second, 100,000 times faster than the glucose transporter operates.

Because each tissue has its own glucose requirements, one might suppose that each would also have a different glucose transporter. Considerable evidence for this hypothesis accumulated by the early 1980s. Transporters reacted differently to chemical inhibitors, and they were more or less efficient at transporting glucose. That is, although they all transported glucose at increasing rates as the concentration rose from zero, their rates topped out, or saturated, at different glucose concentrations. Workers characterize transport systems by the glucose concentration at which the transport rate equals half the saturation rate. The half-saturation concentration for the transporter in liver cells is high, for example, whereas that for the transporter in brain cells is low.

Proof that transporters differed came after 1985, when researchers found the DNA sequence encoding the human erythrocyte glucose transporter and used it as a probe to isolate DNA encoding transporters from other tissues. This approach has been pursued vigorously by many investigators, most notably Graeme I. Bell of the University of Chicago, Morris J. Birnbaum of Harvard Medical School, Lodish and two of us (Mueckler and James). A total of five glucose transporters have been discovered so far.

The transporters form a family whose members are broadly alike in structure and function. Each consists of a polypeptide chain of about 500 amino acids. The amino acid residues at about half the positions in the five sequences are the same or very similar. Moreover, the predicted pattern of folding for each transporter consists of 12 membrane-spanning segments.

Each glucose transporter (GluT) is numbered in the order of its discovery. The first, GluT1, is expressed in high levels in the endothelial cells that line the blood vessels and that form the barrier between brain and blood. It seems to be specialized to provide the steady flow of glucose that the brain requires. Smaller amounts of GluT1 are found in many other tissues, suggesting that it supplies all the glucose they need when their cells are in a comparatively inactive state.

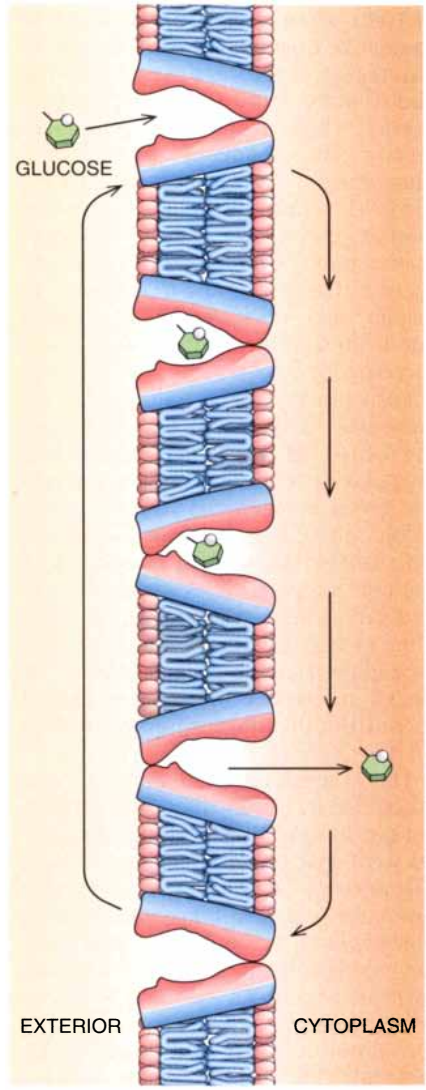
GluT2 appears in organs that release glucose into the blood, such as the intestine, the liver and the kidney, and in the beta cells of the pancreas, which secrete insulin. The high glucose concentration required for half-saturation of GluT2 means that it transports glucose in proportion to the sugar's concentration in the blood. Consequently, changes in the blood glucose level during meals or exercise are effectively transmitted to the liver and beta cells by GluT2.

GluT3 is found in the neuronal cells of the brain. Because it has a higher affinity for glucose than GluT1 does, this transporter ensures a constant movement of the sugar into these cells. One glucose transporter thus cooperates with another, assuring the flow of this vital nutrient into brain cells.

GluT4 is the major transporter in muscle and fat cells, which take up glucose in great spurts and convert it to other energy-yielding compounds. This transporter is distinguished by its extraordinary ability to move back and forth between internal reservoirs and the surface of the cell.

GluT5 is found mainly in the small intestine and kidney. Its function has not yet been described in detail.

These five GluTs all move glucose across the membrane along its concentration gradient, that is, from the higher to the lower glucose concentration. The family is distinct from another transporter that pulls glucose against this gradient. It is called a cotransporter because it couples the transport of a glucose molecule with that of a sodium ion. The energy needed to pull the glucose comes from the movement of sodium along its own gradient. The cotransporter enables cells lining the lumen of the intestine and kidney to absorb even quite small traces of glucose from food and urine, respectively. GluT2 then releases that sugar into the blood.



GLUCOSE ENTERS A CELL by binding to a transporter in an outward-facing conformation. Next the transporter reconforms, closing the pore to the outside and opening it to the cytoplasm. The glucose then dissociates. (This representation is not drawn to scale.)

The transporters also vary in the way they respond to insulin. Such specializations are what one would expect to find in tissues having markedly different metabolic needs. The most marked response is found in GluT4, an isotype first identified in 1988 by James, then at the Boston University School of Medicine, and co-worker Paul F. Pilch.

The effect of insulin on glucose transport is dramatic. We commonly work, for example, with a mouse fat cell in culture, called the 3T3-Ll adipocyte. The addition of insulin to such a culture, held at 37 degrees C, increases glucose uptake 15-fold. The peak rate is attained within 10 minutes.

How insulin works was a mystery un-

til 1980, when Lawrence Wardzala and Samuel W. Cushman of the National Institutes of Health and Kazuo Suzuki and Tetsuro Kono of Vanderbilt University School of Medicine simultaneously and independently discovered the phenomenon of transporter recruitment. They found that cells maintain a pool of extra glucose transporters (now known to be GluT4) and move some of them to the membrane in response to insulin. Later, when blood glucose drops and insulin secretion drops with it, the recruitment is reversed.

Recruitment can be followed by microscopic methods. In one technique the GluT4 in 3T3-Ll adipocytes was tagged with antibodies that fluoresce in the green wavelengths when exposed to blue light. The cells not stimulated with insulin showed many points of the emitted green light inside the cell and almost none at the cell surface. But after insulin treatment, the cell's surface glowed green: a large number of GluT4 molecules must have moved there from the interior [*see illustration on page 87*].

These results were confirmed and quantified by a study that used a different tag. In thin slices of tissue, antibodies were specifically attached to GluT4. The workers then treated the slices with tiny gold particles linked to a protein that binds to the antibodies, specifically marking the GluT4. The particles can easily be seen under the electron microscope. One of us (Slot) has used this technique to locate and count GluT4 molecules in insulin-sensitive cells. Before insulin stimulation, only 1 percent of the tagged GluT4 molecules was on the cell surface; after stimulation, the proportion had risen to about 40 percent.

How does the cell shuttle GluT4 to and from the cell membrane in response to insulin? The answers are still sketchy, and many researchers are trying to fill in the details. Because the glucose transporter is a protein embedded in the membrane both inside the cell and at the cell surface, it surely migrates as part of a membranous vesicle. Insulin probably induces intracellular vesicles containing GluT4 to move to the inner surface of the cell membrane and fuse with it.

The reverse process appears to be more complicated. In a sequence of events, the details of which are not yet understood, small vesicles containing GluT4 pinch off from the inner side of the membrane and then fuse with larger membranous sacs, called endosomes. Within the endosomes the GluT4 molecules somehow segregate into tubular extensions, which repackage themselves into vesicles. This removal of GluT4 to the cell's interior occurs all the time, but when insulin is present, the vesicles immediately re-fuse with the cell surface. Withdrawal of insulin breaks the cycle, causing vesicles to accumulate.

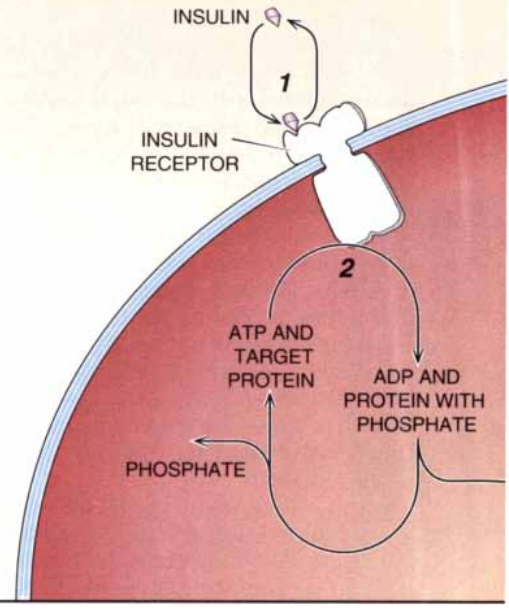
Because GluT4 is the main isotype that moves, and because it normally redeploys from the interior of the cell to the surface (and vice versa, depending on the insulin level), we suspect that it has a guidance mechanism possessed by no other isotype. The key feature of this mechanism would be the placement of GluT4 in intracellular vesicles when insulin is absent; the GluTs in the other tissues reside mainly at the cell surface whether or not insulin is present.

Such a mechanism must depend on a unique segment of amino acids in GluT4, one that might direct the transporter to vesicles by interacting with other proteins. The segment would thus function as a ticket stamped with a destination. Workers are examining this hypothesis by using molecular biological techniques to produce mutant forms of GluT4 that can be expressed in cells. If such a mutant can be found residing at the surface of a cell in the basal state, then the site where the mutation occurred will probably coincide with the ticket.

When insulin binds to the cell, it triggers a cascade of molecular events that ultimately redistributes the glucose transporters to the cell membrane. Only the beginning and the end of this cascade are known. It starts when insulin from the blood binds to a specific protein embedded in the cell membrane. The protein projects from either side of the membrane. When insulin binds to the outer projection, the receptor reconforms, enabling the inner projection to put a phosphoryl group on the amino acid tyrosine at specific locations within specific target proteins. No target protein known to be involved in signaling the recruitment of the glucose transporter has yet been found, although one obvious candidate—the glucose transporter itself—has been ruled out.

Workers are following two approaches to understand the chain of events initiated by the insulin receptor. One approach is to find the target by isolating and characterizing proteins that have tyrosines that are phosphorylated in response to insulin. A complementary approach focuses on other proteins present in the GluT4 storage vesicles. Insulin may change one of these proteins in a way that accelerates the movement of the vesicle to the cell surface or that induces it to fuse with the surface. Other proteins may also be moved by the vesicle to subserve functions that are not yet imagined. Such possibilities are suggested by the vesicular mechanism itself. Although it seems a cumbersome way to regulate the rate of glucose transport into the cell, it would be quite efficient for moving several different proteins to and from the cell surface.

An outwardly projecting part of the insulin receptor binds insulin (*1*), causing the receptor's inwardly projecting part to transfer a phosphoryl group from adenosine triphosphate (ATP) to one or more target proteins, creating

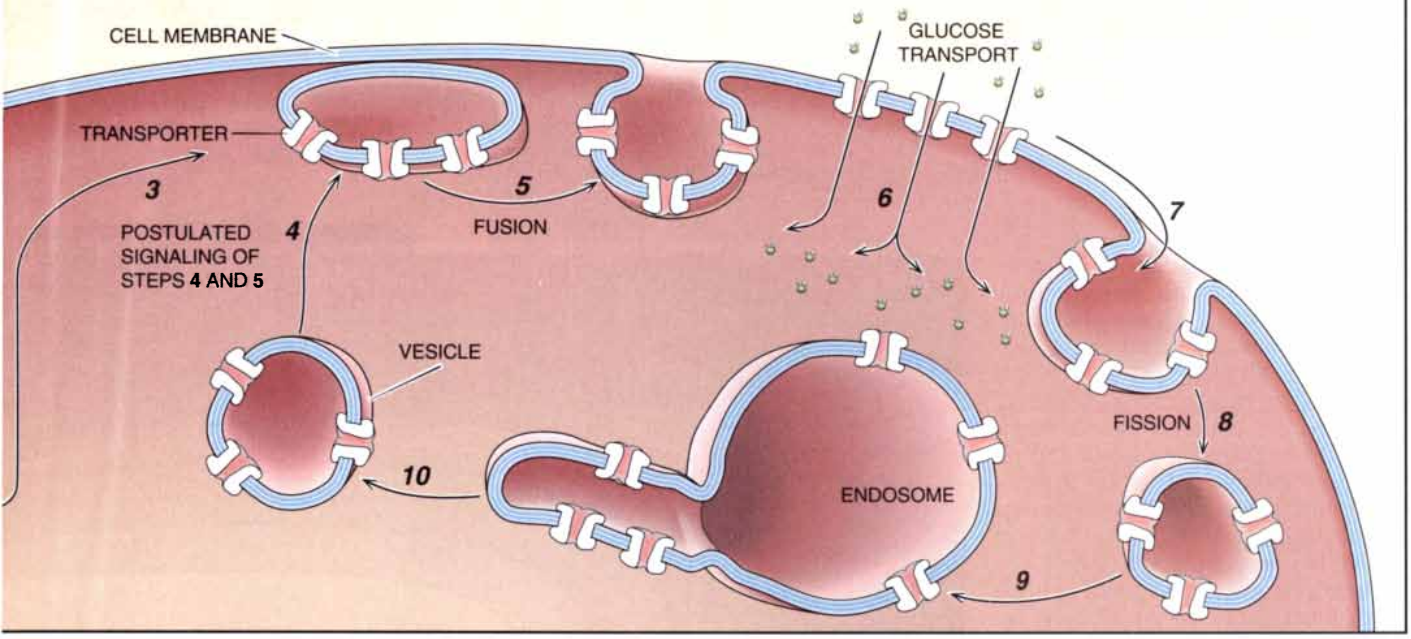


These findings imply no cause for the insulin-dependent form of diabetes mellitus, but they are relevant for the second form: NIDDM. Because the propensity to acquire NIDDM is certainly inherited, at least one gene must predispose individuals to the disease. One possibility is that a defective gene affects the way insulin regulates GluT4.

One of the earliest manifestations of NIDDM is insulin resistance: the inability of muscle, fat or liver to respond appropriately to elevated blood insulin levels. The pancreas responds to such resistance by oversecreting insulin, so that some patients in the early stages of NIDDM exhibit both transient hyperglycemia after a carbohydrate meal and consistently elevated blood insulin levels. As the disease progresses, the pancreas often loses the ability to secrete enough insulin to compensate for insulin resistance. By the time that hap-

How Insulin Helps Cells Recruit Transporters

ADP (*2*). A current hypothesis is that a target protein bearing phosphate signals the redistribution of glucose transporters (*3*) through the movement of transporter-containing vesicles to the membrane (*4*). The vesicles fuse with the membrane (*5*), accelerating the transport of glucose (*6*). The transporters are retrieved to the interior when small vesicles formed through membrane invagination (*7*) and fission (*8*) fuse with larger endosomes (*9*), where the transporter segregates into tubular extensions that pinch off to form new vesicles (*10*). As long as insulin remains, the vesicles will continue to fuse with the cell membrane, but a lowered level of insulin breaks the cycle, and the glucose transporters accumulate in intracellular vesicles.



pens, hyperglycemia persists between meals, and the patient may require the administration of insulin or other drugs to lower blood glucose levels.

A basis for this development is suggested by recent results by Lodish and Bernard Thorens of the Whitehead Institute and Roger H. Unger of the University of Texas Southwestern Medical School. Using two different animal models of NIDDM, these workers found that the beta cells of the pancreas have a reduced amount of GluT2, their isotype. The reduction correlates with the decreased secretion of insulin in response to elevated blood glucose. Because the transport of more glucose into the beta cells normally triggers insulin release, the reduction of GluT2 could be a cause of inadequate insulin secretion.

The key to insulin resistance may well reside in skeletal muscle, which accounts for 80 percent of the body's glucose use in the period after a carbohydrate meal. (At other times, when body metabolism is in the basal state, the brain consumes fully 60 percent of the sugar.) Muscle cells convert excess blood glucose into glycogen at a rate that is limited by glucose transport. Because NIDDM patients deposit glycogen in their muscles at about half the normal rate, they probably have a defect in at least one of the proteins that regulate transport.

Another consideration narrows the scope of the quest. Insulin resistance cannot come from a lack in the total amount of GluT4 protein in muscle cells. Recent measurements of GluT4 in biopsies of muscle from normal and diabetic individuals indicate that those with NIDDM have normal or only slightly decreased amounts of this protein. But GluT4 might cause insulin resistance by another route, perhaps by being targeted to the wrong intracellular compartment—one from which it cannot be recruited to the cell surface. Alternatively, there may be a lesion in some other part of the signaling pathway through which insulin promotes recruitment of GluT4. Such a lesion might involve the insulin receptor on the cell surface or one of the unknown proteins that transduce the signal from the receptor to the GluT4 vesicles.

The big question, then, is whether recruitment is impaired in the muscle cells of diabetic patients. If it is, then the elucidation of the events beginning at the insulin receptor and ending in recruitment will surely show how insulin's message is misaddressed or mislaid.

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Accretion Disks in Interacting Binary Stars

Disks of matter naturally organize themselves around objects ranging from newborn stars to quasars. An unusual class of variable stars is helping theorists understand how these disks behave

by John K. Cannizzo and Ronald H. Kaitchuck

Disks are one of the most common structures found in the heavens. In most cases, disks surround a massive central object such as a star or a black hole. Matter in a disk usually migrates inward and eventually accretes onto the central object; these objects therefore are called accretion disks. Accretion disks are thought to be involved in diverse phenomena ranging from the formation of stars and planets to the powering of quasars.

The best-studied disks reside in interacting binary star systems. We have focused our attention on a particularly intriguing, unstable class of interacting binaries, known as cataclysmic variables, that can brighten by a factor of 100 in just a few hours. These systems, fascinating in their own right, serve as a laboratory for understanding the physics of accretion disks.

One might wonder how highly organized disk shapes would develop so frequently throughout the universe. It turns out that the basic laws of physics favor such formations. Consider, for

JOHN K. CANNIZZO and RONALD H. KAITCHUCK have been drawn together by a shared interest in accretion disks and in interacting binary stars. Cannizzo received his Ph.D. in theoretical astrophysics in 1984 from the University of Texas at Austin. He is a Humboldt Fellow at the Max Planck Institute for Astrophysics in Garching, Germany. He has attempted to model accretion disks in cataclysmic variables and around supermassive black holes; he is also an avid tennis player. Kaitchuck earned a Ph.D. in astronomy in 1981 from Indiana University. He is a faculty member in the department of physics and astronomy at Ball State University in Muncie, Ind. Kaitchuck specializes in time-resolved spectroscopy of binary stars.

INTERACTING BINARY STAR SYSTEM, consisting of a hot, dense white dwarf star and its cool, less massive red companion, quasiperiodically brightens as much as 100-fold. The white dwarf's gravity distorts the red star into a teardrop shape and pulls a stream of gas through the point of the teardrop. Because of its orbital mo-

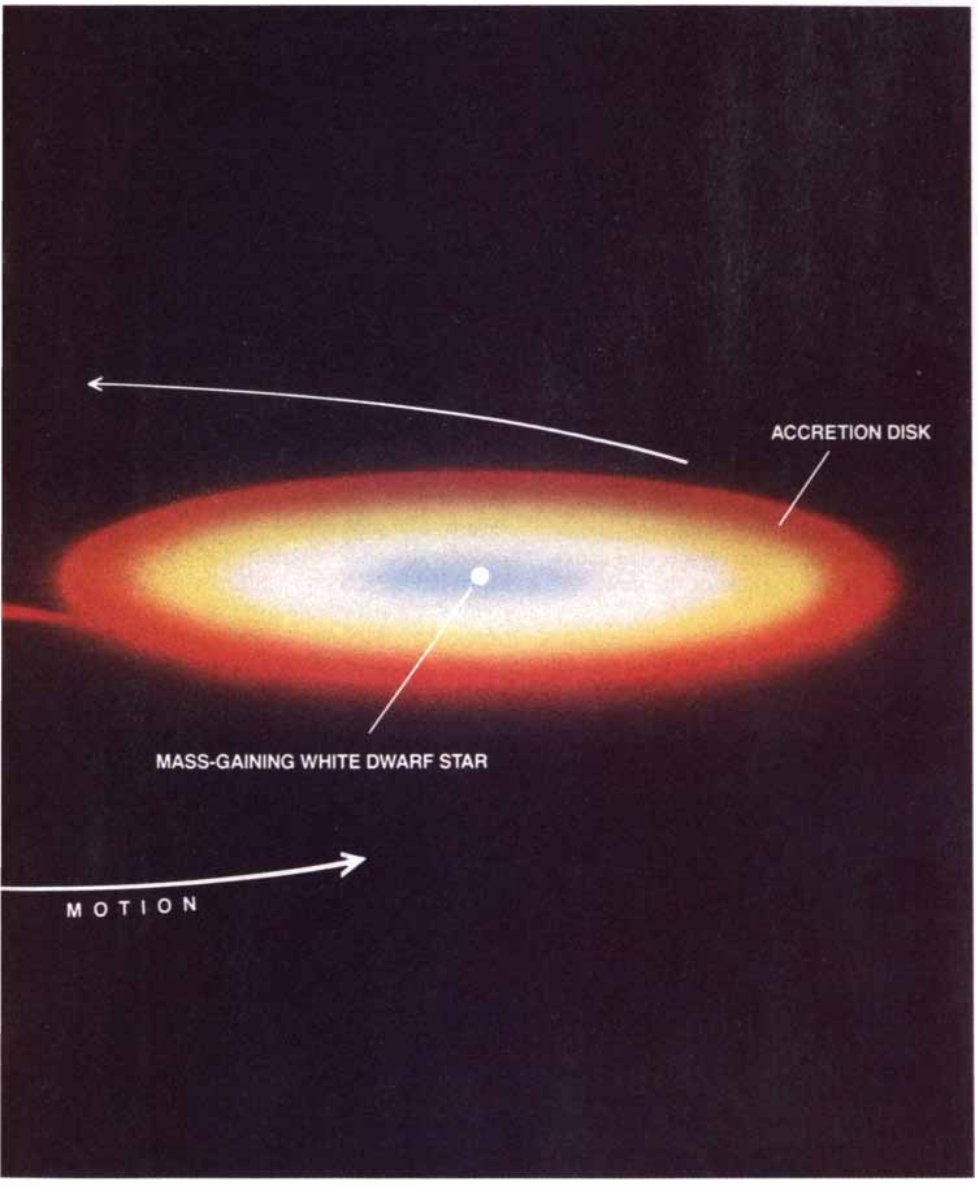
example, an irregularly shaped cloud consisting of particles moving in random orbits, the entire ensemble possessing net angular momentum. (If the cloud is gaseous, the "particle" can be thought of as a small parcel of gas.)

Each particle in the cloud responds to the combined gravitational tugs of all the other parts of the cloud. Particles passing very close to one another experience gravitational and pressure forces that deflect their paths from one of pure orbital motion. Such interactions among the particles dissipate the energy of random motions, whereas conservation of angular momentum preserves the cloud's rotational energy. The particles will eventually settle into the lowest-energy configuration: circular orbits all lying in a single plane [*see illustration on next page*].

Theoreticians have developed a number of models aimed at understanding the behavior of such accretion disks. The simplest models assume that the mass flow into the disk exactly balances the accretion onto the central object. Most of these so-called static accretion disk models are based on a pioneering 1973 paper by the Russian scientists Nikolai I. Shakura of the Sternberg Astronomical Institute in Moscow and Rashid A. Sunyaev, then at the Institute of Applied Mathematics, also in Moscow.

For simplicity, Shakura and Sunyaev pictured the disk as a thin, flat, gaseous object whose gravitational field is negligible compared with that of the central object. The gas therefore obeys Kepler's laws of motion, which means that the orbital velocity of each parcel of gas is inversely proportional to the square root of the distance from the central object.

Inner parts of the disk rotate faster than (and therefore slide past) outer parts. Friction between material at adjacent radii—a phenomenon known as viscosity—heats the gas and transports orbital angular momentum outward. The heated gas emits electromagnetic radiation, which escapes from the system. In the process, gravitational potential energy is converted into radiant energy. As a result, gas slowly drifts inward, at about one ten-thousandth of the orbital velocity.

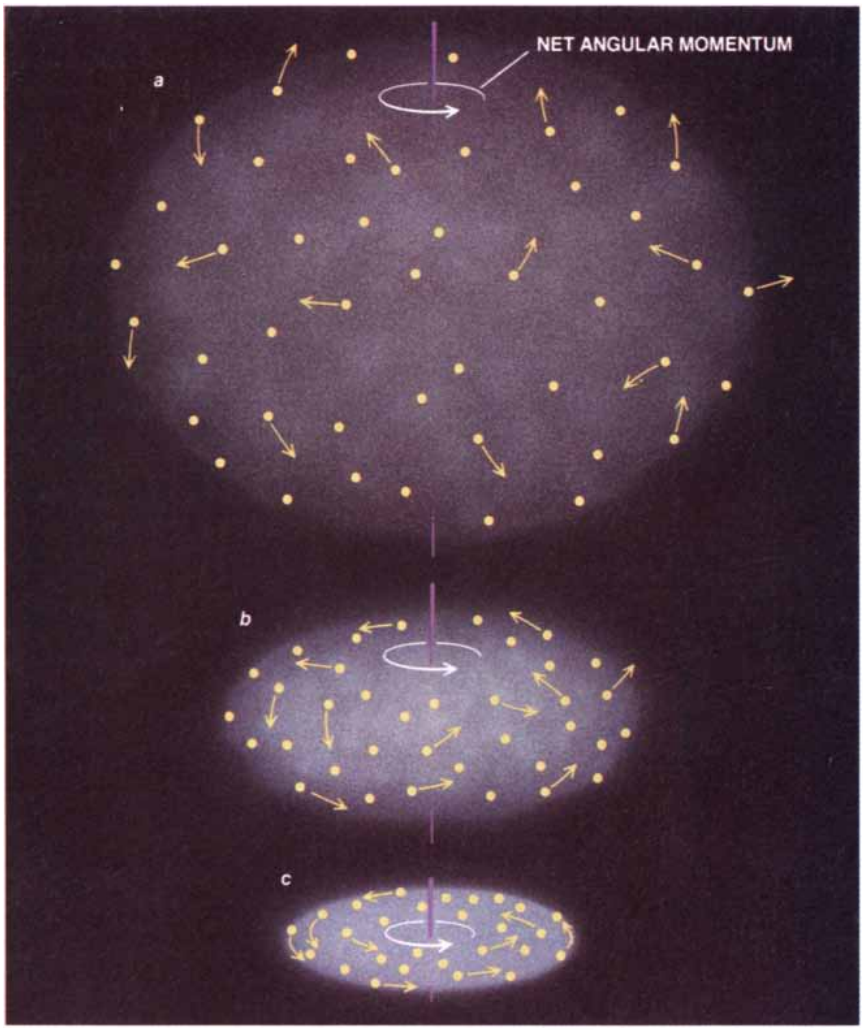


tion, the stream trails behind the white dwarf. Viscosity causes the stream to spread into a disk; gas in the disk falls inward and ultimately accretes onto the white star. As it does so, the gas grows hot and glows prominently. Changes in the flow of gas in the disk cause tremendous fluctuations of the disk's luminosity.

The intensity of the coupling between adjacent radii in the disk, which determines the rate of inflow, is controlled by the strength of the viscosity of the gas. Unfortunately, there is no good theory to predict this viscosity, so Shakura and Sunyaev assumed the viscosity is proportional to the pressure in the disk. In the equations describing the physical state of the disk, the strength of the viscosity appears as an adjustable parameter called alpha. All the unknown physics associated with the viscosity is hidden in alpha. Setting alpha as a constant makes it possible to construct models that predict the physical conditions in the disk. Fortunately, the spectrum of radiation emitted by a disk in a steady state is independent of alpha.

The nature of the central object determines the depth of the gravitational potential well, which in turn determines the energy flux from the disk. When the central object is an ordinary star, the disk radiates primarily in the visible and in the infrared. Matter orbiting a collapsed star, such as a white dwarf or a neutron star, falls much farther before hitting the stellar surface. Disks around these objects release more total energy, and the emission peaks at ultraviolet or X-ray wavelengths.

Because of the great distances involved, it is impossible to observe directly the accretion disks of even the nearest binary star systems. Astronomers have been forced to infer the structure of stellar systems by analyzing the radiation that they produce. Light emitted by the part of a disk moving toward the viewer shifts toward the blue end of the spectrum, whereas light from the parts moving away shift in the red direction, an effect called Doppler shifting. The swirling gas



DISKS ARISE NATURALLY in irregular systems that possess net angular momentum (*a*). Interactions between particles in the system cancel out random motions (*b*), ultimately yielding a flat, circular, rotating disk (*c*). Viscosity effects can cause particles to spiral inward and to accrete onto more central regions of the disk.

in an accretion disk therefore produces a distinctive spectral signature.

In this way, Arthur Wyse of Lick Observatory detected the first known accretion disk in a double star system in 1934. He was studying the spectrum of RW Tauri, a binary consisting of a hot, main-sequence star and a large, cool red companion. The orbital plane of the two stars is viewed nearly edge-on, so that once during each orbit the cool star obscures its companion. Wyse obtained a spectrum of the red star during the 90-minute interval when the companion was completely blocked from view. He observed Doppler-shifted emission lines, indicating the presence of hot, rapidly moving gas.

In the early 1940s Alfred H. Joy of Mount Wilson Observatory obtained additional spectra of RW Tauri. He found that at the beginning of an eclipse, the emission lines were Doppler shifted to the red; at the end of an eclipse, the lines were shifted to the blue by an equal amount. Joy inferred from his observations that the hot star is surrounded by a rapidly rotating ring of gas. As an eclipse begins, the side of the ring rotating away from the observer remains visible beyond the limb of the cool star, producing redshifted emission lines. As an eclipse draws to a close, the side rotating toward the observer is visible, yielding blueshifted lines.

Over the following years, astronomers came to suspect that Joy's gaseous ring was actually a disk whose inner edge lay at the surface of the central star. In the 1940s Otto Struve of McDonald Observatory and a few others suggested that matter flows from the companion star into the disk and then accretes onto the central star, a concept now accepted by most astronomers.

The flow of matter in binary systems is sometimes a direct result of stellar evolution. When a star reaches the end of its stable life, its core becomes depleted in hydrogen fuel and so begins to contract; as the core shrinks, it grows hotter and releases more energy, causing the outer parts of the star to swell. If a star in a close binary system expands beyond a certain volume, called the Roche lobe, matter moving outward from the star falls under the gravitational influence of its companion. The size and shape of the Roche lobe are largely determined by three forces felt by a particle at rest with respect to the orbiting stars: the gravitational attraction of each star and the centrifugal force produced by the orbital motion of each particle. These competing forces give the Roche lobe's surface a teardrop shape.

If the star expands beyond this surface, the gas follows the least energetic path and falls toward the companion star. The gas emerges through the point of the teardrop, called the inner Lagrangian (L1) point, where the companion's gravitational influence is greatest. Gas leaving the L1 point forms a narrow stream that moves toward the companion star. Because the gas still carries the momentum of the orbital motion of the star it just left, it does not fall directly onto the companion. Instead the stream follows a curved path toward the trailing side of the mass-gaining star [*see illustration on preceding two pages*].

The events that follow depend on the size of the accreting star in comparison to the orbital separation between the stars. If the accreting star is small, the stream of gas curves around it and forms a ring. The ring quickly spreads into a flat disk as a result of viscosity, which causes some gas to lose angular momentum and spiral inward while a smaller volume of gas gains the lost momentum and spirals outward.

If the accreting star is comparatively large, the stream of gas collides with the body of the mass-gaining star. Oddly enough, something resembling an accretion disk still manages to form. But the resulting disk is turbulent and unstable; it disappears quickly if the mass transfer temporarily stops, much the way the spray from a garden hose falls to the ground and disappears when the faucet is turned off. As it turns out, RW Tauri is a transient-disk binary system.

Accretion disks can act in more complicated and violent ways, as seen in a class of binary stars called cataclysmic variables. These stellar systems contain a dense, hot companion that accretes matter from its cooler neighbor. Here the mass transfer is driven by a loss of orbital angular momentum, which slowly draws the stars closer and causes the Roche lobe to shrink around the

red star. The disks in cataclysmic variables seem far from stable. Because the flow of matter through these disks may not be at all steady, understanding cataclysmic variables poses a difficult challenge. But it is a challenge worth accepting: the erratic behavior of these objects holds important clues to the general nature of accretion disks.

As their names imply, some cataclysmic variables undergo severe outbursts, during which their brightness jumps as much as 100-fold in a matter of days or even hours. One subset of cataclysmic variables, called dwarf novae, flare up in a quasiperiodic fashion. Dwarf nova eruptions recur on intervals of weeks to years; each episode typically lasts from a few days to a few weeks. Dwarf novae are distinct from ordinary novae, which are thought to be powered by the nuclear fusion of hydrogen accreted onto the surface of a white dwarf star. Dwarf nova outbursts seem to draw on gravitational energy only, which explains why they are 1,000 times less energetic than ordinary novae.

Ground-breaking work by Robert P. Kraft of Mount Wilson Observatory in the 1960s revealed that cataclysmic variables are binary stars whose components orbit very close to each other. A typical cataclysmic binary has an orbital period of four hours, and a few have periods of less than 90 minutes. Such rapid orbits mean that the separation between the two stars, and hence the stars themselves, must be extremely small. In fact, the typical cataclysmic system could fit inside our sun.

Studies of light spectra and radiation fluxes at a broad range of wavelengths indicate that there are three major components to a cataclysmic binary: a red dwarf star, a white dwarf star and an accretion disk surrounding the white dwarf. The red dwarf is a cool, faint, low-mass star that is losing matter through its L1 point. The white dwarf is much hotter, more luminous and more massive. White dwarfs are the remnant cores of evolved stars that have depleted their hydrogen fuel. Lacking an internal energy source, the core grows fantastically dense—about 10 million times as dense as water. White dwarfs are roughly as massive as the sun but are only about the size of the earth.

Because a white dwarf is so small and massive, it has a very deep gravitational potential well. Matter falling onto it from the accretion disk releases a large amount of gravitational potential energy via viscous heating in the disk. So intense is the heating that the disk becomes brighter than the stars.

Observational astronomers have deduced that enhanced mass flow through the accretion disk powers the outbursts of dwarf novae. This was demonstrated by Brian Warner of the University of Cape Town, who conducted photometric observations of the dwarf nova Z Chamæleontis. As seen from the earth, the red star in this binary eclipses the white dwarf and its surrounding accretion disk once every orbit. During an outburst, the light loss at mideclipse is much greater than during times of quiescence, indicating that the source of the outburst cannot be the red dwarf star. Furthermore, the duration of successive eclipses lengthens as the outburst progresses, implying that the eruption is spreading across the face of the disk.

The optical spectrum of a dwarf nova changes drastically during the course of an outburst. The quiescent spectrum shows a blue continuum on which are superimposed lines of radiation emitted by hydrogen and by singly ionized helium (helium that is missing one electron). The continuum originates in the dense inner regions of the disk, whereas the emission lines are formed in the more rarefied outer regions. In systems where the orbital plane is seen nearly edge-on, the emission-line profiles appear as double-peaked curves. The peaks appear because each profile consists of two Doppler-shifted components: one from the side of the disk rotating toward the observer and one from the side rotating away.

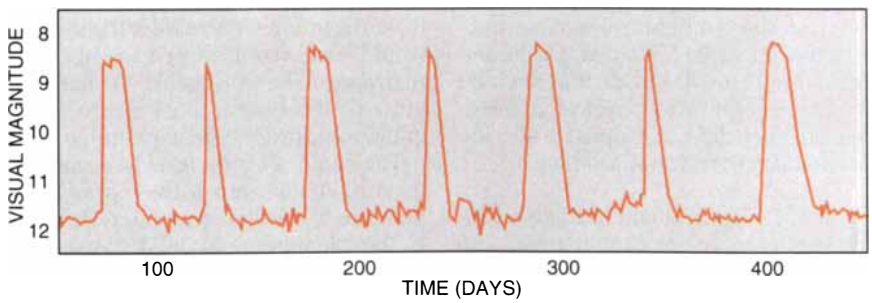
During an outburst, the continuum radiation brightens sharply; at the same time, the emission lines can become difficult or impossible to see. Broad hydrogen absorption lines often appear, the result of radiation being absorbed by cooler gas surrounding the bright part of the disk. As the outburst declines in brightness, the continuum fades, and the emission lines once again become prominent.

Dwarf nova outbursts seem to result from a sudden increase in the flow of mass through the accretion disk onto the white dwarf star. The speedier inflow could result from a surge from the mass-losing red star or from a change in the accretion disk itself. The first possibility, proposed some 20 years ago by Geoffrey T. Bath, who was then at the University of Oxford, requires that the red star periodically overflow its Roche lobe, dumping excess material into the accretion disk. The extra matter causes the rate of accretion to increase, which in turn makes the disk shine more brilliantly.

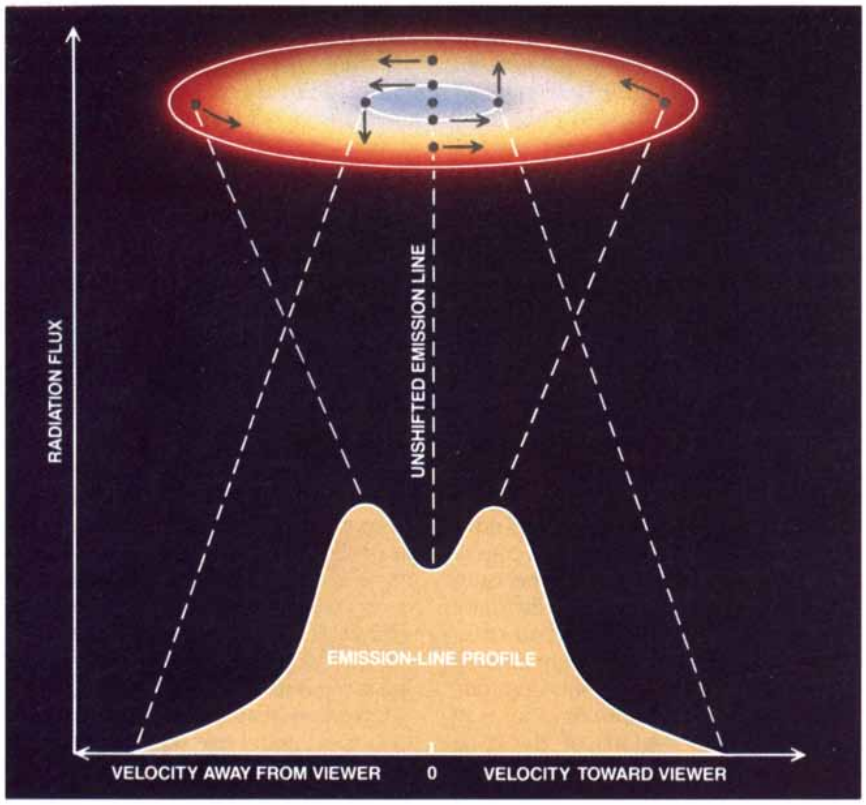
A few years later Jozef Smak of the Copernicus Astronomical Center in Poland and Yoji Osaki of the University of Tokyo independently presented a competing idea. The Smak-Osaki hypothesis holds that mass flows from the secondary star at a constant rate. Some mechanism in the accretion disk itself stores up matter and then dumps it onto the white dwarf whenever the disk's mass exceeds a critical level.

Astrophysicists largely favor the disk instability model that has grown out of the work of Smak and Osaki. Most researchers now think the instability is triggered when a critical local surface density is attained somewhere in the disk. Once the density in a local region reaches the critical value, viscosity increases tremendously, and the stored-up matter accretes onto the white dwarf star, producing an outburst. When the surface density drops below a certain level, disk viscosity plummets, and the accumulation process starts anew.

For years, theorists have labored to create mathematical models that could describe accretion disk instabilities. These models predict the local surface density and temperature when values are specified for the accretion rate and for alpha at a certain radius. An increase in the accretion rate leads to higher surface density, which in turn causes increased viscous heating. Disk



BRIGHTNESS OF SS CYGNI varies by a factor of 20. The semiregular outbursts probably reflect changes in the rate at which mass flows through an accretion disk. SS Cygni exhibits many kinds of long-term behavior; one of the more common modes, shown here, involves an alternation between long- and short-duration outbursts. Data courtesy of the American Association of Variable Star Observers.



DOUBLE-PEAKED EMISSION LINES appear when accretion disks are seen nearly edge-on. Emission radiation occurs at a single wavelength. Parts of the disk moving toward the viewer shift the line toward the blue; parts moving away shift it toward the red. The innermost regions of the disk move the fastest and so yield the most highly shifted light. Because of its small surface area, the innermost disk contributes the least amount of light. Gas moving across the line of sight produces no shift.

temperature is therefore expected to vary in proportion to surface density; a graph of local temperature versus surface density at a particular radius in an accretion disk should produce an upward-sloping curve.

The outburst models of Osaki and Smak required that at a given location in the disk there exist two possible stable values for temperature for the same value of surface density. The outburst corresponds to the high-temperature solution, the quiescent state to the low-temperature solution. In this case, the curve in the temperature–surface density plot must be S shaped. Osaki and Smak implicitly assumed that such an S curve relation was physically plausible, but they did not propose a specific mechanism that would produce it.

In 1979 Reiun Hoshi of Rikkyo University in Tokyo demonstrated the existence of such a mechanism. Hoshi worked with a model that considered the vertical structure of the accretion disk (the physical conditions that prevail in a thin perpendicular slice through the disk). Although his model for the vertical structure was crude, he found that an S curve relation naturally emerged when his model accounted for the temperatures at which hydrogen becomes partially ionized, that is, when the disk becomes so hot that some of the hydrogen atoms lose their surrounding electrons.

To see how the S curve relation works, one must examine the physical conditions in a stable disk (said to be in a state of thermal equilibrium). In a system whose temperature remains constant, the energy escaping into space must be balanced by that released from the interior. Otherwise, the system would either cool off or heat up. Furthermore, to be truly stable, the temperature of the system must return to its initial value despite small perturbations.

The sun, for example, is in a state of thermal equilibrium. If the central temperature of the sun were lowered slightly, the gas pressure would decrease, and the sun would contract. The contraction would in turn raise the central temperature and increase the nuclear reaction rates, causing the sun to expand to its initial size. In the end, the sun would return to its original temperature and energy output.

The situation for an accretion disk is broadly similar. If the midplane temperature declines slightly for a short interval of time, the local viscosity would decrease because of reduced frictional interaction. The surface density would then increase: reduced viscosity would slow the inward flow of mass while matter from outlying radii continues to fall into the region at a constant rate. Increased surface density would result in greater viscous heating, which would return the temperature and the surface density to their initial values. Under these conditions, a graph of temperature versus surface density has the expected upward slope, because regions with high temperatures require high surface densities in order to supply sufficient viscous heating.

The above mechanism can maintain thermal equilibrium in the disk provided that the opacity does not change substantially as the temperature changes. Opacity of the gas determines how freely the energy in the disk can escape into space; a substantial change in opacity can largely control the disk temperature. At a temperature of about 10,000 kelvins, hydrogen atoms begin to lose their electrons (become partially ionized), and the opacity of the hydrogen changes abruptly, increasing roughly as the tenth power of the temperature.

In regions of the disk close to the critical temperature, a slight cooling leads to an enormous drop in opacity, allowing more energy to escape into space and causing the temperature to drop even further. By the same argument, a small increase in temperature enhances opacity, impeding the flow of radiation and causing further heating. Critical regions in the disk will either heat or cool until they reach the stable branches at the top or bottom of the S curve. This thermally unstable behavior corresponds to the middle, negatively sloping portion of the S curve.

The flow of energy vertically out of the disk depends on local opacity and on the local surface density (which is proportional to the amount of gas along the line of sight). The lower branch of the S curve is thermally stable because at these low temperatures very little hydrogen is ionized, and so the opacity varies only weakly with the temperature. Likewise, the upper branch is stable because the disk is so hot that hydrogen is completely ionized; in this state, opacity again changes little as a consequence of changes in temperature. On the connecting middle branch, however, the extreme sensitivity of opacity to temperature variations leads to thermally unstable conditions. Using these physical arguments, Hoshi showed

that a zone of partially ionized hydrogen in the accretion disk could produce the double-valued temperature solutions that would provide a physical mechanism to account for the disk instability idea of Osaki and Smak.

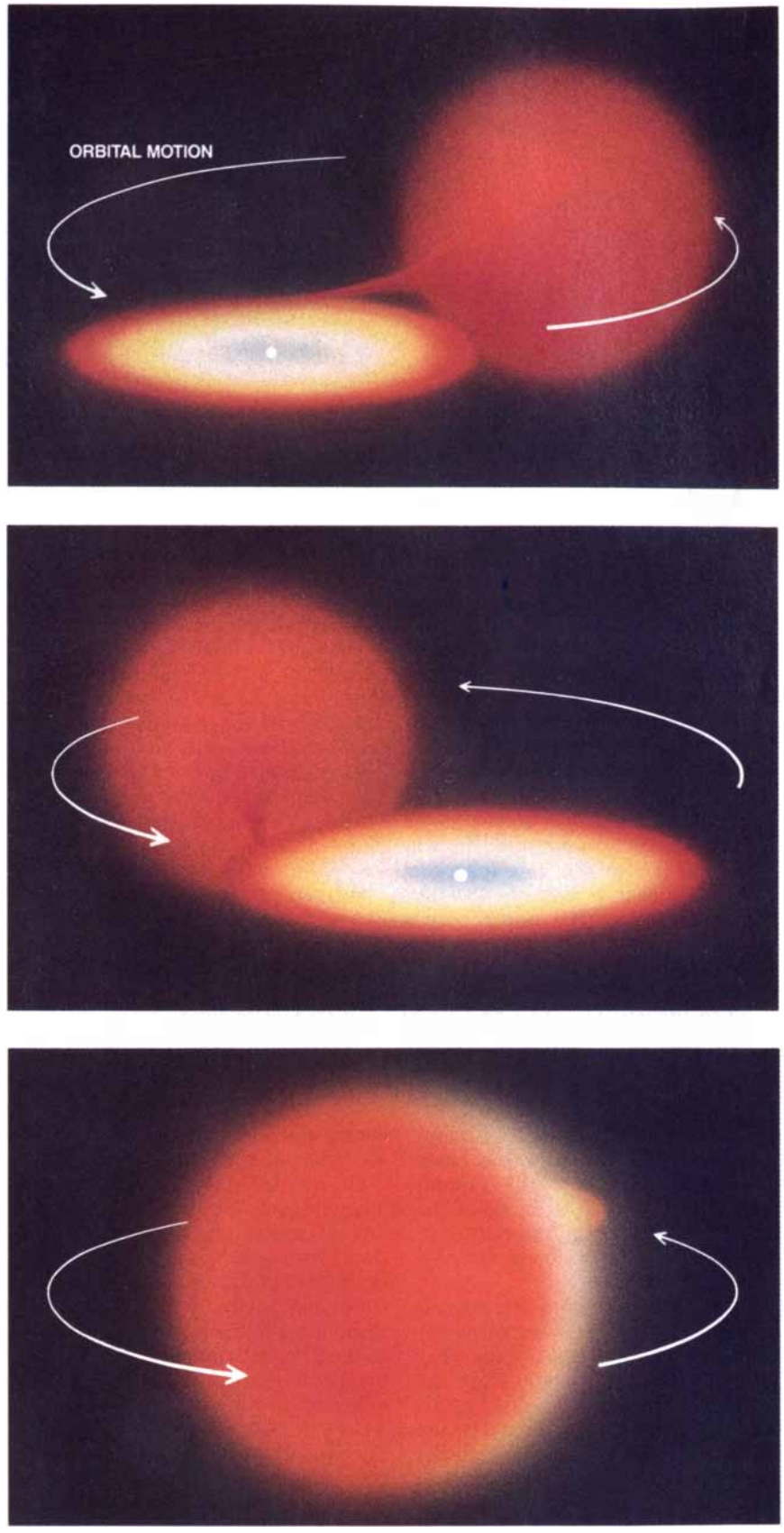
Surprisingly, Hoshi's work attracted little attention. In July 1981 James E. Pringle of the University of Cambridge gave a talk at a conference at the University of California at Santa Cruz in which he discussed in general terms how an S-shaped temperature-density relation could yield the conditions that would lead to dwarf nova eruptions. In the audience were several accretion disk modelers who immediately realized the importance of calculating in detail the disk's vertical structure.

Five months later Friedrich Meyer and his wife, Emmi Meyer-Hofmeister, both of the Max Planck Institute for Astrophysics in Garching, published a short article that contained a physical basis for Pringle's suggestion. Shortly thereafter, articles on the disk instability mechanisms appeared by Smak in Poland; Pranab Ghosh, J. Craig Wheeler and one of us (Cannizzo), then all at the University of Texas at Austin; Douglas N. C. Lin and John Faulkner of the University of California at Santa Cruz and John C. B. Papaloizou of Queen Mary College; and Shin Mineshige (now at Ibaraki University) and Osaki.

These workers all recognized that dwarf nova eruptions are a natural consequence of accretion disk instability. The conditions at each radius in the disk correspond to some point on the temperature–surface density S curve. The temperature or, equivalently, the accretion rate at a given radius is determined by the surface density and by the evolutionary history of the matter there. When local conditions move into the unstable region of the S curve, the disk switches from a quiescent state to an outburst, or vice versa [*see box on next page*].

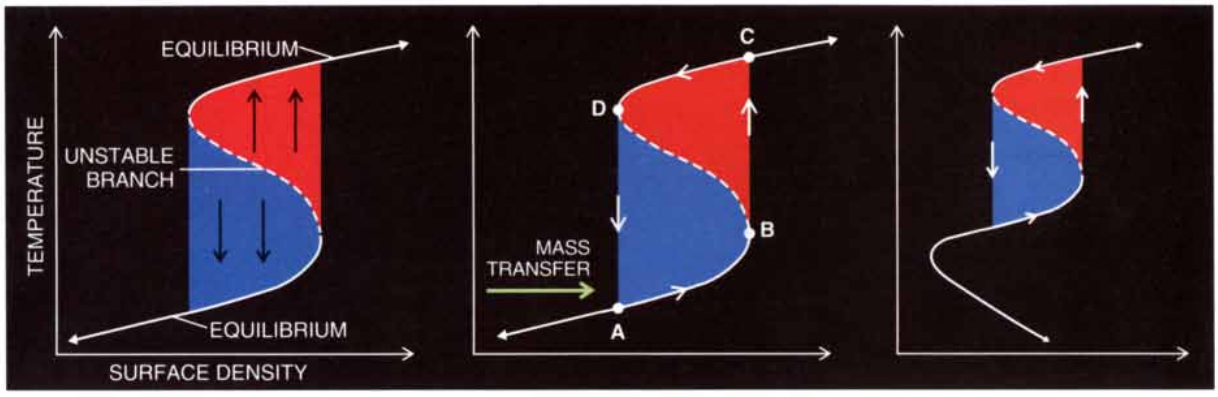
The disk instability model makes a number of predictions that can be tested by observations of dwarf novae. Smak delineated many of these predictions in a landmark article that appeared in 1984. Similar studies appeared by the other researchers mentioned above at about the same time. Using computer models to simulate the time-dependent behavior of an accretion disk, Smak was able to produce artificial light curves that closely resemble the observed ones.

Several aspects of dwarf nova eruptions seem quite consistent with the disk instability model. Light curves produced by disk instabilities can show either a slow or a rapid increase in bright-



EDGE-ON DWARF NOVA SYSTEMS undergo regular eclipses that help to reveal the geometry of the system. During an outburst, the star's maximum brightness increases considerably. But while the accretion disk is in eclipse, the system dims much more than it does during times of quiescence, proving that the extra light comes from the disk, not from the intervening red dwarf star.

How the Dwarf Nova Cycle Works



One likely model of dwarf nova eruptions holds that the accretion disk around the white dwarf experiences quasiperiodic episodes of instability. The above plots of temperature versus surface density in the disk illustrate how this model works. At any location in the disk there are two stable branches, or equilibrium states, one at high temperatures and one at low temperatures (*left*). The middle branch is thermally unstable.

A region of the disk where conditions correspond to the red area grows hotter until it settles at the high-temperature state. Regions corresponding to the blue area cool down until they reach the low-temperature state. The upper branch corresponds to an outburst; the lower branch, to the quiescent state.

The accretion disk surrounding the white dwarf in a dwarf nova system alternates between the two branches in the following manner. Consider a circular region, or annulus, at some fixed radius from the white dwarf star where the temperature and surface density lie at point A (*center*). The horizontal arrow shows the rate at which matter is added from the secondary, red dwarf star. Matter is flowing into the annulus faster than it is accreting onto the white dwarf, so both surface density and temperature increase.

When the annulus reaches a state corresponding to point B, it falls out of thermal equilibrium. Viscous heating now exceeds energy losses by radiation, so the region swiftly grows hotter until it reaches the upper, thermally stable branch at point C. At these high temperatures, the viscosity in the disk is quite strong. As a result, the accumulated matter rapidly flows inward and accretes onto the white dwarf.

Because of the sudden draining of the disk, the local surface density and temperature decrease, so that the region moves from point C to point D. At point D, thermal instability again sets in. This time the radiation losses overwhelm viscous heating, and the temperature plummets. After a period of cooling, the annulus ends up back at point A, and another cycle commences.

The above model assumes an arbitrary value for the intensity of viscosity in the disk. Cannizzo and A.G.W. Cameron of Harvard University have developed a more physically complete model in which viscous heating is assumed to arise from turbulence associated with convective motions in the accretion disk. In this case, the S-shaped temperature-density relation discussed above appears to be only part of a more general, W-shaped curve (*right*). Further work should lead to increasingly realistic accretion disk models.

ness. Computer models show that instabilities that begin near the outer edge of the disk produce the fast increases. In this case, the radius of the disk should increase during an outburst, a phenomenon that has been observed in several dwarf novae.

In such "outside in" eruptions, the ultraviolet emission should increase after the visible light does because the energetic ultraviolet rays come from the hot, inner regions of the disk, which should be the last ones affected by the outburst. Observations made with the *International Ultraviolet Explorer* (*IUE*) satellite have shown that in several dwarf novae the outburst appears at ultraviolet wavelengths about a day after it shows up in the optical. But Pringle, Frank Verbunt and Richard A. Wade, then working at Cambridge, showed in 1986 that this behavior can be explained at least as well by Bath's secondary-star instability model.

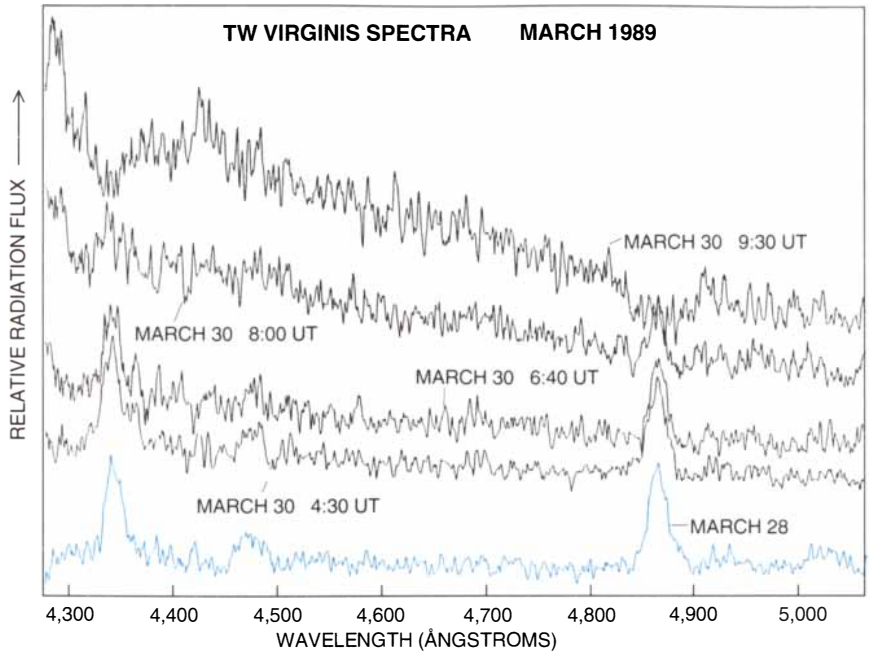
The disk instability model makes another important prediction: when the rate of mass transfer from the red dwarf rises above a certain critical level, the flow of matter inward should occur at a steady but very high rate, corresponding to the upper stable branch of the S curve. Warner and Smak independently examined this question by inferring the rates of mass transfer for a large number of interacting binaries. They found that those systems experiencing high values of mass transfer do not exhibit eruptions, whereas those below a certain value do. Their observed dividing line fits well with the theoretically expected value, a quantity that is independent of the unknown parameter alpha. There is no reason to expect such an upper limit from Bath's model.

Observing the spectral evolution of a dwarf nova flare-up might provide important observational constraints for disk instability models. The intensity of the radiation from the regions that produce emission lines can be sensitive to small changes in the local physical conditions. Changes in the strength of the emission lines therefore might herald the coming of an eruption.

Such an effect was observed by Cathy S. Mansperger and Panayiotis Hantzios, who were then working at Ohio State University, and one of us (Kaitchuck) in the emission lines of the star RX Andromedae 18 hours before the start of an outburst. Also, the system seems to brighten a few percent during the 24 hours before the main outburst. These observations and others indicate that there is sometimes a pre-outburst stage in the dwarf nova cycle.

Mansperger and Kaitchuck have managed to observe the transition from pre-outburst to outburst in the dwarf nova TW Virginis. On one evening, the star system appeared somewhat brighter than on previous nights. For the next two and a half hours, the system brightened only slightly. Then, within 15 minutes, the slope of the spectrum of the continuum radiation abruptly steepened, indicating that the temperature of the disk had suddenly begun to increase. At the same time, the brightening of the system accelerated. Over the remainder of the night, the continuum slope steepened further, and absorption lines replaced the emission lines in the spectrum, revealing that most of the disk had become hotter than the surface of the sun. When dawn called a halt to the observations, the system had brightened by a factor of 12. By the next day, it had flared to 100 times its pre-outburst brightness.

Much of the observed pre-outburst behavior was predicted in a disk model developed by Mineshige when he was at the Institute for Astronomy at Cambridge. In his model the main outburst is preceded by a warm phase that lasts for about one day. Then a hot front moves through the disk from the site of the thermal instability, producing the main outburst. The observed pre-outburst brightening of TW Virginis closely matches the predicted warm phase, as do the observed rates of change of the disk temperature and brightness.



DWARF NOVA SPECTRUM changes dramatically at the start of an outburst, as seen above for the double star TW Virginis. The bottom spectrum shows the star in a quiescent state. The other spectra document the changes that occurred a few nights later. For about two hours, the system was in a pre-outburst state and brightened only slightly. The star then grew rapidly brighter, especially at bluer wavelengths. By the following day, TW Virginis had brightened by a factor of 100.

If the disk instability model for dwarf nova eruptions proves correct, it should help answer many of the questions about the physics of accretion disks in general. The greatest mystery in accretion disk research is the nature of the viscosity. Clearly, a preliminary step in understanding the physical mechanism that produces viscosity involves determining empirically the magnitude of the effect and how it depends on surface density and on radius of the disk. Researchers using time-dependent computer models have tried adjusting the relation between temperature and surface density in order to make the model outbursts resemble those observed. In this way, it is possible to check theories of viscous heating to make sure they are consistent with the behavior of dwarf novae.

Two main mechanisms have been proposed to account for viscous heating of the disk. One focuses on turbulence associated with convective motions that accompany the vertical transport of energy out of the disk; the other invokes energy released by the breaking and reconnecting of magnetic field lines in the disk. Cannizzo, working with A.G.W. Cameron of Harvard University, showed that convection-induced heating can reproduce some aspects of the relation between temperature and surface density needed to produce dwarf nova eruptions.

Steven Balbus and John Hawley of the Virginia Institute for Theoretical Astronomy have recently uncovered a mechanism by which motions in the ionized (and hence magnetic) gas in the disk would amplify the weak magnetic fields that should always be present. The next task for theorists is to incorporate the results from such studies into a global theory that follows the temporal evolution of the entire disk to see if the models can reproduce in detail the recorded behavior of dwarf nova eruptions.

The disk instability model may explain not only cataclysmic variables but also distant, energetic quasars. Astrophysicists have long speculated that these objects harbor accretion disks that channel matter onto central black holes having masses millions of times that of the sun. Lin and Gregory A. Shields of the University of Texas at Austin found in 1986 that the S curve relation should operate in these giant accretion disks as well. The two researchers suggested that disk instabilities may collimate oppositely directed jets of matter when the disk is in its high state, thereby producing the sequence of knots seen in the radio-emitting jets that extend from some active galaxies.

A better understanding of accretion disks will be essential to determining the true nature of quasars and other violent phenomena that occur in the nuclei of galaxies, including the mysterious object at the center of the Milky Way. The information should also lead to new insights into the disks that seem to surround infant stars, the likely birthplace of planets such as the earth.

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How Sea Turtles Navigate

As soon as they hatch, sea turtles swim across hundreds of miles of featureless ocean; as adults, they navigate home to nest. Research has begun to identify the biological compasses and maps that guide them

by Kenneth J. Lohmann

After sunset on summer nights, when the heat of Florida's Atlantic coast beaches finally dissipates, newly hatched loggerhead sea turtles lying dormant in underground nests begin to stir. In sporadic bursts of activity, the hatchlings squirm and thrash, dislodging sand from the roof of the nest chamber and trampling it onto the floor. The floor slowly rises, and the chamber ascends like a miniature elevator until at last the baby turtles break through the surface of the sand.

The hatchlings, each no bigger than a child's hand, immediately confront a dangerous world. Pursued by ghost crabs, foxes and raccoons, the turtles scramble across the dark beach to the ocean and plunge into the surf. They quickly establish a course away from land and toward the open sea. Buffeted by waves and currents, attacked by predatory fish and seabirds, the turtles maintain their seaward bearings day and night as they swim toward the relative safety of the Gulf Stream. There, some 30 to 50 miles offshore, they may find shelter in floating sargassum seaweed, as well as food in the form of small invertebrates. Years later those that survive to adulthood (perhaps one out of every 1,000) navigate back, often returning to the same, specific beach each nesting season.

How do the turtles navigate through a vast ocean that contains no obvious landmarks? Only recently have investigators, through observation in the laboratory and at sea, begun to identify the environmental cues the turtles use to maintain their bearings.

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A turtle's ability to orient itself seems quite sophisticated and reliable. For some sea turtle populations, the initial offshore migration appears to be just the first step of a transoceanic journey lasting several years. After leaving Florida as hatchlings, for example, loggerhead turtles (*Caretta caretta*) are not seen again in U.S. waters until their shells have grown to more than half a meter in length. No one has yet tracked the tiny turtles through the miles of open sea into which they vanish. Circumstantial evidence, however, suggests that the Florida loggerheads eventually cross the Atlantic and navigate back. There is an orderly progression of juvenile turtle sizes along the North Atlantic gyre, the clockwise oceanic current system that encircles the Sargasso Sea (the relatively still portion of the central north Atlantic). Thus, after entering the Gulf Stream, young turtles may swim eastward across the Atlantic, then south around the Sargasso Sea and westward back to the Florida coast.

Adult turtles navigate even more skillfully than young turtles do. For instance, green turtles (*Chelonia mydas*) that frequent feeding grounds off the coast of Brazil regularly migrate eastward across more than 1,400 miles of open ocean to reach their nesting grounds at Ascension Island. This remote speck of land is so isolated and difficult to find that during World War II air force pilots required to stop there for refueling summed up the situation with a rhyme: "If you miss Ascension, your wife gets a pension."

Tagging studies at Ascension Island have shown that females remain remarkably faithful to their nesting site; no turtle seen at Ascension has ever been found nesting elsewhere. Instead the turtles swim to the Brazilian feeding grounds from Ascension after nesting, then repeat the long migration to the island and back once every two to four years. Recent studies by John C. Avise and his colleagues at the University of Georgia have shown that the mitochondrial DNA of Ascension Island green turtles is distinct from that of other green turtle populations. This genetic study is additional evidence that these turtles consistently navigate back to their natal beaches to nest and do not mix with other populations.

Green turtles that nest at Tortuguero, Costa Rica, demonstrate a similar fidelity to their home beaches. Turtles tagged there have been recaptured at feeding grounds dispersed throughout the Caribbean and as far north as Florida, but no turtle in the more than 30 years of tagging at Tortuguero has ever been found nesting elsewhere.

A logical first step toward uncovering the mechanisms used in navigation by sea turtles is to determine the orientation cues hatchlings use. Their offshore migration resembles the long-distance migrations of adult turtles in that both require oriented movement through seemingly featureless ocean. Hatchlings and adults probably have similar sensory abilities. But hatchlings are small and easily studied in the laboratory, whereas adults may exceed a meter in length and 180 kilograms (about 400 pounds) in weight. Working with my colleagues Michael Salmon and Jeanette Wyneken of Florida Atlantic University, I began to study how hatchling sea turtles on the east coast of Florida maintain their seaward orientation while swimming offshore.

We knew right from the very beginning that many orientation cues might be available to the hatchlings. Other migratory animals, for example, rely on multiple cues such as the position of the sun or stars, polarized light, odors, wind direction, infrasound (low-frequency sound, such

GREEN TURTLE swims in the waters off Hawaii. Such turtles may use the earth's magnetic field and the direction of ocean waves to navigate between their feeding grounds and nesting sites.

as that from waves breaking on a beach) and the earth's magnetic field.

Indeed, the geomagnetic field is one of the most pervasive and consistent sources of directional information available to animals. Unlike most other potential cues, it is essentially constant throughout the day and night and remains largely unaffected by weather changes. Although physicists and biologists alike once ridiculed the idea that certain animals can sense the geomagnetic field, research during the past 15 years has shown that a surprising number of diverse animals are able to do so. Among these are various migratory birds and fish (such as salmon, tuna and shark), as well as certain amphibians, insects and mollusks. We reasoned that a search for this ability in hatchlings would be a good beginning.

We began by testing the orientation of Florida loggerhead hatchlings in a water-filled arena made from a fiberglass satellite dish about one meter in diameter. In each experiment, a hatchling turtle was placed in a nylon-Lycra harness and tethered to a lever arm. Because the lever arm was free to rotate in the horizontal plane and could easily be pulled by a swimming turtle, the arm reliably tracked the turtle's position. Hatchlings could swim freely within a radius defined by the tether. In an adjacent room, a chart recorder or a computer wired to the lever arm provided a continuous record of the turtle's direction.

At the start of each experiment, we provided a dim light in the magnetic east so that hatchlings would begin swimming in the appropriate seaward direction. (In their natural habitat, turtles emerging from their nests at night encounter a similar light cue in the direction of the ocean, which reflects more starlight and moonlight than land does.) After an hour or more, we turned the light off, plunging the hatchlings into complete darkness.

Immediately after the light went out, the hatchlings circled the satellite dish as if confused. After several minutes, the turtles usually established a consis-

tent course toward a specific direction, which they held for several minutes before circling again. The hatchlings continued this curious behavior for hours in complete darkness, alternating between brief periods of oriented swimming and periods of circling.

When we calculated the average direction that different hatchlings swam toward in darkness, it became clear that the turtles were not swimming randomly. Instead most hatchlings swam toward points between magnetic north and east, adopting bearings that would lead them away from the east coast of Florida and toward the Gulf Stream.

We hypothesized that this directional preference in complete darkness was based on magnetic orientation. To verify the hypothesis, we needed to show that changing the direction of the magnetic field around the turtles changed the course in which they swam. We therefore constructed a system of five square coils of copper wire (known as a Rubens cube coil) and placed it around the orientation arena. When activated, the coil generated a weak, relatively uniform magnetic field throughout the area it enclosed. The coil was adjusted to generate a field twice as strong as the horizontal component of the earth's field but opposite in direction. Thus, we could reverse at will the magnetic field experienced by the turtles.

Now we could test the orientation of hatchlings under two different magnetic field conditions. Each hatchling began the new experiment swimming in the earth's magnetic field while a light shone in the magnetic east. We then turned the light off and let each hatchling swim in complete darkness under one of two magnetic fields. Half of the turtles swam in the unaltered magnetic field of the earth (with the coil turned off). For the other half, we turned the coil on, so that the direction of the magnetic field was reversed.

As in the preliminary experiments, hatchlings tested in darkness in the geomagnetic field usually adopted bearings between magnetic north and east. Turtles tested in the reversed magnetic field, however, swam in approximately the opposite direction. These data demonstrated that hatchling loggerhead turtles can sense the magnetic field of the earth and orient themselves to it.

Armed with this new information, we thought we had solved the puzzle of how hatchlings maintain their bearings during the offshore migration. We reasoned that soon after entering the ocean, hatchlings must begin to rely on a magnetic compass. The compass would continue to function after hatchlings passed beyond sight of shore, enabling them to maintain their steady seaward path to the Gulf Stream.

But this hypothesis, formulated in the laboratory, needed to be tested in more natural settings. To study the orientation of hatchlings in the ocean, we devised a floating orientation cage [*see bottom illustration on page 104*]. By tethering a hatchling to a floating buoy in the cage, we could observe the direction in which the turtles swam.

During our next few field experiments, the turtles paddled vigorously toward the open ocean, even when tested nearly 15 miles from shore where land could not possibly be seen. They swam seaward, we initially presumed, by detecting the geomagnetic field.

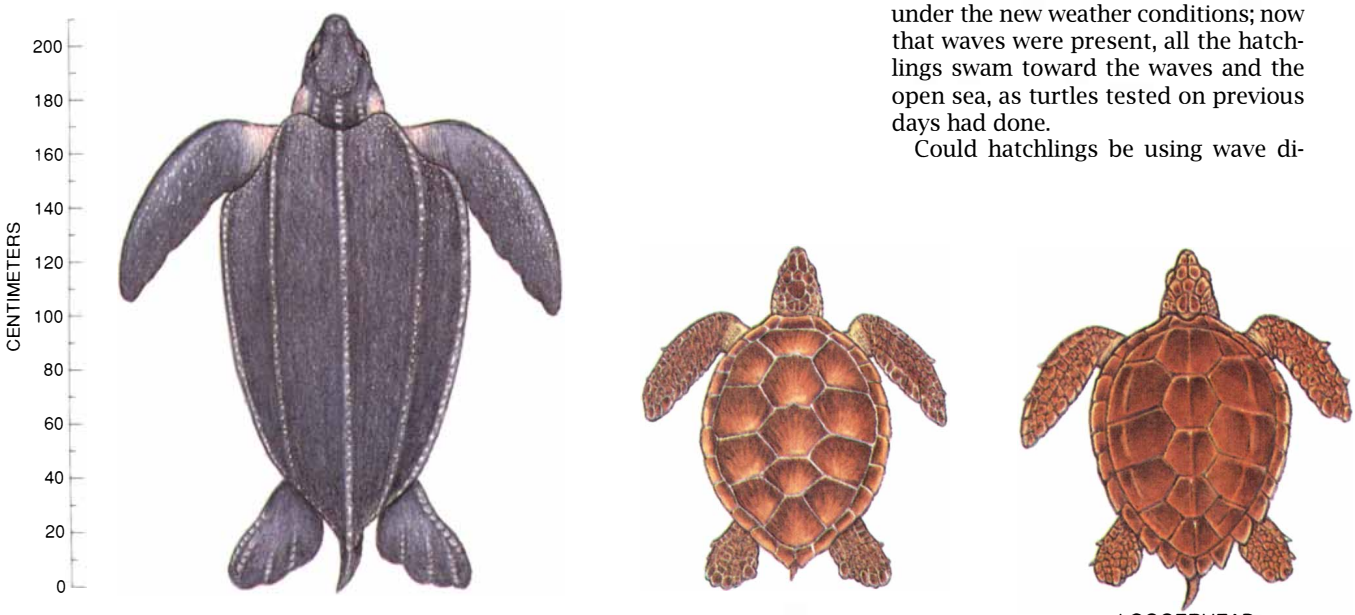
But a few days later, on a hot, unusually calm morning with almost no breeze, the behavior of the hatchlings took a surprising twist. We had run our research boat just a few miles offshore and tethered hatchlings to the floating buoy as before. For the first time, the turtles behaved as if confused: some swam aimlessly in circles; others established courses in seemingly random directions, including back toward shore. We were confused as well. If the hatchlings were using the magnetic field of the earth to guide them toward the open ocean, why didn't they behave like the turtles we had tested before?

As we sat in the boat pondering this unexpected change in behavior, a breeze slowly picked up, generating small waves on the glassy ocean surface. Almost as soon as we noticed these tiny waves moving westward toward shore, the hatchling turtle under observation turned abruptly and began to swim out toward the open ocean, adopting a course straight into the approaching waves. We continued to test hatchlings under the new weather conditions; now that waves were present, all the hatchlings swam toward the waves and the open sea, as turtles tested on previous days had done.

Could hatchlings be using wave di-

Sea Turtles of the World

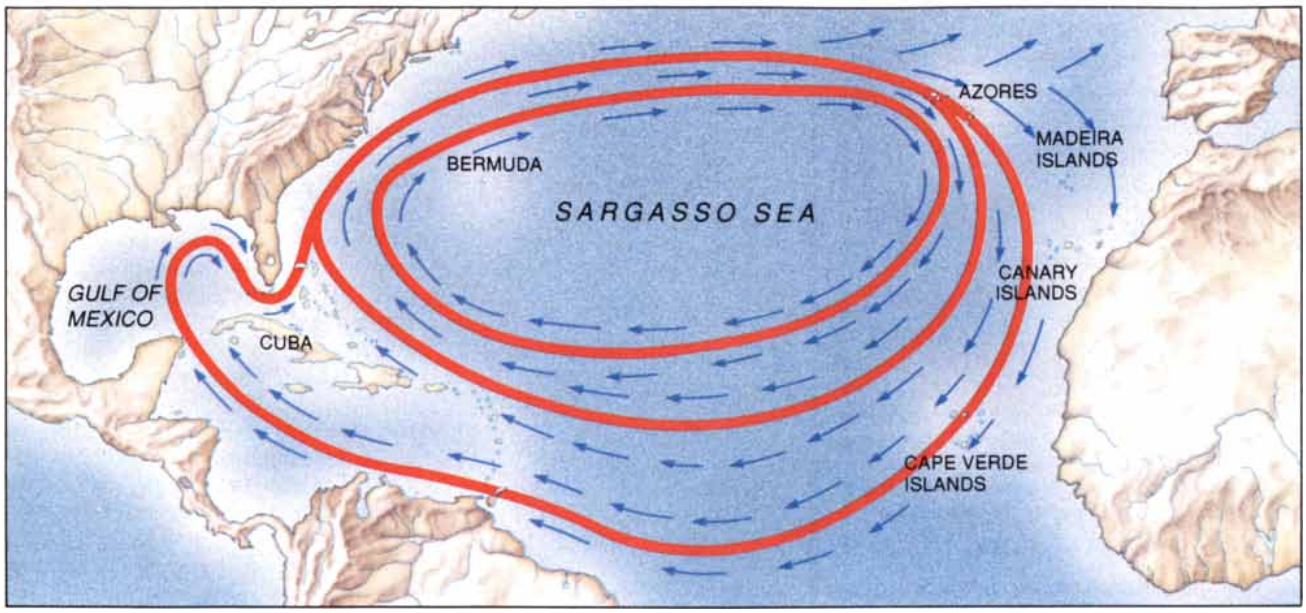
Most species are found throughout the world's tropical and subtropical waters; leatherbacks are occasionally sighted as far north as Scandinavia. Some species, however, do not range far. Kemp's ridley turtles remain in Atlantic waters, and flatbacks inhabit the South Pacific, near Australia. Some taxonomists consider the green turtle in the eastern Pacific Ocean to be a distinct species.



LEATHERBACK
(*Dermochelys coriacea*)

GREEN
(*Chelonia mydas*)

LOGGERHEAD
(*Caretta caretta*)



MIGRATORY PATHS of sea turtles (*red*) provide evidence of extraordinary navigational abilities. After leaving their Florida nesting beach, loggerhead hatchlings may swim around the Sargasso Sea a number of times before returning to their home area to nest several years later. They are about half-grown at that time. Arrows indicate the flow of ocean current.

rection as an orientation cue? To find out, we took hatchlings of three species of sea turtles—loggerheads, green turtles and leatherbacks (*Dermochelys coriacea*)—to the laboratory and tethered them inside a wave tank. The tank was partly constructed of steel beams, which distorted the local magnetic field. Under these conditions, hatchlings did not show directional preferences when waves were absent. When waves were generated, however, the turtles swam into them, demonstrating that they could maintain a consistent course by using waves as an orientation cue.

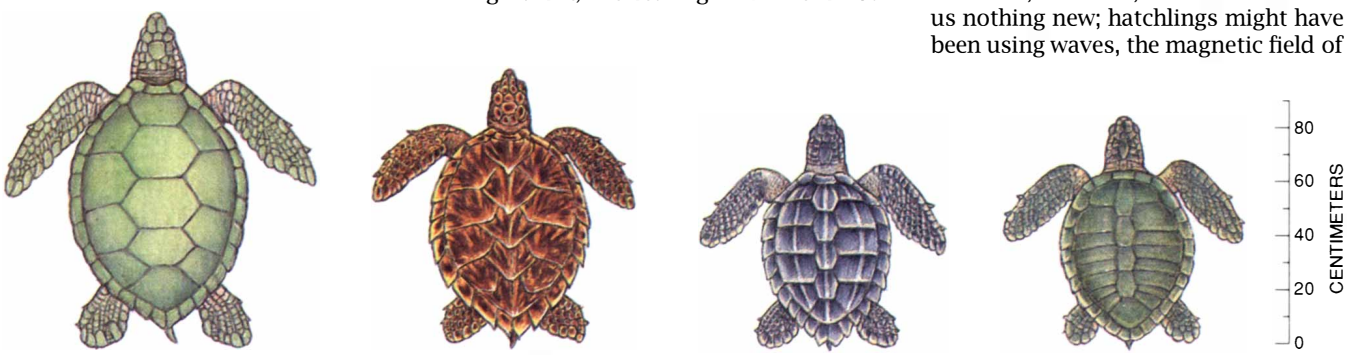
So we knew, at least in the laboratory, that hatchling turtles could orient themselves by detecting waves as well as by detecting the earth's magnetic field. But under natural conditions, do sea turtles use waves, the geomagnetic field or some completely different cue to guide their offshore migration? When would they prefer one cue over another or use a combination of cues? If the geomagnetic field is used, then why did turtles tested on the calm day in the ocean fail to swim seaward using their magnetic compass sense?

The questions were not easy to answer. On the few occasions when waves moved in directions other than toward shore, hatchlings in the floating cage usually swam toward the waves regardless of the direction from which the waves came. Suggestive as the results were, a problem persisted: the restraint imposed on the turtles by the tethering system might conceivably have prevented hatchlings from using other, as yet unidentified cues.

For example, nearly two decades ago laboratory studies by Marion Manton and his colleagues at Columbia University showed that juvenile green turtles can detect chemicals dissolved in water. If hatchlings normally migrated offshore by detecting a chemical gradient (or even a temperature or salinity gradient) stretching from the Gulf Stream to the Florida coast, then tethering turtles in one location would prevent them from comparing the water in different locations, thus precluding detection of a gradient at all. Tethered hatchlings might therefore swim toward waves because other cues they might prefer to use were not available.

To examine these possibilities, we studied the orientation of unrestrained hatchlings released offshore. In contrast to the floating-cage experiments, we made no attempt to monitor the orientation of turtles for prolonged periods. We simply dropped each hatchling into the ocean and recorded the direction it swam as it paddled away. The hatchlings presumably had access to all cues available to them during the normal offshore migration.

In initial tests conducted under typical weather conditions, unrestrained hatchlings oriented themselves into waves as they swam away. Because waves approached from the seaward direction, however, these results told us nothing new; hatchlings might have been using waves, the magnetic field of

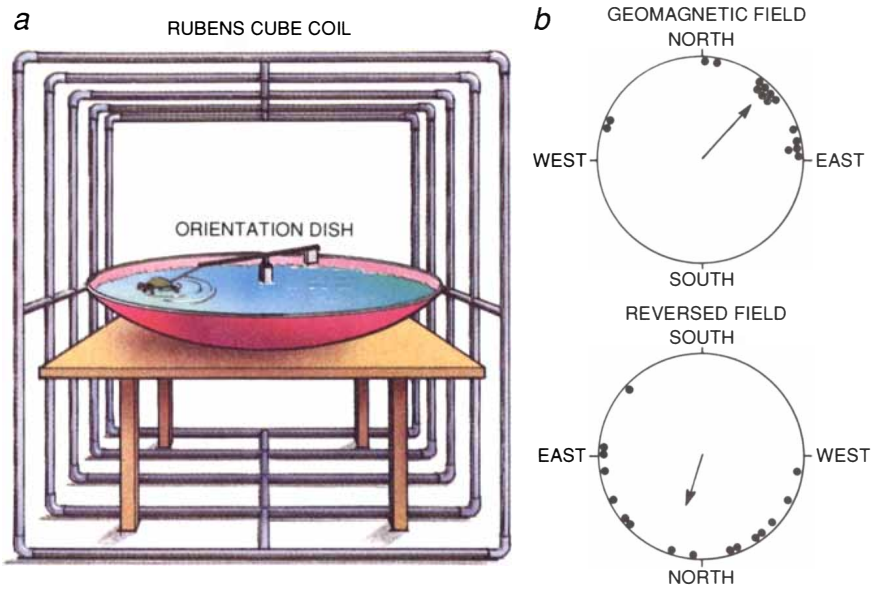


FLATBACK (*Chelonia depressa*)

HAWKSBILL (*Eretmochelys imbricata*)

KEMP'S RIDLEY (*Lepidochelys kempi*)

OLIVE RIDLEY (*Lepidochelys olivacea*)



MAGNETIC-ORIENTATION APPARATUS demonstrates that Florida loggerhead hatchlings can detect the earth's magnetic field (*a*). Each turtle is tethered to the lever arm, which electronically tracks the turtle's swimming direction. The Rubens cube coil is used to reverse the direction of the magnetic field. Findings (*b*) show that most individuals (*dots*) swim in directions between magnetic north and east under both conditions. The arrow represents the average direction of the group.

the earth, a chemical gradient or some other cue to establish their offshore bearings. To determine whether waves were of primary importance, we needed a day in which waves moved in an unusual direction—that is, in some direction other than straight toward shore. Then the hatchlings would have to decide whether to swim toward the waves or to move seaward using another cue.

Our chance to resolve the issue finally arrived in the autumn of 1989, when Hurricane Hugo swept north along the coast of Florida. On its way to landfall, the storm spawned peculiar weather throughout much of the Southeast. One morning soon after the hurricane passed, we awoke to find a strong wind blowing out of the west, away from land and toward the open sea. Recognizing a unique research opportunity, we loaded hatchlings into a Styrofoam cooler and hastily ran our research boat out to sea.

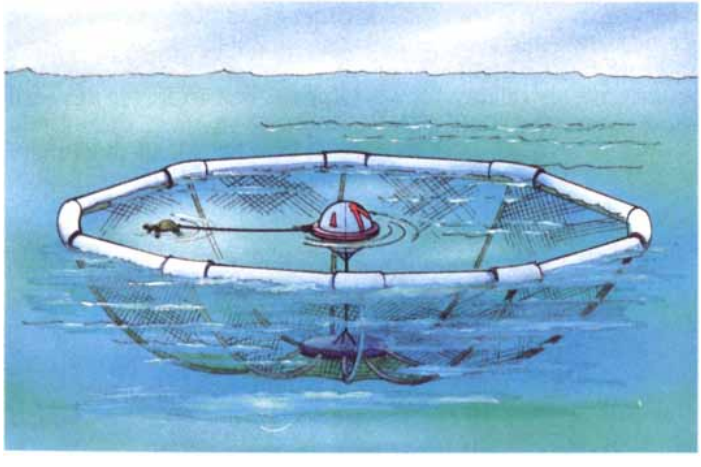
Five miles offshore we found what we were looking for: an area in which waves were clearly moving eastward toward the open ocean and away from land. Under these rare and short-lived conditions, we released hatchlings one by one and observed the direction in which they swam. The results were remarkably clear: most of the turtles swam toward the waves, even though this orientation led them back toward shore.

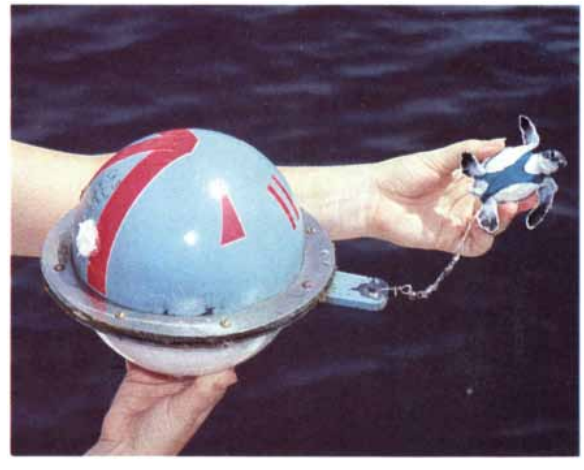
We were fortunate enough to be able to repeat this experiment several times during the next few weeks, as more unusual weather temporarily generated waves in other atypical directions. In each case, the hatchlings swam toward approaching waves, regardless of the magnetic direction from which the waves came. These results indicated that the hatchlings were indeed using the direction of wave propagation to guide their migration.

Why might hatchlings use ocean waves as an orientation cue? Waves entering the shallow waters near the beach refract until they move toward the shoreline. Thus, wave movement is normally a reliable indicator of offshore direction, and swimming into waves usually results in movement toward the open sea.

Although wave direction is apparently the primary cue used by hatchlings during the early phases of the offshore migration, other cues may simultaneously or subsequently be used. The magnetic sense, for example, might eventually supplant wave orientation when hatchlings enter deeper water, where waves are a less reliable indicator of offshore direction. Partial reliance on other mechanisms, including chemosensory, visual or other as yet unidentified cues, also cannot be ruled out.

As remarkable as the orientation abilities of hatchlings seem, adult sea turtles are capable of even more complex and sophisticated navigational feats. Unfortunately, it is difficult to track these creatures over the immense stretches of water through which they migrate, and their size and weight



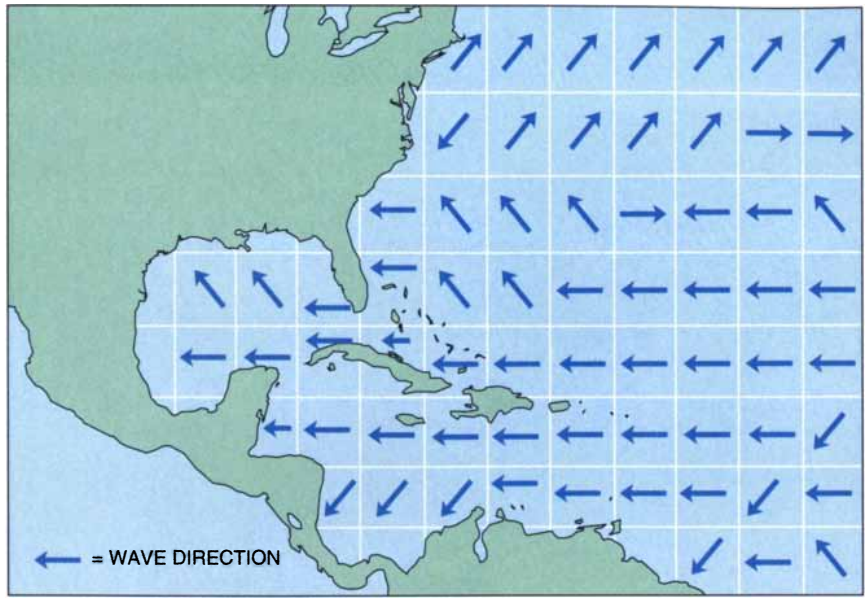


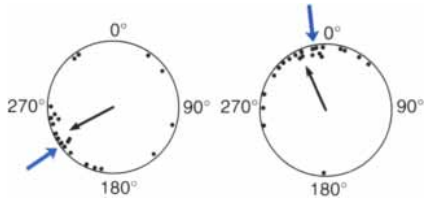
FLOATING ORIENTATION ARENA studies the cues hatchlings use in the ocean. A harnessed turtle (*photograph*) is tethered to a partially submerged buoy. The net around the buoy protects the hatchlings from predatory fish. Because the buoy rotates easily, a turtle can swim toward any direction. Most hatchlings head directly into approaching waves.

make them mostly unsuitable for laboratory experiments. But based on the limited research done on adults (mostly tagging studies) and our own experience with hatchlings, we can infer the navigation problems adult turtles face and speculate about how they might overcome them.

One important difference between hatchlings and adults is that adult turtles seem to be able to fix their position with respect to their destination. Because the Gulf Stream flows parallel to the coast, Florida hatchlings need only maintain a consistent offshore course to intersect the current. Such orientation can be accomplished with a simple compass sense or perhaps just by swimming into the waves. But a compass sense alone is not sufficient to guide an adult female turtle back to a specific nesting beach; she also needs to know where she is. Researchers refer to such an ability in animals as a "map sense."

To understand the difference between compass sense and map sense, consider the dismal situation you would confront if you were blindfolded, flown by helicopter to a clearing in a forest too enormous to walk out of, given a compass and told to meet your return flight in an hour at another clearing, which is located exactly at the center of the forest. By using the compass, you could maintain a straight course, but this ability alone could not guide you directly to your destination in time. You would first need to know where you were with respect to the central clearing—whether, for example, you were located east or north of it. A compass, then, would not be enough. You would also need a map, or a map sense.





WAVE DIRECTION = 234 DEGREES

WAVE DIRECTION = 357 DEGREES

WAVE DIRECTION ordinarily provides a good orientation cue: during the hatching season, waves typically move toward the coast (*above*). The swimming directions of hatchlings dropped into the ocean during unusual weather conditions confirm that the turtles use waves to guide their offshore migration. They swim into waves even if the direction leads them back to shore (*left*).

Relatively little is known about the map sense of animals. Detailed investigations have been carried out only on birds, and experts do not agree on either the precise nature of the map or the cues used. In both birds and sea turtles, however, the ability to detect magnetic fields is theoretically well suited for determining position.

Several geomagnetic parameters vary in a consistent and predictable manner according to latitude, such as the field-line inclination (the angle at which magnetic field lines intersect the surface of the earth, sometimes called the dip angle) and the field intensity in the horizontal and vertical directions. Any of these features could be used as one component of a map for determining position with respect to a goal.

An additional source of magnetic information potentially available to sea turtles exists in the form of the magnetic maxima and minima stripes on the ocean floor. Such stripes occur in seafloor-spreading zones, that is, areas where continental plates diverge. The plates move apart at a rate of a few centimeters per year. Molten material here continually seeps out along the ocean floor. As the material cools, it acquires a magnetization parallel to the direction of the geomagnetic field.

Because the polarity of the earth's magnetic field has reversed at irregular intervals over geologic time (at least 23 times in the past five million years alone), stripes of ocean floor formed during periods of opposite geomagnetic polarity are magnetized in opposite directions. As the seafloor spreads, the plates diverge further, eventually resulting in a series of alternating stripes along the ocean floor. The magnetic signal of each stripe either adds to the local geomagnetic field, enhancing the total field slightly (creating magnetic maxima), or opposes the present earth's field, decreasing it (resulting in magnetic minima).

These stripes of maximum and minimum magnetic intensity are detectable over large regions of the open ocean. Studies by Joseph L. Kirschvink and his colleagues at the California Institute of Technology have shown that whales and dolphins often become stranded on beaches where magnetic minima intersect land, suggesting that cetaceans may follow such pathways during migrations. These pathways might also provide migrating sea turtles with directional information.

Just as the nature of the map sense remains mysterious, so too are the compass cues used by adult turtles to guide them as they migrate. The magnetic field is one clear possibility. Wave propagation direction is another; in many parts of the open ocean, waves and swells provide a consistent directional cue for much of the year. Ocean swells reflect wind patterns that prevail over huge expanses of open water and endure for considerable periods. Thus, because the propagation direction of swells in a given area is determined by prevailing wind conditions hundreds or thousands of miles away, swell direction is largely independent of local weather patterns and varies little over weeks or months. The seasonal constancy of swell direction has long been recognized; Polynesian navigators, for example, employed it in their long-distance voyages.

Whether adult turtles use waves as a cue is not known. During migrations, adults almost certainly swim in directions other than straight toward waves. Thus, the tendency of hatchlings to

HATCHLING SEA TURTLES scamper down Nancite Beach, in Santa Rosa, Costa Rica, to the relative safety of the ocean. Researchers think the few of these olive ridleys that reach adulthood will navigate back to the same beach to nest.

swim directly into waves might be supplanted in juveniles and adults by the ability to hold courses at fixed angles to waves (a wave compass).

Chemosensory cues might also be used by sea turtles in at least some migrations. Several researchers have theorized that the Ascension Island green turtles might home in on their nesting beach by detecting dissolved chemicals unique to the island (a chemical signature) from hundreds of miles away. Calculations by Arthur L. Koch and his colleagues at the University of Florida have suggested that the concentration of natural chemicals entering the sea at Ascension Island might dilute surprisingly little—only about 100 to 1,000 times—before reaching Brazil.

Several considerations, however, cast doubt on the hypothesis that turtle navigation is based solely on chemical cues. Green turtles near the coast of Brazil almost certainly cannot detect a chemical gradient originating at Ascension without sampling and comparing the water in locations separated by many miles. Moreover, the ability of green turtles that nest at Tortuguero (and elsewhere) to converge on specific nesting beaches from widely dispersed feeding grounds (both upstream and downstream) argues for navigational mechanisms that are not strictly chemosensory.

Orientation based on the positions of the stars also seems unlikely. Although many migratory birds use star patterns in orientation, anatomic studies of sea turtle eyes by Koch, now at Indiana University, and his colleague David W. Ehrenfeld of Rutgers University have revealed that adult sea turtles are extremely myopic when their heads are above water. They are therefore almost certainly unable to discern star configurations at night.

The extraordinary navigational abilities of sea turtles have no doubt contributed to their evolutionary success, enabling them to exploit feeding grounds far removed from nesting sites. They are an ancient group of animals, relatively unchanged in the fossil record for millions of years.

Yet despite their long history, sea turtles now face unprecedented threats to their survival. Years of relentless turtle fishing and egg harvesting have wiped out some nesting populations entirely. Many other populations—faced with widespread loss of nesting beaches from human encroachment, growing marine pollution and accidental drowning in fishing nets—are also in jeopardy. Two of the three species of sea turtle that nest in Florida (the leatherback and the green turtle) are now classified as endangered, and the third (the loggerhead) is considered threatened. Moreover, the strong fidelity for the nest site exhibited by many sea turtles means that depleted populations are not likely to be replenished by individuals from other areas.

Some hope exists. Knowledge of the orientation cues hatchlings use now enables workers to release laboratory-reared turtles under conditions that maximize their chances of successfully migrating offshore. Conservationists are also trying to exploit the turtles' navigation prowess by moving eggs to protected beaches. The turtles hatching in the safe havens may return there to nest. Understanding how adult turtles navigate may one day enable returning females to be tricked into nesting on protected beaches. Studying the orientation mechanisms of sea turtles not only provides insight into one of the most sophisticated navigation systems ever to evolve, it may also help save these animals from extinction.

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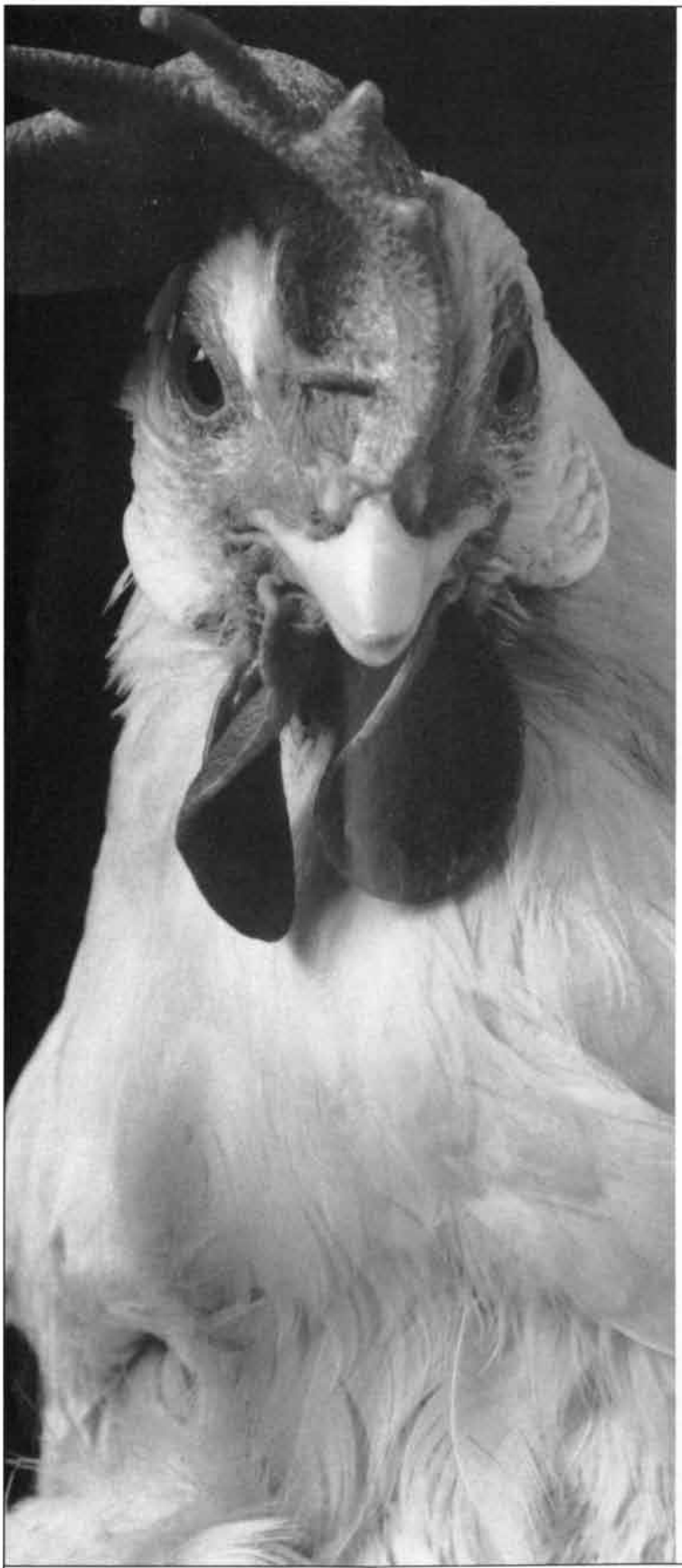

SHE'D BE SMILING AT THE WAY THE FRENCH TREAT HER, IF ONLY SHE HAD LIPS.

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SCIENTIFIC AMERICAN FRONTIERS

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THE POWER IS ON

Tribal Warfare

Contact between Europeans and Native Americans may have shattered a delicate social balance that had existed among local tribes. One result was widespread violence

by R. Brian Ferguson

On the sixth day of January 1493, Christopher Columbus began his voyage back from the New World, leaving 38 of his crew on the island of Hispaniola. Their settlement, Villa de la Navidad, was near the village of the Taino chief, Guacanagari, who Columbus said "was proud to call me, and to treat me as, a brother." Columbus was convinced of the peaceful character of the local Indians.

But when he returned less than a year later, the men of Villa de la Navidad were dead. The settlement and blockhouse had been destroyed. Guacanagari blamed the destruction on more powerful chiefs who lived inland, and Columbus soon witnessed their continuing attacks on the villages of Guacanagari. But his crew also found the possessions of the dead Spaniards, including a ship's anchor, which Columbus believed would not have been bartered, concealed in the houses of Guacanagari's people. Columbus never discovered what actually happened.

The explorers and conquerors who followed Columbus often dwelt on lurid stories of unbridled native violence. When the philosopher Thomas Hobbes wrote in 1651 of the primeval war of "every man against every man," he observed that "the savage people in many places of America…live at this day in that brutish manner." Accepted wisdom even now holds that "primitive" cultures are typically at war and that the primary military effect of contact with the West

R. BRIAN FERGUSON is a cultural anthropologist who studies the causes and consequences of war. He has also investigated directly the interaction of local and large-scale processes involved in the relations between Puerto Rico and the U.S. Ferguson hopes eventually to merge these two distinct interests to develop a general approach for understanding social conflict and change. He is currently associate professor of anthropology at Rutgers University.

POLITICAL CARTOON from the War of 1812, drawn by the Scottish-born caricaturist William Charles, illustrates one of the ways that Native Americans could become embroiled in violence as a result of European presence. During the 18th cen-

is the suppression of ongoing combat.

In fact, the initial effect of European colonialism has generally been quite the opposite. Contact has invariably transformed war patterns, very frequently intensified war and not uncommonly generated war among groups who previously had lived in peace. Many, perhaps most, recorded wars involving tribal peoples can be directly attributed to the circumstances of Western contact.

Only in the past decade have anthropologists come to recognize that such a course of events is indicative of what could be called a "cultural Heisenberg effect." If Westerners are there to record events, be they anthropologists or conquistadors, their presence may be influencing native behavior.

People of the New World are not the only ones whose social patterns have been disrupted in this fashion. European imperial expansion around the globe has occasioned similar transformations of war—although with important variations related to local resistance to Western diseases, the implementation of metallurgy and so on. Nor is the colonial expansion of Europe unique. Contemporary states of the Third World, along with ancient states from the Chinese to the Aztecs, have had major impacts on war among the nonstate peoples at their peripheries.

Neil L. Whitehead of the University of Oxford and I have attempted to map the contours of what we call "war in the tribal zone"—the area that extends outward from a state frontier and is affected in demonstrable ways by the proximity of the state. Patterns of war in this zone are transformed both directly by contact with the state and through interaction with larger changes resulting from the state presence. War is, after all, an expression of politics, and politics is a function of the total organization of society. That organization may undergo dramatic change in response to an expanding state, and the change often begins long before any literate observer arrives on the scene.

Anthropologists have identified three major causes of social change that can destabilize the tribal zone: diseases introduced by settlers, transformation of ecosystems by alien animals and plants, and changes in the way of life made possible by new goods and technologies. There is much debate about the extent of Native American deaths from new diseases before face-to-face contact with Europeans, but there is no question that massive losses followed quickly on the establishment of missions, forts and trading posts. Frequently these first epidemics were interpreted as a result of witchcraft by local enemies, and aggressive retaliation against presumed culprits ensued. More generally, for groups whose society, economy and politics all rest on a base of kinship, the sudden loss of a third or half of a population is catastrophic—perhaps even more destabilizing than was the Black Death in Europe.

Ecological transformation often preceded the European advance as plants and animals introduced by colonists began to spread by themselves. In some cases, these changes were so widespread that is difficult to assess what the natural environment was like in places such as New England before 1500. As the natural world changed, so did the interaction between native peoples and that world. This change often revolutionized both the organization of work and social arrangements built on that organization.

Trade in manufactured goods has dominated the interaction of states and their nonstate neighbors since the time of Mesopotamia, but industrial production puts European expansion in a class by itself. Steel tools, for example, are several times more efficient

tury, colonists offered bounties both to natives and to other colonists for the scalps of enemy natives and Europeans. In addition, all nonnative warring factions in the New World employed native tribes as auxiliaries.

than are stone implements. The acquisition of axes and machetes enabled many Amazonian groups to expand their forest gardens and to begin production of manioc for trade with Brazilian woodsmen.

In most of the New World, metal tools passed along indigenous trade networks far ahead of the Europeans themselves. The passage of large quantities of such valuable items restructured those trade systems, and the exploitative terms imposed by native groups who had a monopoly on the supply of European goods often generated violent disputes. Other items besides steel rapidly became necessities in indigenous societies, in particular guns and ammunition. Guns were not always superior to native arms in the early centuries of contact (as many Europeans learned), but they nonetheless led in many situations to a marked intensification of the killing.

Epidemics, ecological change and new technologies can precede face-to-face contact. The actual presence of Europeans adds even more complexity to the tribal zone. One especially complicating factor is the number of states attempting to operate in the same area. The simultaneous presence of English and French colonial agents in 18th-century North America, for example, gave the local population more political latitude in which to maneuver, but it also embroiled them in foreign rivalries.

The relations between Europeans and natives were also complicated by issues such as the dominant enterprise of a settlement (military, scientific, religious or economic), the degree of administrative control or influence sought by the Europeans, the mix of coercive and seductive measures used to control local peoples and the extent to which natives were incorporated into the colonial society. The interactions of Europeans and local groups—each with their own political hierarchies, group affiliations and factional divisions—generated new arrangements of indigenous people, either locked in the divisive opposition of war or joined by common interests of trade or alliance.

Paradoxically, there is strong evidence that much of the tribal structure recorded by Europeans was in fact called into being by their presence. State agents have great difficulty dealing with indigenous people as they are often organized—without authoritative leaders or fixed group identities. So they strive to create both, appointing chiefs and imposing cultural and political boundaries. These artificial boundaries in turn quickly become integrated into the fabric of native society because they are instrumental in the crucial matter of interacting with state agents.

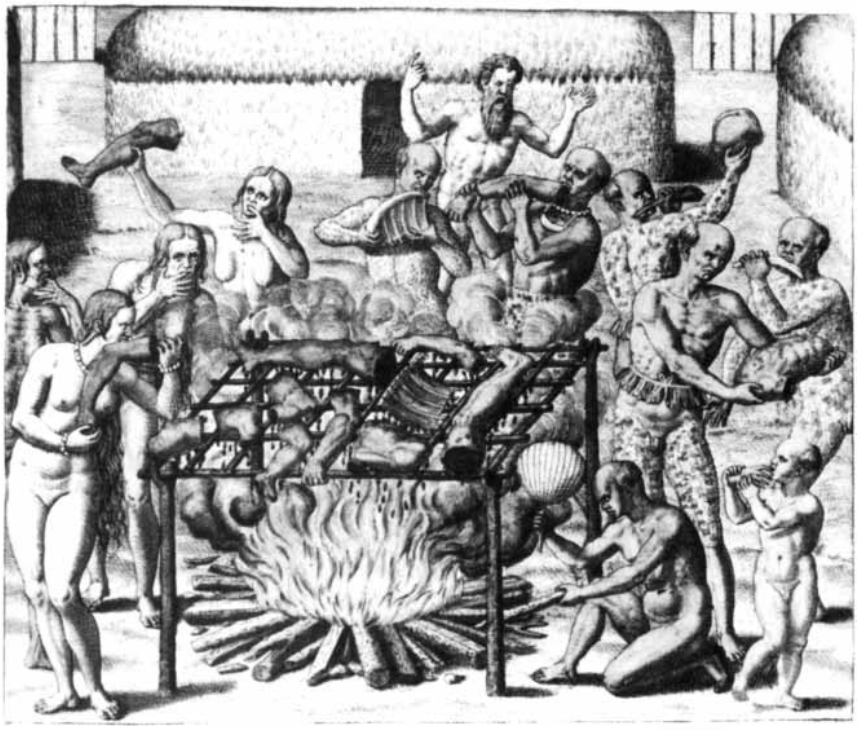
The direct and indirect effects of European contact combine to foster many kinds of war. Whitehead and I divide these conflicts into three broad types, although in actual practice they often appear in combination. First are wars of resistance or rebellion, in which natives seek to hold back or to push out Europeans.

This type of reaction was by no means automatic: generally Europeans were well received, until their predatory behavior became intolerable. Nor was colonial victory in battle assured, especially in the early centuries. Ultimately, however, the ability of states to reinforce their troops from overseas, skillful use of a divide-and-rule strategy, readiness to violate local conventions of war, and technology and military organization led to the defeat of indigenous forces.

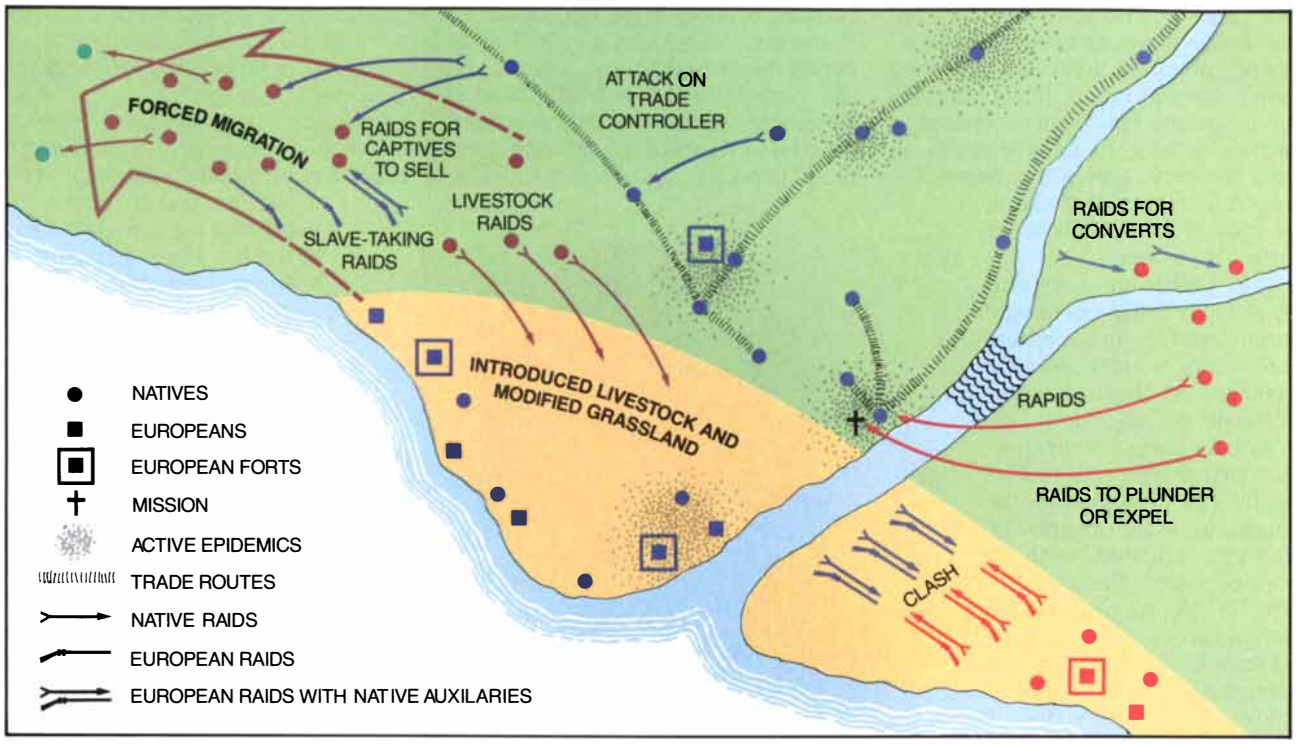
The second type of war pits native against native under European direction. This ethnic soldiering was most prominent in the 16th and 17th centuries, when foreign armies rarely went to war without masses of native auxiliaries. Local people were trained in European combat formations and sometimes equipped with European arms. Even as late as 1883, U.S. forces pursuing Geronimo were made up mostly of recruited Apache scouts.

The third type is internecine warfare waged by sovereign peoples within the tribal zone. Conflict over Western goods is only one cause of such wars. Another is hostility resulting from population displacements: as native peoples fled or were pushed by expanding frontiers, refugees were often forced into territory occupied by others or compelled to compete with similar groups for a shrinking total area. The most devastating wars, however, are those aimed at procuring captives to sell or barter to the Europeans. This type of raiding, combined with the ravages of new diseases, decimated the populations in many parts of the Americas.

These different kinds of war are illustrated in a number of well-studied cases, ranging from shortly after the time of Columbus to the present. The published narrative of Hans Staden, held captive around 1550 by the Tupinamba of the Brazilian coast, titillated Europe with images of savagery. Even by this early date, however, the Tupinamba had been enlisted as allies in wars between the Portuguese and the French, embroiled in raids to capture slaves for the Europeans, impoverished by loss of land to colonialists and deliberately encouraged in factionalism and vengeance by settlers who



CANNIBAL FEAST, portrayed in 1594 by Theodore de Bry, may have reflected an ulterior motive. Once a tribe had been designated as cannibals, Spanish law held that anyone could capture its members and force them into slavery.



TRIBAL ZONE is a region extending outward from state boundaries in which the life of tribal groups is disrupted. It is often marked by war, epidemic and ecological change. This zone is the scene both of direct conflicts between settlers and natives and of hostilities between native groups fleeing state influence or competing for access to trade groups.

were following a divide-and-rule policy.

Another people made infamous in early reports were the Carib, notorious for cannibalism and slave raiding. Although both practices do appear in the earliest contact reports, as my colleague Neil Whitehead has shown, the Carib reputation for cannibalism was deliberately inflated. The more careful and less self-serving accounts show that cannibalism was a limited ritual practice in which warriors ate small portions of individuals they captured. Because Spanish law made cannibal tribes fair game for immediate enslavement, Europeans employed stories of huge cannibal buffets as a pretext.

Similarly, the limited information about captives not eaten suggests that they were generally well treated and integrated into the captor society. Only after contact with the West was the sporadic taking of captives transformed into a massive and far-reaching industry supplying the colonial markets.

Late in the 19th century the Mundurucu of the Upper Tapajos River had the reputation of being the most warlike tribe in all of Amazonia. It is not coincidental that they also had the reputation of being the greatest friends of the Portuguese. Indeed, their ferocious long-distance raiding was directed by the Portuguese, who paid them to attack more troublesome peoples and encouraged the warriors to bring back trophy heads.

A few decades later the description of "most warlike" passed to the Jivaro of the Andean foothills, a reflection of their renown for producing shrunken heads. By this time, burgeoning demand in Europe and North America had made the ancient, ritualistic practice of headshrinking a major export business. The standard payment to the Jivaro, one gun for one head, set off a deadly internecine arms race and led to virtually indiscriminate slaughter.

North America saw similar reorientations of warfare. Probably the best-known case is that of the Great Plains tribes. The introduction of horses and guns transformed their entire way of life, and the subsequent intertribal conflicts were closely linked to this continuing upheaval. Encroaching settlements and the growth of trade in buffalo pelts stimulated competition for buffalo rangeland. Raiding for horses contributed to a constant state of war, and peoples such as the Blackfoot and Cheyenne relied on force to preserve their monopolistic access to Western traders.

In the Pacific Northwest, groups such as the Kwakiutl, Haida and Tsimshian had established a centuries-old pattern in which residents of localities with few resources raided those who controlled major salmon rivers and other prime fishing grounds. These hostilities subsided after European contact, as epidemics killed a third or more of the native population. The intensity of war, however, increased as the development of a fur trade incited battles to control the trade. In addition, the growing wealth of some successful tribes stimulated a local demand for slaves. Slave raiding intensified as some local groups found slaves to be the only commodity they could barter for the firearms they needed for self-defense.

In the Northeastern woodlands, competition over fur trading sparked long-distance warfare between the Iroquois and the Huron. The tribes fought to obtain access to trading posts and prime beaver-hunting areas, and they plundered each other's trade goods and pelts. The British and the French, meanwhile, encouraged native warfare as a way of advancing their own competing colonial ambitions.

In other parts of North America, particularly the Southeast and the Southwest, a similar pattern manifested itself. In response to the European demand for slaves, the Cherokee raided tribes to their west, the Pima raided the Yavapai and yet other groups raided the Navaho.

The same factors that can be seen in the historical record still influence war in the tribal zone today. Possibly the

best case study is the Yanomami, a relatively unacculturated people traditionally inhabiting the highlands separating Venezuela and Brazil. In recent years the Yanomami have been victimized by settlers seeking to mine minerals in their territory. They are currently the subject of international efforts to protect their lands from further incursions.

The Yanomami are also known for their seemingly chronic warfare. In the widely read works of anthropologist Napoleon A. Chagnon of the University of California at Santa Barbara, they are portrayed as a virtual type case of savage ferocity. Chagnon cites the Yanomami as an exemplar of Hobbes's primeval state of war and asserts that their society is typical of pre-state conditions.

Chagnon's interpretation has been challenged by William J. Smole of the University of Pittsburgh, the Brazilian anthropologist Alcida R. Ramos and others who have conducted field research among the Yanomami. These researchers have found his reports of violence inapplicable to the people they studied.

Others have contested the claim that Yanomami conflicts result from male competition over women. Marvin Harris of the University of Florida at Gainesville, for example, has long argued that the disputes over women are themselves a result of other problems. He contends that the scarcity of nutritionally necessary game animals creates a sexually charged competition among hunters. The resulting violence, Harris asserts, reduces population growth and leads to a closer match between people and available game. Revenge and belief in witchcraft have also been suggested as explanations for chronic war among the Yanomani.

I believe that all these factors are of secondary importance compared with the continuing effects of "civilized" incursions. Contrary to most scholarly opinion, the Yanomami are not an isolated people. Their location in the rugged Parima highlands appears to be a reaction to slave raids going back to the early 17th century, and their staple food, the plantain, is generally, though not universally, believed to be a European introduction. Slave raids occurred again during the 18th and 19th centuries, and the rubber-tapping industry entered Yanomami territory in force around the turn of the 20th century. The most recent period of direct contact with outsiders is therefore the fourth or fifth wave, not the first.

***TSANTSA* (shrunken head) is sometimes considered an archetypal symbol of native savagery, but most *tsantsas* were produced for the European and North American market. As natives bartered *tsantsas* for rifles, the trade set off an arms race that slowed only when the population had been decimated.**

By examining all available reports of war or peace among all Yanomami from the early 1800s to the 1980s, I have found that in the overwhelming majority of cases, instances of war followed abruptly on some significant change in the Western presence—either a new penetration, a withdrawal or a change in location. Constancy in the presence or absence of Westerners is usually accompanied by peace.

Although many factors are involved in this association, access to Western manufactured goods, especially steel tools, has proved critical to explaining the actual patterns of combat. The Yanomami find steel tools roughly 10 times as efficient as stone axes. They rapidly become necessities for many basic subsistence tasks, such as clearing gardens and gathering firewood.

The Yanomami place extraordinary value on these tools and on other Western manufactured goods used for utilitarian and ornamental purposes. These items are scarce and unequally available. The Yanomami have made hazardous treks and repeatedly relocated villages in their effort to obtain better access to suppliers of Western goods.

Although the Yanomami sometimes raided Western settlements or other villages to obtain goods, plundering is a risky, short-term solution. It is far better to establish a position that allows access to a regular source of goods either by moving the village along a trade route or, even better, by settling next to a mission or some other Western outpost. A powerful group in such a location can obtain a relative abundance of new Western trade goods. Furthermore, a group can derive great benefits by acting as monopolistic middlemen in trade to more remote villages.

Such a group often trades Western goods after they have been worn down by use. In return, they receive a wide variety of valuable local products, such as spun cotton, woven hammocks, bows, quivers, curare-tipped arrows, dogs and food. They also gain an advantage in the intermarriage between villages. Remote villages wishing to establish a trade connection often do so by ceding a wife to the middlemen. In these marriages, middlemen substitute manufactured goods for the years of onerous labor, or bride service, that the groom would normally owe his father-in-law. Those who control access to the Westerners rise in status and in political and mili-

tary reputation, both because of their control of trade and because of (usually well-armed) Western support.

In this context, collective aggression can accomplish several ends. For Yanomami separated from a source of Western goods, raids or an assault on a trading party can force out a middleman or establish a presence along a trade route. For established middlemen, violence can protect their position by keeping a potential competitor from moving in or by thwarting an attempt to travel around their area of control. Within an existing trade relationship, bellicose confrontations in the form of club fights can alter the direction of trade or the rate of exchange for Western goods.

Almost invariably, force is used soon after some change in the source of the goods. Most commonly a more remote group attacks a village located between them and the source. Whether the distant group is successful in driving out the middlemen or whether the middlemen consolidate their position by successful retaliation, a new power relationship tends to be established quickly. Active raiding between two villages rarely lasts more than two years.

The distribution of sources of Western goods can explain major variations in the pattern of combat, but that is not the whole story. The Yanomami around the confluence of the Orinoco and Mavaca rivers, well described by Chagnon and several others, displayed a greater readiness to resort to aggression in the mid-1960s than they did in the early 1940s, at the start of the current wave of contact. The threshold at which conflict turns to war was lower, and factors in addition to trade antagonism were very much implicated in the increased violence.

These and other aspects of life in the tribal zone—including some suggested as the root cause of Yanomami warfare—fit together to create a war complex that pervades society and makes these Yanomami appear to be "the fierce people." Foremost among them is disease—malaria and measles as well as pulmonary and gastrointestinal illness. A series of epidemics began with the current wave of European contact soon after 1940 and has continued with terrible frequency over subsequent decades. As many as 40 percent of the people in a village may die in a single epidemic. Such a catastrophe disrupts the family-based social system, shattering the carefully crafted balance of marriages that once existed.

Over these same decades, large villages anchored near missions have depleted the local supply of game. This loss has led to a decrease in the communal sharing of meat, a practice that serves as the primary basis of solidarity between families in more mobile villages. Epidemics and the disappearance of plentiful game have combined to undermine social solidarity. In its place is an atomistic and competitive situation in which a disposition to violence plays a key role in daily interactions.

The villages that reconstituted themselves after these disruptions were accommodated to the atmosphere of warfare. They were much larger than more traditional villages and so able to field more fighters. The married men tended to remain with their natal kin, rather than moving in with the wife's family as some other Yanomami do. As a result, they were able to mobilize rapidly to defend their interests. Village leaders were elevated in power by the exigencies of war, by their key role as trade controllers and by the support of local Westerners. Usually unobtrusive in traditional villages, some headmen became almost despotic. In addition, relations among villages were structured by possibilities of trade and took on the character of formal military alliances.

These changes ramified through the Yanomami's system of values and beliefs. Status became a central concern, as any perceived slight could signify the beginning of a disastrous erosion of one's position in war and trade. As a result, the Yanomami encouraged belligerence in the young. Those seeking to persuade others of a course of military action skillfully manipulated the idioms of witchcraft and revenge.

Even mythology was adapted to the social climate. The Orinoco-Mavaca Yanomami have an origin myth in which their violence is explained as a result of the blood of a wounded moon falling to the earth. Yanomami in more pacific areas are unfamiliar with this myth.

Perhaps all societies have their origin myths for war. Western civilization has that of Hobbes. Certainly tribal peoples of the Americas knew war before the arrival of Columbus. Militaristic states such as the Inca and Aztec had their own tribal zone, although these areas were probably less turbulent than those created by European colonialism. Even in the absence of any state, archaeology provides unmistakable evidence of war among sedentary village peoples, sometimes going back thousands of years.

Yet the wild violence noted by Hobbes was not an expression of "man in the state of nature" but a reflection of contact with Hobbes's Leviathan—the states of western Europe. To take the carnage as revealing the fundamental nature of human existence is to pass through the looking glass.

In addition to reconstructing the modern understanding of warfare among tribal peoples exposed to Western influence, an appreciation of the war-generating effects of contact may illuminate the mysterious deaths that followed the very first meeting between Europeans and Native Americans. Elements of the events on Hispaniola bear comparison to the Yanomami case: an apparently peaceful local situation turns to war shortly after the establishment of a Western outpost, remote groups raid those closer to the foreigners and the intruders' possessions are looted.

Although the sequence of events can never be known, it is plausible that the men left at Villa de la Navidad, perhaps weakened by disease and internal fights, pressed demands for hospitality on their hosts at the same time that they appeared to have been abandoned and were running short of items to barter. Whether or not Guacanagari's people did all the killing, they unquestionably came to possess many highly desired Western goods. Successful raids against Guacanagari's villages by the traditionally more powerful interior villages would have netted the attackers a share of these precious items and also restored the balance of power that had been upset by Guacanagari's alliance with Columbus.

If this scenario is true—and it has been played out many times in the succeeding five centuries—it would mean that the destabilizing, violence-provoking impact of European contact in the New World began as early as 1493.

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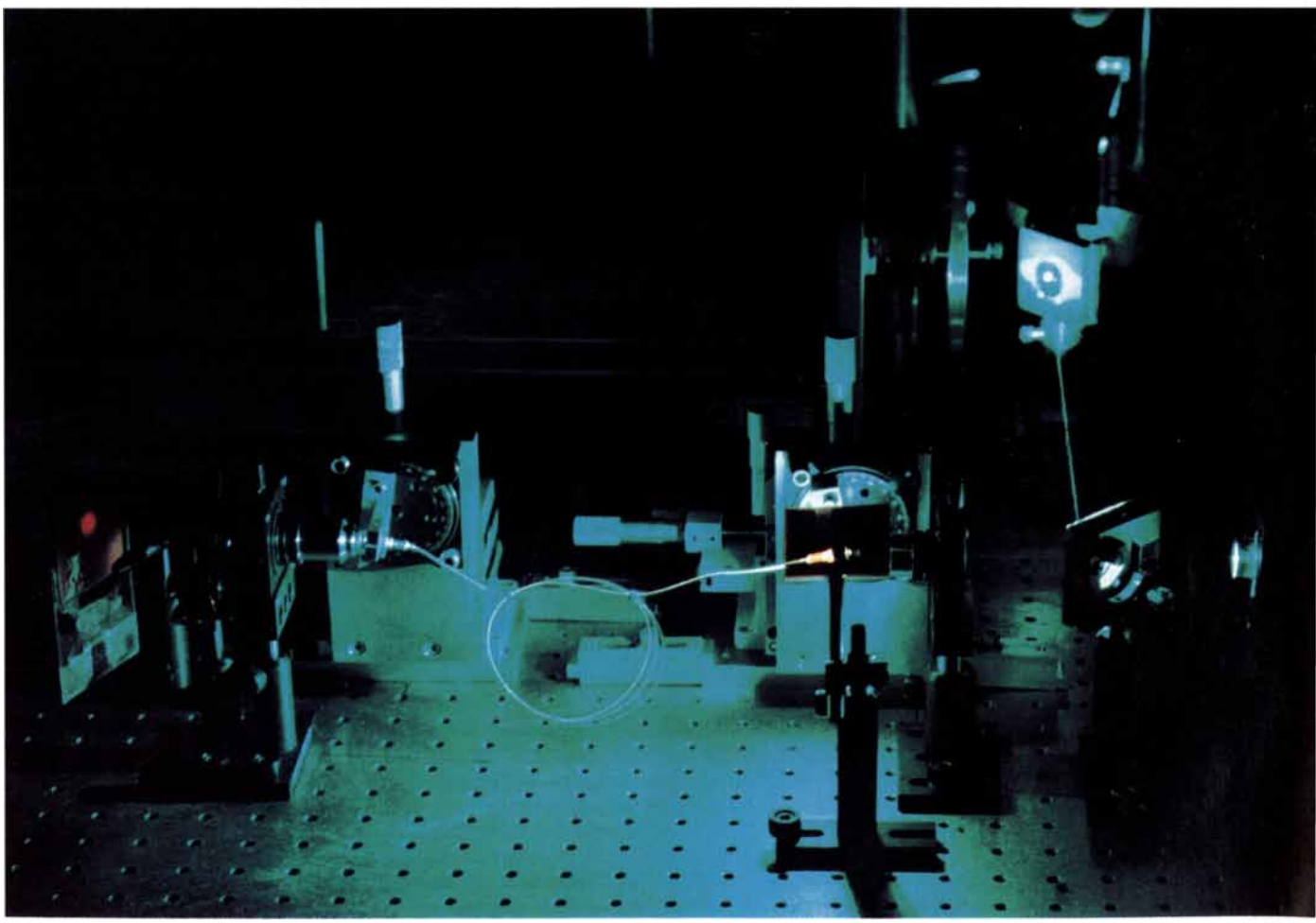
Lightwave Communications: The Fifth Generation

Optical fibers doped with erbium and powered by tiny laser chips are revolutionizing the way signals are regenerated for transcontinental communications and for fast data transmission over fiber-optic networks

by Emmanuel Desurvire

Sometimes innovations emerge when existing technologies or old ideas are applied in unconventional or original ways. Some five years ago many researchers predicted that lightwave communications systems were approaching their peak performance. Ignoring such opinions, a team of researchers reexamined a 20-year-old technology: optical fibers made from silica glass and traces of a rare-earth element. Such fibers can amplify light signals when they are energized by infrared radiation.

Within three years investigators, including myself, had developed a novel type of optical amplifier that is based on a fiber doped with the rare-earth element erbium and is powered by a tiny, efficient radiation source called a laser diode chip. When this fiber amplifier was integrated into communications systems, it increased the transmission capacities of the systems by a factor of 100. In principle, billions of bits of information can be transmitted in a fraction of a second through an uninterrupted cable that stretches a quarter of the way around the planet. In the middle of this decade AT&T Bell



Laboratories and Kokusai Denshin Denwa (KDD) plan to deploy such a cable across the Pacific Ocean, and many other companies are likely to do the same. Each cable will have the capability to carry 500,000 phone calls simultaneously—more than 12 times the capacity of existing transoceanic systems.

Erbium-doped fibers eliminate the need for complicated devices called repeaters, which are used in conventional systems to regenerate weakened signals. Fiber amplifiers can boost signals by greater factors than repeaters, and they can transmit data at higher rates.

The erbium-doped fiber amplifiers will play a major role not only in long-distance communications but also in local-area networks. Fiber amplifiers are ideal for networks that carry vast quantities of information to thousands of users. Such networks could bring high-definition television and video teleconferencing to every home and business.

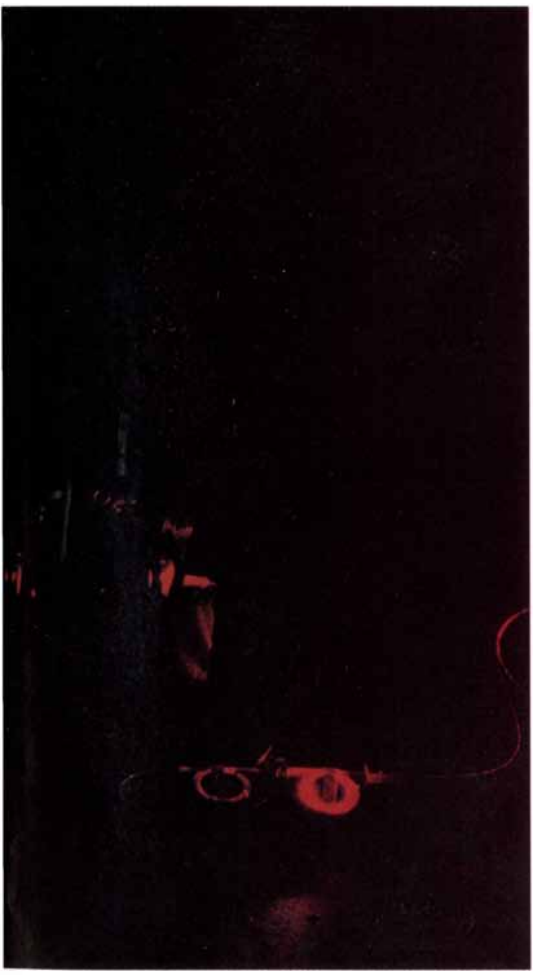
Fiber amplifiers should also be an integral part of future communications systems. They may be incorporated in systems that convey information as a change in the phase and frequency of light rather than as a modulation in intensity as all current systems do. Fiber amplifiers may be important for systems in which information is carried by solitons. These short light pulses can in theory propagate indefinitely in a defect-free optical fiber. If a practical system emerges from any of these concepts, it should greatly exceed the performance of existing systems.

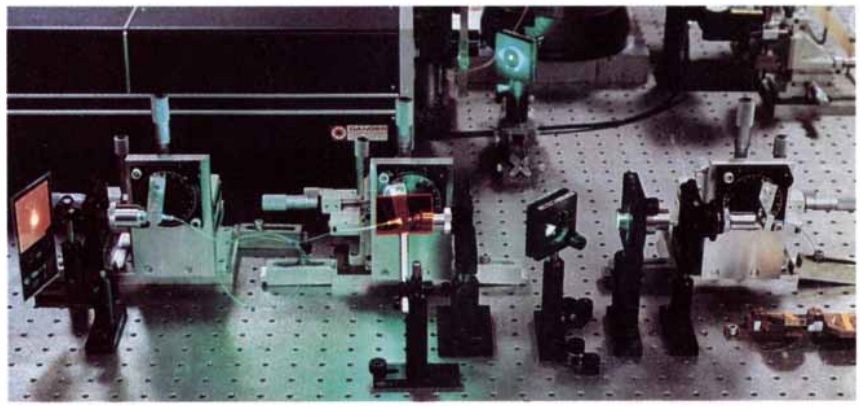
Since 1975 the technology of lightwave communications has progressed, by any standard, at an extremely rapid pace. The technology has evolved as scientists have worked persistently to invent systems that transmit more information at faster rates over longer distances. Innovative systems must also prove practical and cost-effective. During the past 20 years, researchers have launched five generations of lightwave communications systems, each representing a major advance in the technology.

When the first generation of lightwave communications systems was introduced around 1975, it could transmit far more information than could systems carrying electrical signals through copper wires. First-generation systems and those that followed consist of the same basic components: encoding and decoding devices, a transmitter, silica fibers, repeaters and a receiver. The encoding device first converts information into an electrical signal. The transmitter then converts the signal into light. The transmitter, at least in 1975, was a light-emitting diode that produces infrared radiation at a wavelength of 0.87 micron. The diodes respond to changes in the electrical signal by emitting light of various intensities.

In all generations of lightwave systems, light from the transmitter is carried through fibers made of silica glass. A fiber consists of a core, which carries the light, and a cladding, which guides light through the core. As the light signal travels along the fiber, it broadens and weakens. The signal disperses, in part, because radiation of different frequencies propagates at different speeds through the core. The signal attenuates largely because defects or impurities in the glass absorb or scatter light.

A system can compensate for attenuation with repeaters. These devices are placed between lengths of fiber to detect, amplify and reemit the signal.





ERBIUM-DOPED OPTICAL FIBER (the green-glowing coil at the left) will be one of the key components in the next generation of lightwave communications systems. To demonstrate the capabilities of the erbium-doped fiber as an amplifier, the author and his colleagues, then at AT&T Bell Laboratories, built the apparatus shown here in the light (*above*) and dark (*left*). The fiber amplifies infrared light signals when it is energized by green laser light. The erbium atoms in the fiber absorb the green light and jump to a high-energy state. As an infrared light signal passes through the fiber, the erbium atoms transfer their energy to the signal by a process known as stimulated emission. Red light is used to indicate the path of the signal. The signal travels from the right of the apparatus, propagates through the erbium-doped fiber and emerges on the left, where the amplification of the signal is measured.

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Eventually the signal reaches the receiver, which transforms the light back into an electrical signal. Finally, the decoding device translates the electrical signals into a form a telephone or computer can interpret.

The success of each generation of lightwave communications systems ultimately depends on two quantities: how much information can be transmitted in a second through the system and how far signals can travel through a fiber before the signal must be regenerated. The success of the system can therefore be expressed as the transmission capacity, which is defined as the highest bit rate of the system times the maximum transmission length. By 1978, one billion bits (a gigabit) could be transmitted each second through a system 10 kilometers long. The transmission capacity was therefore about 10 gigabit-kilometers per second.

During the next three years, lightwave communications systems reached nearly 100 gigabit-kilometers per second as the second generation emerged. Scientists had improved the technology in two ways. First, by reducing the size of the core of the fiber, they created "single-mode" fibers, which force the light signals to travel at a nearly uniform velocity. This advance greatly reduced dispersion. Second, they developed transmitters and receivers that could handle light at a wavelength of 1.3 microns. This change reduced attenuation because silica glass is more transparent at 1.3 microns than at 0.87 micron.

In 1982 the third generation began to appear as researchers developed manufacturing techniques that increased the purity of silica glasses. By doing so, scientists greatly enhanced the transparency of fibers in the wavelength region from 1.2 to 1.6 microns. To take advantage of this advance, they perfected the technology of the laser diode chip—a high-speed, monochromatic source of laser light. In particular, laser diodes could generate light of 1.55 microns, the wavelength at which silica glass is most transparent. These improvements raised the transmission capacity to hundreds of gigabit-kilometers per second.

By 1984, many researchers believed the basic design of lightwave communications systems had been worked out. But to their surprise, the fourth and fifth generations emerged from a community of scientists working on forward-looking approaches and novel devices.

The fourth generation consists of innovative systems that modulate the frequency or phase of light instead of its intensity. Because such systems preserve the phase and frequency of light, they are described as coherent, just as lightwaves that travel together with the same phase and frequency are called coherent. Systems based on intensity modulation are known as direct detection, because the detectors used in these systems can translate a change in intensity directly into a fluctuation in electric current.

In the laboratory, coherent systems outperform direct-detection systems. Coherent receivers can accurately detect light signals whose intensity is much lower than the minimum that direct-detection systems can discern. Signals can therefore travel farther through a coherent system than through a comparable direct-detection system.

By 1987, coherent systems had transmission capacities almost as high as those of direct-detection schemes. It was far from clear, however, whether either scheme could be improved. Some investigators favored coherent systems because of their greater potential. But they faced serious technical obstacles. They needed to produce light sources whose frequency and phase were very stable. And they had to develop devices that could modulate and detect the phase and frequency of light as easily as conventional components could change and monitor the intensity of radiation. Indeed, researchers had found devices that could accomplish these tasks, but at the time the approaches were too complex and expensive for practical considerations.

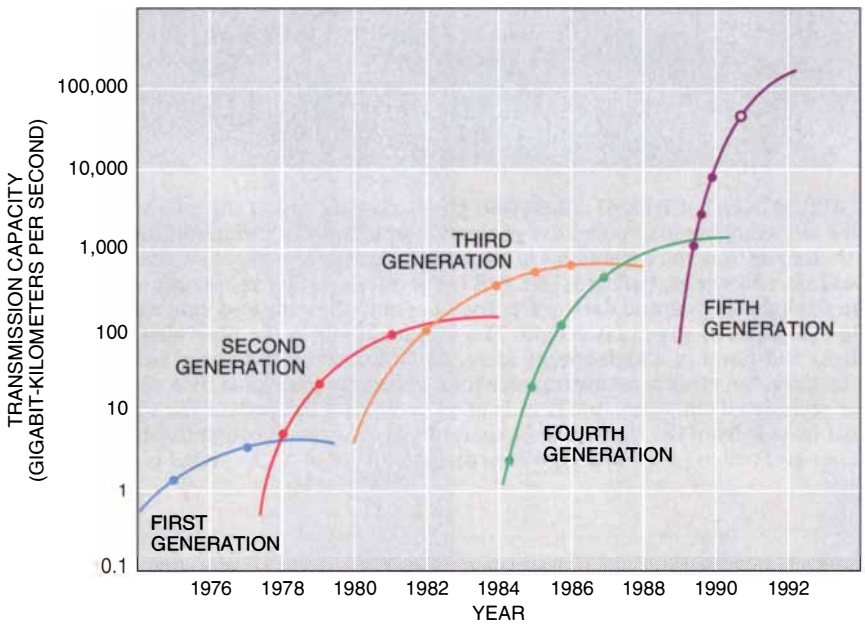
Workers were also struggling to improve direct-detection systems. They knew that if they could invent powerful amplifiers, they could compensate for the limited sensitivity of direct-detection systems. The amplifiers would boost the signals, enabling them to travel over increased transmission lengths.

Many researchers were attempting to build an optical amplifier on a single chip. They succeeded but had difficulty making the devices perform on the lab bench. It was hard to imagine that optical amplifier chips would be implemented on a large scale within several years.

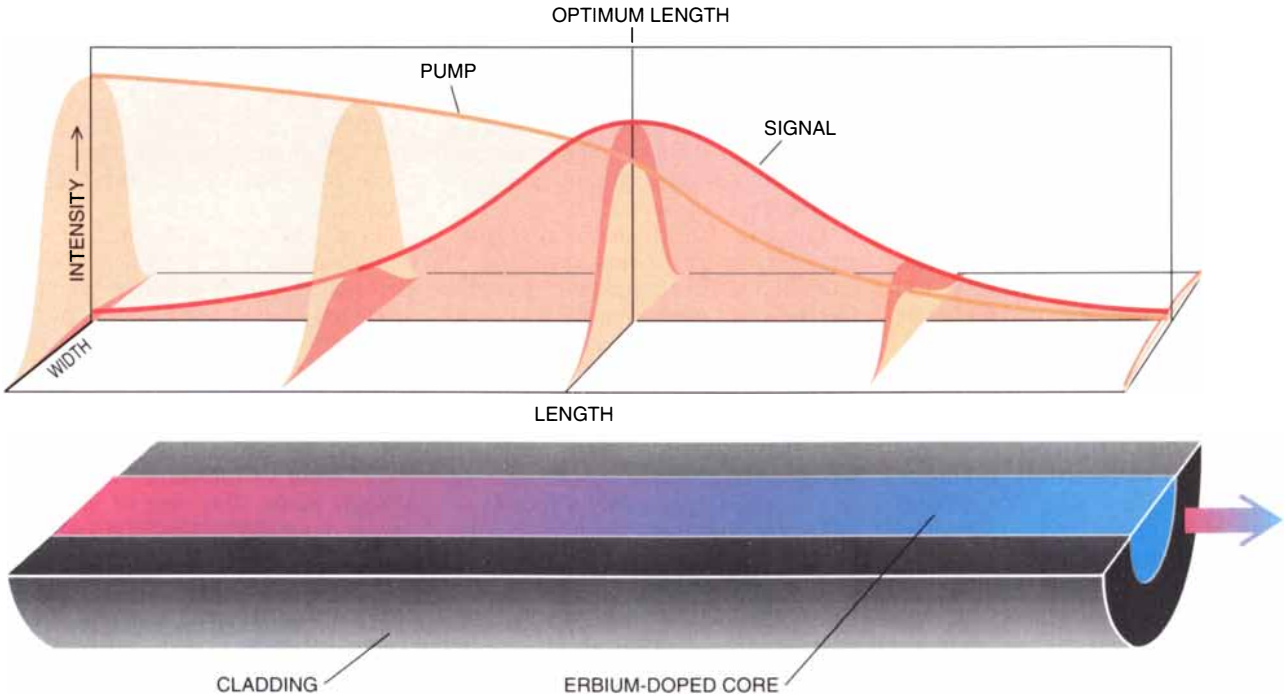
At the end of the 1980s, it seemed likely that both direct-detection and coherent systems would benefit from optical amplifiers. Yet it was not clear what kind of amplifier would prove beneficial. Some researchers, therefore, turned their attention to "exotic" devices.

The breakthrough was the development of the erbium-doped fiber amplifier. The main components of the amplifier are laser diodes and lengths of erbium-doped fiber. The laser diodes power the amplifier by providing infrared radiation at a wavelength of 1.48 or 0.98 micron. The light is absorbed by the erbium atoms, "pumping" them to a high-energy level. When a weakened signal enters the erbium-doped fiber, the "excited" erbium atoms transfer their energy to the signal through a process that Einstein called stimulated emission. In this way, the erbium-doped fiber regenerates the signal.

Erbium-doped fibers are not considered to be "repeaters" even though they



TRANSMISSION CAPACITY of optical fibers has increased 10-fold every four years since 1975. The five generations of the technology are shown. The open circle (*purple*) represents the results from an experiment that simulated long-distance transmissions using a loop of fiber amplifiers and optical fibers.



FIBER AMPLIFIER requires a source of pumping radiation and a single-mode optical fiber whose core is doped with erbium. The fiber amplifies signals as erbium atoms absorb the pumping radiation and transfer their energy to the signals. Hence, the intensity of the pumping radiation decreases over the length of the fiber. As the signal travels through the fiber, its intensity increases until the intensity of the pumping radiation drops below a certain threshold.

act as signal regenerators. Repeaters convert light into electric current, amplify the current and transform it back into light. Erbium-doped optical fibers do not interrupt the path of the light signal as it propagates from transmitter to receiver.

The introduction of the erbium-doped fiber ushered in the fifth generation of lightwave communications systems. Transmission capacities shot up from hundreds to tens of thousands of gigabit-kilometers per second.

The idea of doping optical fibers with erbium and other rare-earth elements dates to the early 1960s, when Charles J. Koester and Elias Snitzer of the American Optical Company investigated fibers doped with the rare-earth neodymium. They discovered that the fibers could be used as a lasing medium and could amplify light. To measure the amplification, they coiled a one-meter length of the fiber around a flash lamp. They found that infrared radiation at a wavelength of 1.06 microns could be amplified by a factor of 50,000, a gain of 47 decibels. (Amplification is usually expressed in decibels, which are defined as 10 times the common logarithm of the ratio of the output power to the input.) A decade later Julian Stone and Charles A. Burrus, Jr., of Bell Laboratories were the first to demonstrate that neodymium-doped fibers could be energized by laser diodes rather than by cumbersome flash lamps or water-cooled lasers.

But during the 1970s, this promising line of research was abandoned. The neodymium-doped fiber amplifiers did not meet the needs of the time. Whereas the fiber amplifiers operated in the range of 1.06 microns, researchers were concentrating on applications that would work at wavelengths close to 1.3 or 1.55 microns, the wavelengths at which silica is most transparent. Could fibers be doped with other elements to make a device that would operate in the proper wavelength range?

The issue was not studied until 1985–86, when David Payne and his coworkers at the University of Southampton revitalized interest in fibers doped with rare-earth elements. In particular, they demonstrated that an erbium-doped fiber could make a novel type of optical amplifier at 1.55 microns. One year later they achieved a 25-decibel gain at this wavelength by pumping an erbium-doped fiber with 60 milliwatts of red light at 0.65 micron.

Most scientists who learned about the work at Southampton probably considered it an interesting piece of physics but nothing very practical. They were justified in their criticism because it is difficult to generate intense red light at 0.65 micron; one must use a large, ponderous laser. But these critics overlooked the fact that erbium can be pumped at other wavelengths. In particular, erbium can be energized with infrared radiation, which can be produced by a very practical device, the laser diode chip.

I was very interested in the work of the Southampton team, having spent a few years experimenting with fiber amplifiers that boosted signals through a process known as Raman scattering. When I joined AT&T in 1986, I wanted to investigate whether the technology of fiber amplifiers could be refined to improve lightwave networks. Just before my arrival, John B. MacChesney and Jay Simpson, who were working in the laboratory, had patented a process for fabricating optical fibers made up of many constituents—including rare-earth elements. I collaborated with them and Philippe Becker, also at Bell Labs, to study erbium-doped fibers.

We used an argon-ion laser to pump an erbium-doped fiber with green light at 0.51 micron. By the middle of 1987, we obtained an encouraging 22-decibel gain using 100 milliwatts of green light. But such results did not generate excitement among network engineers, who justifiably considered the device impractical.

My colleague Randy Giles and I then made a rather unorthodox decision. The next logical step would have been

to give up the approach or to work toward building a more practical fiber amplifier. Instead we wanted to see how well the amplifier could transmit data. We proceeded to measure the error rate of data flow through the strange, green-glowing fiber amplifier. After spending a few hours fighting spurious effects, we obtained an error rate of one part in a billion at a data flow of two gigabits per second. This rate is the industry standard for "error-free" communications.

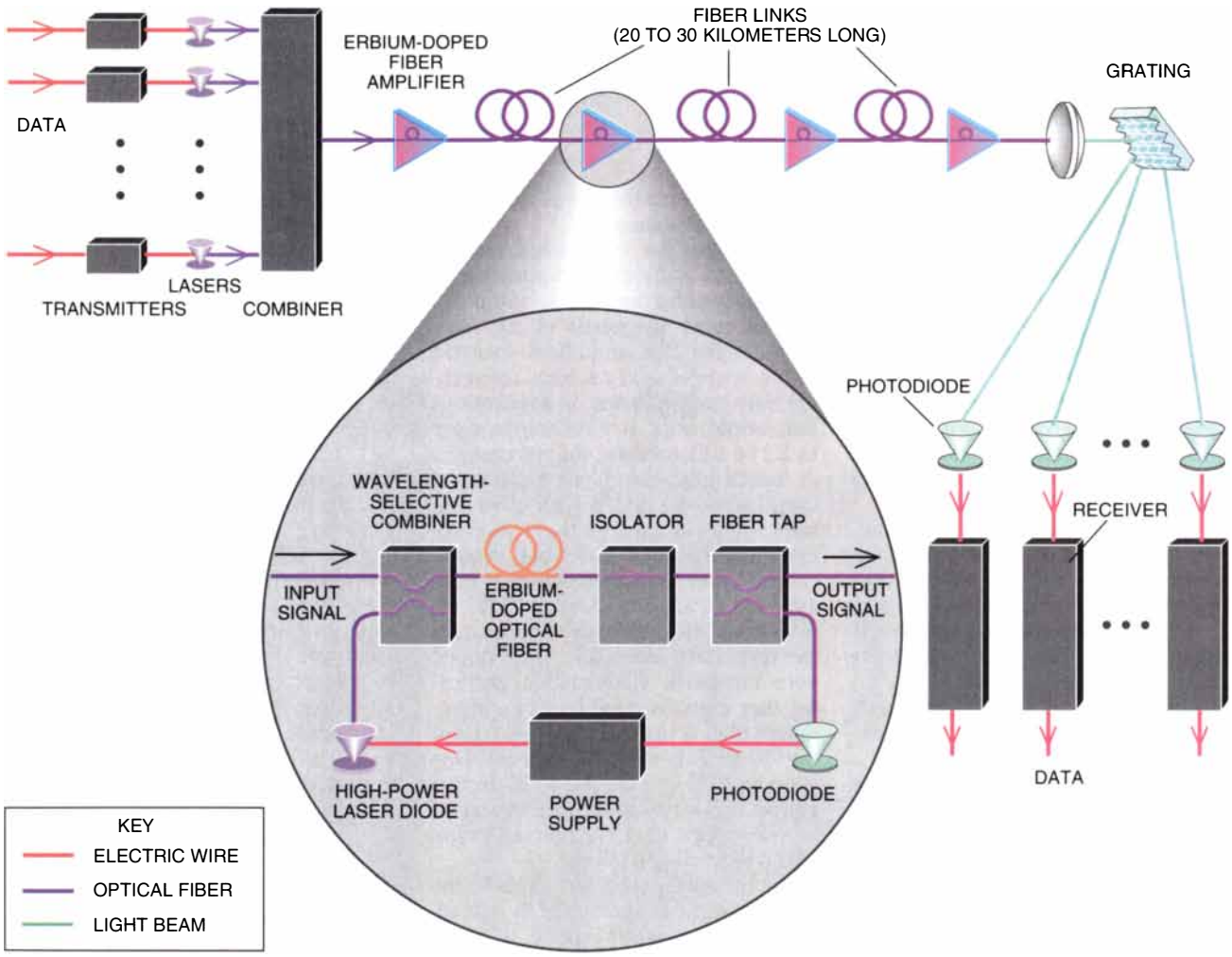
Most important, the observed gain did not depend on the polarization of the signal, whereas the semiconductor amplifiers that have been developed are sensitive to polarization. This result was the first sign that erbium-doped fibers might have a real advantage over other amplifiers.

Encouraged by these findings, we conducted an experiment to determine whether erbium-doped fibers could regenerate several signals at the same time. We found that they could. The signals did not interfere with one another, or more specifically, the cross talk between signals was negligible. We had identified a second advantage of erbium-doped fiber amplifiers.

During the late 1980s, my colleagues and I set out to construct a practical erbium-doped fiber amplifier. First and foremost, we need to prove that compact laser diodes could replace massive lasers as an efficient means for powering erbium-doped fiber amplifiers.

Our efforts were complicated by the fact that although several different wavelengths of radiation can be used to energize erbium, only a few do so efficiently. For instance, when an erbium atom is pumped with light of 0.67 or 0.80 micron, it absorbs a photon, achieving the desired energy state, but it may then jump to a second state by absorbing a second photon. In a fiber amplifier, a fraction of the erbium atoms will jump to this second state, which prevents them from transferring their energy to the optical signal. As a result, the efficiency of the amplifier is reduced.

Luckily, by a trick of nature, radiation at 0.98 or 1.48 microns can energize erbium without suffering from this unwanted effect. These wavelengths can be produced by semiconductor laser diodes fabricated from compounds of indium, gallium, arsenic and phosphorus. It is also fortunate that a silica fiber can be designed so that light at 0.98, 1.48 or 1.55 microns will travel in a single mode. This type of propagation is desirable because it allows the fiber to carry high-intensity light, which can energize the erbium atoms with great efficiency.



LONG-DISTANCE COMMUNICATIONS SYSTEMS will rely on erbium-doped fiber amplifiers in the near future. In such systems, several optical transmitters generate signals, which are combined and directed into a single fiber. Fiber amplifiers are placed between ordinary strands of optical fiber and boost the signals periodically. When the signal emerges from the array of fibers, it is focused onto an optical grating, where it is separated. The split signals are then guided toward several receivers. In the inset, which depicts the details of the fiber amplifier, a photodiode measures the intensity of the output signal and provides feedback to keep the amplification at a constant level.

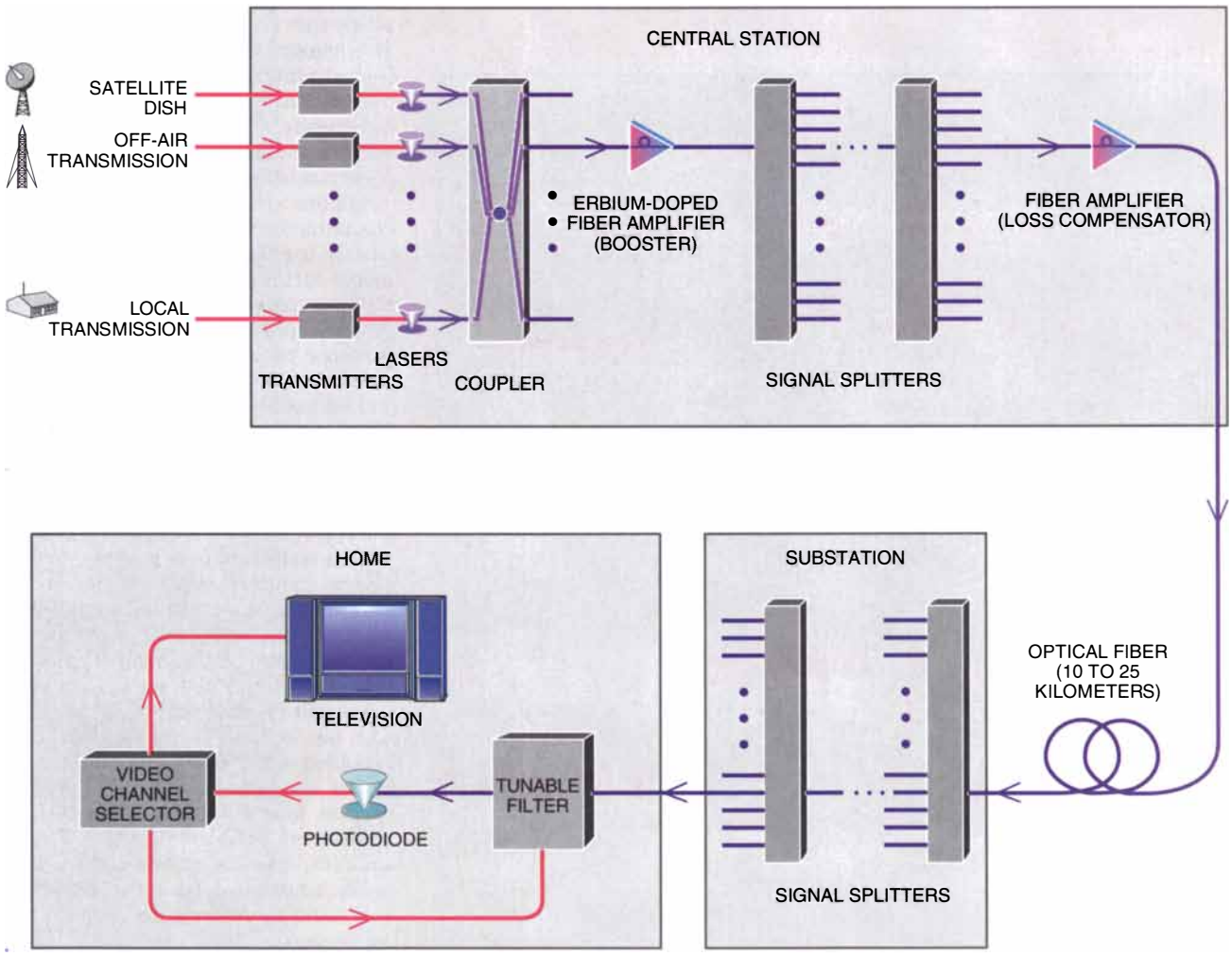
To determine whether laser diodes might be practical, my group and others first used conventional lasers to test how erbium-doped fibers would perform powered by radiation of either 0.98 or 1.48 microns. Researchers at Southampton conducted many of the first experiments at 0.98 micron, which they identified as the most efficient wavelength for pumping. Meanwhile my co-workers and I focused on 1.48 microns, the wavelength for which the laser diode technology was more mature. Other institutions, including the Nippon Telegraph and Telephone (NTT) Research Laboratories near Tokyo, joined the investigation. So far the best results, as reported by AT&T for the 1.48-micron wavelength and NTT for the 0.98-micron wavelength, are that an erbium-doped fiber amplifier powered by a mere 10 milliwatts of power can achieve a gain in the range of 30 to 40 decibels. Such power levels were shown to be well within the capability of laser diodes, which can now generate more than 200 milliwatts of light at 0.98 and 1.48 microns.

Perhaps most significant, in 1989 NTT was the first to demonstrate that an amplifier could be efficiently pumped with a laser diode. The same company successfully tested a prototype system of erbium-doped fiber amplifiers and ordinary fiber links. The system carried about two gigabits per second over a distance of 212 kilometers, at the time.

Once NTT had shown that the transmission capacity could be greatly increased, research groups began competing for world records as fiercely as Olympic teams. In the middle of 1989 both NTT and Bell Communications Research reported transmission rates of about 10 gigabits per second over distances of 150 kilometers, bringing the maximum transmission capacity to 1,500 gigabit-kilometers per second. Near the end of 1989, workers at KDD announced even more startling news. By using a series of 12 fiber amplifiers, they were able to transmit data at 1.2 gigabits per second over the incredible distance of 904 kilometers.

Then, early in 1990, workers at NTT made a remarkable comeback. They were the first to construct a coherent system that included fiber amplifiers. The system could transmit data at 2.5 gigabits per second over 2,223 kilometers. The industry had entered the era of 1,000-kilometer-long systems.

But even these results do not demonstrate the full potential of erbium-doped fiber amplifiers. Using an experimental system that emulates a very long transmission link, Neal S. Bergano and his colleagues at AT&T achieved transmission capacities as high as



BROADCAST NETWORK for high-definition television and other communications services is one system that could benefit from erbium-doped fiber amplifiers. According to recent estimates, the system could transmit signals as far as 25 kilometers and could reach as many as 10 million users. Once the signals are received or generated, they travel to a series of transmitters and lasers that convert the signals into light. The signals are combined into one and guided into several ordinary fibers. Amplifiers boost the signal as it is split numerous times and as it decays over lengths of ordinary fiber. The signal ultimately reaches the user, who can select the desired portion of the signal.

50,000 gigabit-kilometers per second. This capacity is 100 times greater than what can be achieved so far in an optical fiber system without amplifiers, and it is 10 times greater than what has been attained in systems deployed across the oceans.

The group placed a few erbium-fiber amplifiers between strands of low-loss fiber and joined the ends to form a loop. When they injected light pulses into the loop, they succeeded in transmitting 2.4 gigabits per second over 21,000 kilometers and five gigabits per second over 9,000 kilometers. The output signals emerged undistorted except for a small, unavoidable amount of noise generated by the fiber amplifier. Although these results were achieved using a fiber loop, which differs somewhat from a demonstration of point-to-point communications, the achievement indicates that fiber amplifier systems have enormous potential.

Whereas some investigators have focused their efforts on achieving record-breaking transmission capacities during the past four years, others have made significant progress in the study of solitons and their use in communications systems.

A soliton can travel indefinitely through a "perfect" fiber, that is, one that does not attenuate light. A soliton, like an ordinary light pulse, consists of many components that differ slightly in wavelength. A soliton also varies in intensity over its length, width and height. Lightwaves of different wavelengths travel through fibers at different velocities. This effect is known as dispersion. And when the intensity of light exceeds a certain level, lightwaves of the same wavelength but different intensities propagate at different speeds. This phenomenon is known as the optical Kerr effect. The principle behind solitons is that the optical Kerr effect can be used to counteract dispersion. If each wavelength component is generated so that it has a particular intensity, all the components can be made to travel at the same speed. As a result, the soliton will neither broaden nor compress as it travels through a lossless fiber.

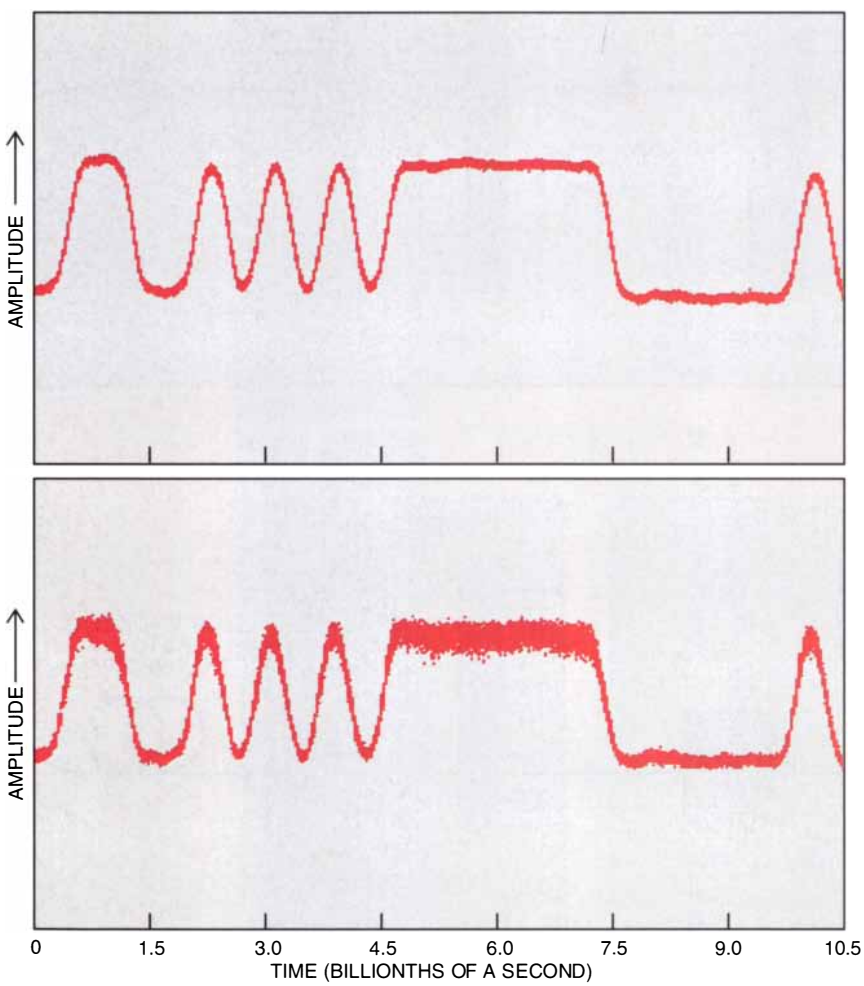
Of course, all fibers attenuate signals to some degree, and the soliton will slowly decay as the pulse propagates. Yet it will retain its shape until the power of the soliton drops below a certain level.

Linn F. Mollenauer, who pioneered the field of solitons in optical fibers, proposed that fiber amplifiers could compensate for the losses in fibers, making it possible to sustain the propagation of solitons over long distances. In 1988 he proved it at AT&T. By trapping solitons in a 40-kilometer loop of fiber and fiber amplifiers, Mollenauer and his colleagues ultimately observed solitons that propagated for 10,000 kilometers with little broadening. Recently they showed that solitons enable information to be transmitted, error free, at a rate of 2.5 gigabits per second over a distance of 14,000 kilometers. This result gives every indication that solitons could be used for long-distance communications.

Solitons are the ideal light pulse for communications. They can be spaced closely together because they do not merge into one another and because they are short (about 10 trillionths of a second). Soliton systems—in which the presence or absence of a soliton represents a single bit of information—should attain transmission capacities of at least five gigabits per second over distances of 10,000 kilometers.

Soliton systems should achieve even greater capacities if they can take advantage of other emerging technologies. Signals transmitted as solitons enable several channels of information to be sent simultaneously at different wavelengths. This approach, called wavelength-division multiplexing, is impractical with nonsoliton signals because the signals disperse and mix irreversibly with one another over long distances. In soliton systems the maximum number of channels is ultimately limited because fiber amplifiers boost signals of different wavelengths by different amounts. A soliton system could realistically support at least five channels and could therefore carry 25 gigabits per second.

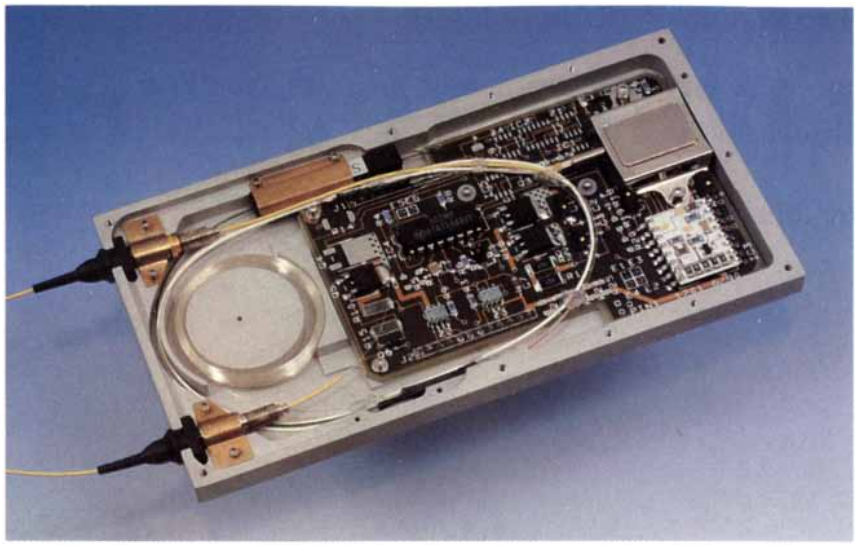
Mollenauer and his colleagues have also investigated "polarization multiplexing" for soliton systems. In such schemes the number of channels can be doubled by transmitting signals that have the same wavelength but two



SIGNALS (*top*) traveled 9,000 kilometers through a loop of ordinary fiber and erbium-doped fiber amplifiers, emerging (*bottom*) virtually undistorted and free from noise. These results, which were obtained by Neal S. Bergano and his co-workers at AT&T Bell Laboratories, show the great potential of fiber amplifiers.

different polarizations. This approach would bring the total transmission rate to the high rate of 50 gigabits per second. The techniques used for generating, modulating and detecting soliton pulses are still being developed in the laboratory. For this reason alone, soliton systems may not be deployed for some time.

Another alternative for the future of communications is coherent systems. Coherent techniques could exploit the entire wavelength region from 1.2 to 1.6 microns and would allow optical channels to be packed very closely together. To make a practical system, workers must still develop frequency-agile devices, which have better absolute frequency control and stability. If progress continues in this field, workers may well find a way to eliminate the need for optical amplifiers in local-area networks. It seems clear, however, that long-distance communications will continue to depend on optical amplifiers. Furthermore, it is too early to predict when frequency-agile devices will be ready for use.



FIBER AMPLIFIER can boost telephone signals through fiber-optic cables that span continents. The amplifier contains an erbium-doped optical fiber, which is wound around a spool at the left. The fiber is energized by light from a laser chip, which is housed in the small metallic case at the top right. Light signals enter and exit the fiber through the yellow cables at the left. The device, which is 15 centimeters long, was designed by Terry W. Cline and his colleagues at AT&T Bell Laboratories.

Erbium-doped fiber amplifiers are already having a tremendous impact on long-distance communications. And in the next decade fiber amplifiers should play an even greater role in the field of lightwave networks. Indeed, the technological challenge of such networks is to exchange the maximum amount of data among the largest possible number of users in the shortest interval of time with the smallest probability of failure. For this type of communication, the advantage of employing optical fibers, rather than microwave cables, comes from their low loss and their ability to convey data at higher bit rates over longer distances.

The simplest form of a fiber network is called a broadcast network, in which optical data are transmitted from a central station to an ensemble of users. A fiber amplifier could compensate for losses as the signals from the central station are split over and over again. Other fiber amplifiers in the branches of the network could compensate for propagation losses over extended distances of 10 to 25 kilometers, permitting the scale of the network to be increased. The number of homes that could be reached through such a network is enormous.

The company British Telecom has recently demonstrated the broadcasting of 384 video channels to nearly 40 million potential users within a 50-kilometer-diameter area. Such systems can be expanded in area by increasing the fiber length and using more fiber amplifiers to compensate for the loss. The maximum number of users is limited, however, because as the signal passes through one amplifier after another, it eventually accumulates so much noise that it becomes unusable for communications purposes.

Networks that include fiber amplifiers can transmit data at very high rates because they are able to support many channels. The number of channels is not reduced by dispersion, which is negligible over the short distances covered by fiber networks. The number of channels is finite, however, because of four effects. First, if the combined strength of the signals from each channel exceeds a certain level, the erbium amplifier will not amplify the signal. Second, the fiber amplifier can transmit only a limited range of wavelengths (from 1.53 to 1.55 microns). Third, the wavelengths of any two optical channels must differ enough that the channels do not interfere or mix together. And finally, the gain of the amplifier varies with wavelength. The number of channels may also be reduced because of limitations in the ability of photonic devices to discriminate optical channels.

Despite these limitations, lightwave networks that employ fiber amplifiers may ultimately carry an estimated 2,000 to 3,000 gigabits per second. So far no other technology can compete with these rates.

As erbium-fiber amplifiers and other lightwave technologies are introduced into long-distance systems and local-area networks during the coming decades, people will have access to new types of powerful communications services. Lightwave communications systems will integrate the functions of telephones, facsimile machines, computers and televisions. They will also offer many new services: Businesses will have access to vast data banks and will be able to take advantage of interactive video networks for teleconferencing. Researchers will be able to exploit fully the resources of supercomputers located thousands of kilometers away. Homeowners will be able to choose programs from video libraries. It is reasonable to infer that just as telephones and televisions have transformed work and leisure in this century, lightwave communications systems promise to influence society profoundly in the 21st century.

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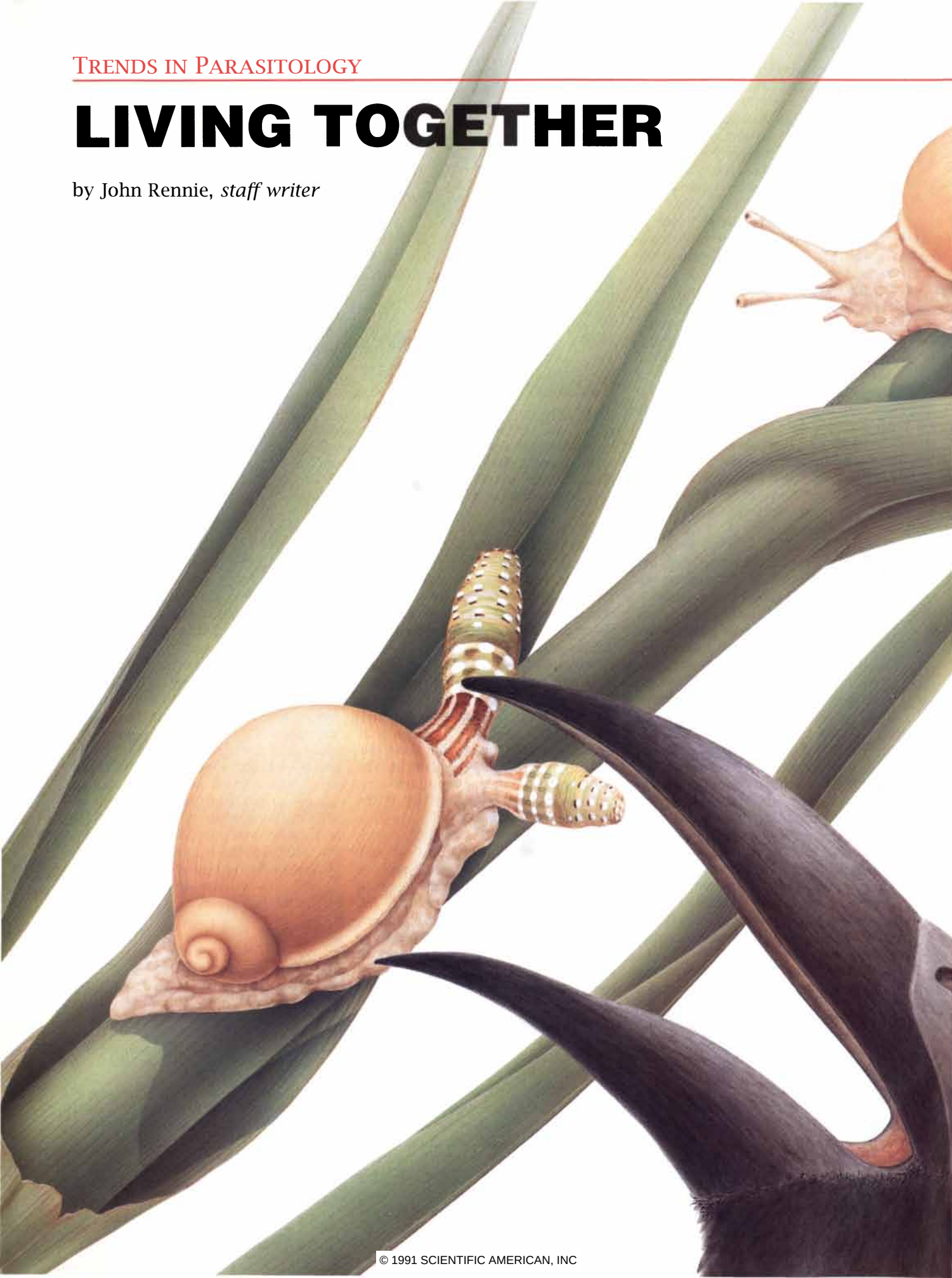
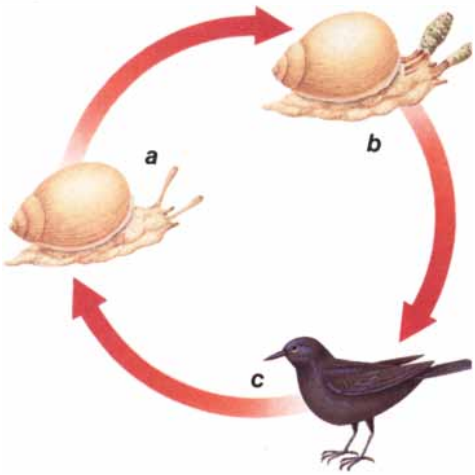
LIVING TOGETHER

by John Rennie, *staff writer*





Parasites and their hosts have devised many odd strategies—perhaps even sex—in their endless game of adaptive one-upsmanship. Yet sometimes they seem to cooperate.

The snail might as well be flashing neon signs on its head that read, "Eat Here." Its slender eyestalks have been transformed into throbbing, brightly colored sausages that bear more than a passing resemblance to caterpillars. Birds apparently agree: they can easily spot such snails from the air and make a quick meal of them.

If the snail's conspicuous headgear seems maladaptive, don't shrug it off as an evolutionary fluke. Blame the parasitic worm *Leucochloridium paradoxum* and its kin, which actually cause the bizarre changes in succineid snails that live in North America and Europe. *Leucochloridium* must spend its youth maturing inside a snail, then find a way into a bird's digestive system to complete its life cycle. By invading the snail's eyestalks in huge numbers and assuming vivid hues, the parasites turn their childhood home into bird food to solve their transportation problem.

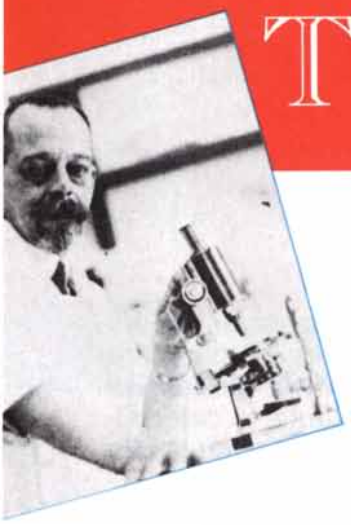
Small wonder, then, that when Paul D. Lewis of the University of Lethbridge brought a box of parasitized snails to the annual meeting of the American Society of Parasitologists (ASP) last summer, they were a big hit. "Every person who looked at them got really excited," he recalls.

Parasitic worms, mites, fungi, bacteria and other organisms are drawing the attention of many biologists these days, and not just at meetings of parasitologists. Inspired by the complex relationships between parasites and their hosts, growing numbers of researchers are exploring the possibility that parasitism is an important but largely overlooked force in evolution. "I'm persuaded that the action of parasites on hosts is determining much of what we see in the world," says Douglas E. Gill, an evolutionary ecologist at the University of Maryland at College Park. "It's this world of vibrant interactions that have just been ignored."

Gill and others argue that biologists have too frequently treated parasites as merely a different type of predator—one that eats its prey from the inside. To parasites, a host can be far more than food: it can be a shelter, a nursery or incubator, a vehicle for reaching other organisms or even an ally in a struggle against some common foe. Whereas most predators consume a variety of prey, many parasites are utterly dependent on a single species of host. Hosts, too, sometimes depend on their parasites. Termites, for example, would perish without the bacteria in their digestive tracts that convert wood fibers into sugar.

PARASITIZED SNAILS of the genus Succinea *become highly attractive prey for birds. As the* Leucochloridium *parasites mature inside the snail* (a)*, they invade the eyestalks. As a result, the eyestalks begin to resemble edible caterpillars* (b)*. This disguise aids the parasites, which must release eggs in the excretory tracts of birds to complete their life cycle* (c)*.*

The Study Of Viruses: It's A



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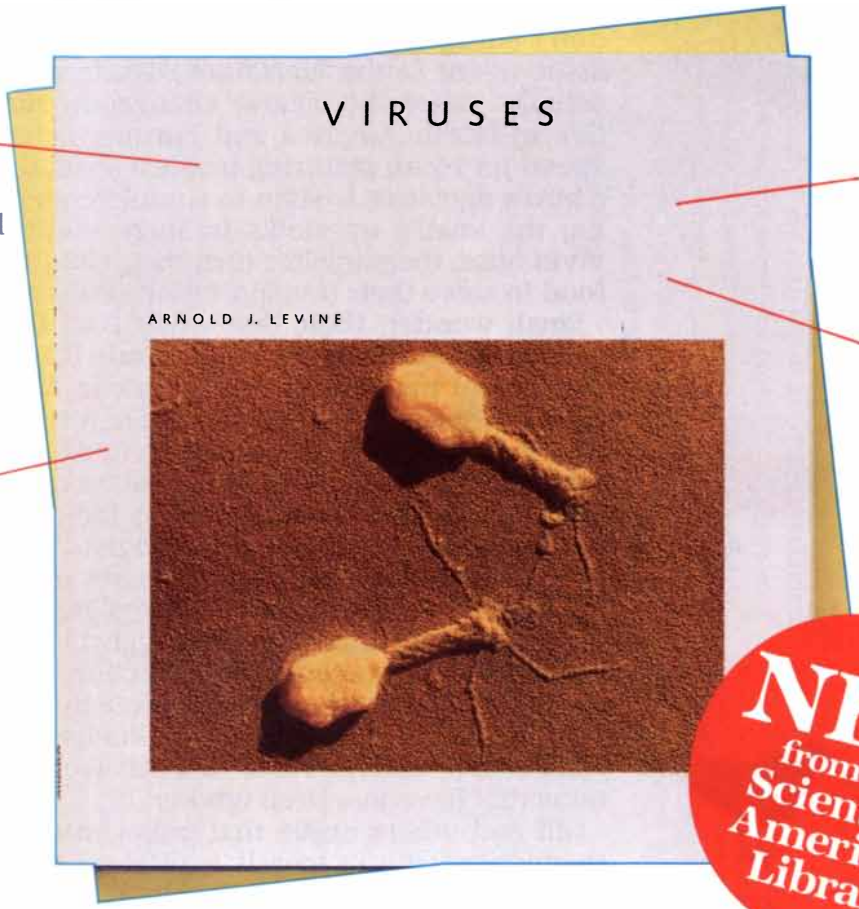

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◄ Camellia leaf showing the result of a viroid infection

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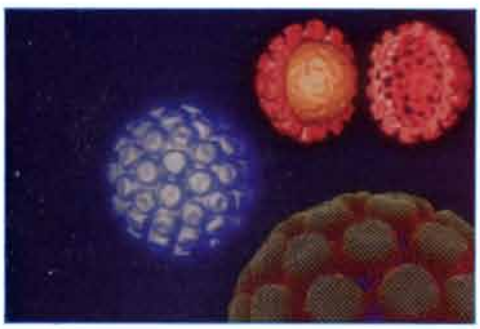

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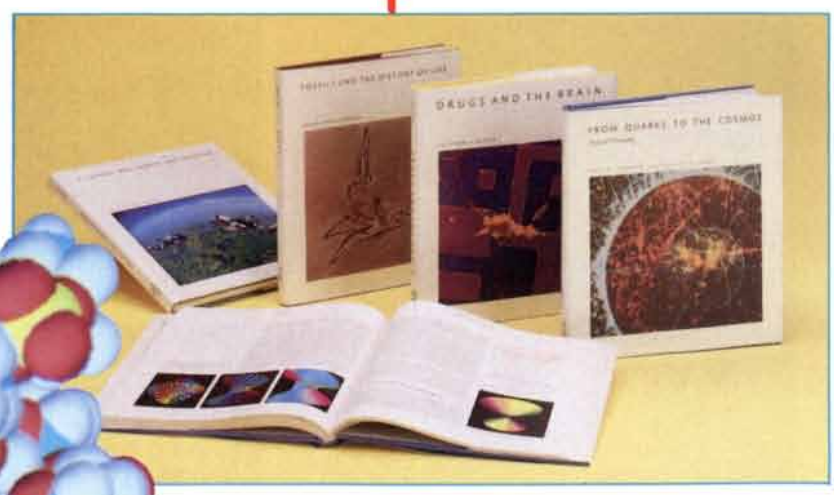

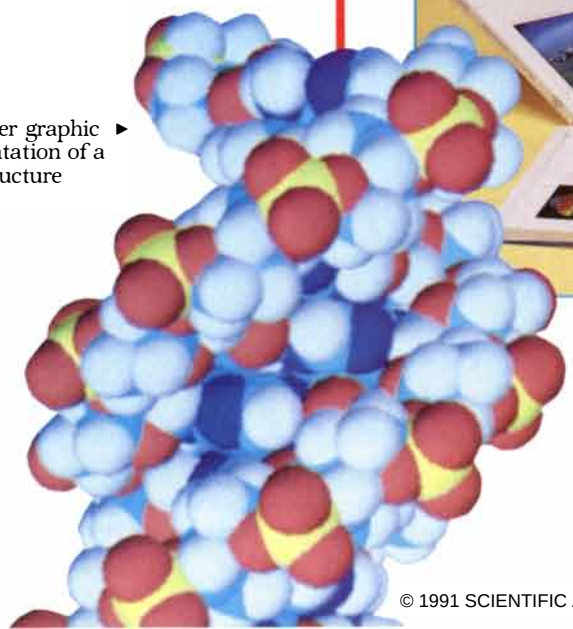

Computer graphic representation of a DNA structure ►

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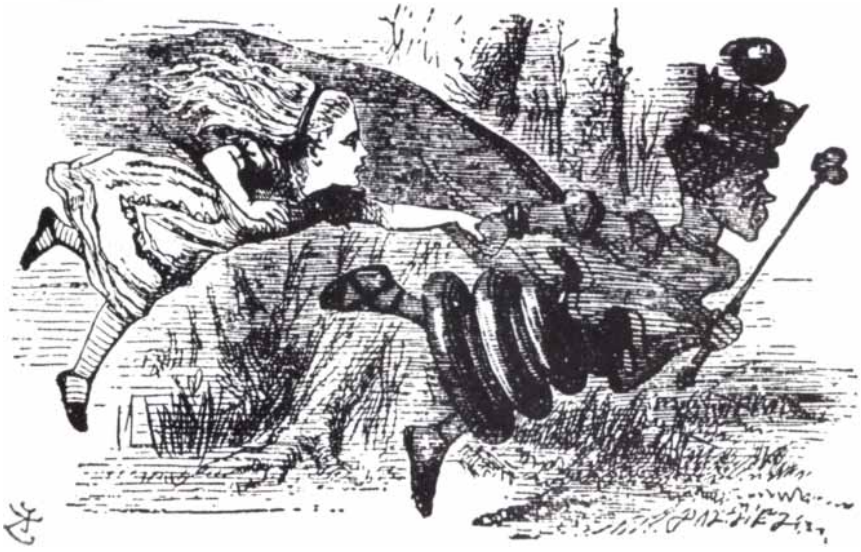


IN THE RED QUEEN'S RACE, described by Lewis Carroll, competitors run as fast as they can just to stay in one place. Parasites and hosts may be in a similar stalemate.

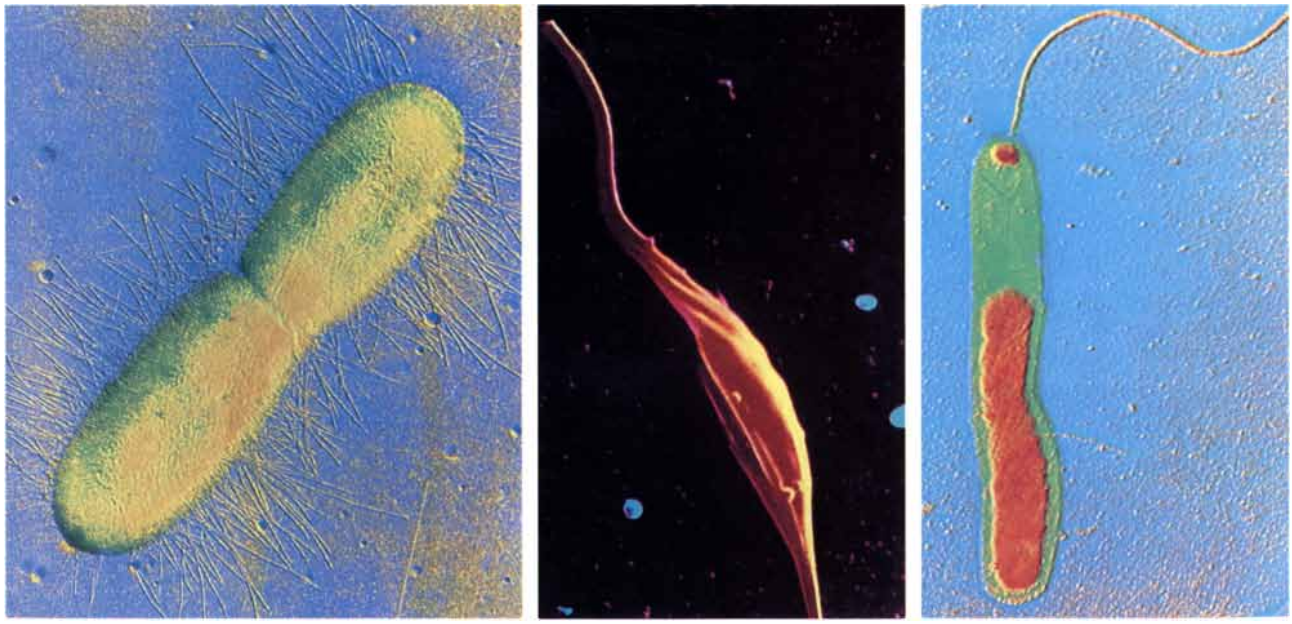
With natural history studies and mathematical models, investigators are now trying to understand how parasites and their hosts coevolve such intimate associations. They hope to learn why certain pairs of organisms steadily escalate their animosity, whereas others move toward at least grudging cooperation with one another. Some of the preliminary conclusions—that sex may have originated as a gambit for thwarting parasites, for instance—are controversial. The researchers' findings leave little doubt, however, that the phenomenon of parasitism has profoundly shaped life since its inception.

With the new appreciation of parasites as agents of evolutionary change has come an overdue reappraisal of them as organisms in their own right. "Historically, parasites have been seen as primitive, degenerate and uninteresting," explains Gerhard A. Schad of the University of Pennsylvania, a former president of the ASP. "Rather than being looked at as specialized and highly adapted to their way of earning a living, they were looked at as unusual."

Daniel R. Brooks, a parasitologist at the University of Toronto, agrees. "If you consider a tapeworm and compare it with a human being, the tapeworm is pretty simplified," he says, observing that basically it is a gut with gonads. "But that's not an evolutionary comparison; that's an ecological comparison," he notes. "The appropriate evolutionary comparison is between tapeworms and something like *Planaria,* which are also flatworms but not parasitic. Parasitic organisms are routinely larger than their free-living relatives, and they are often more complex."

Although parasitologists are generally pleased by the new respect that their organisms command from evolutionary biologists, the alliance between these disciplines is still uneasy. Parasitologists charge that the mathematical models used by evolutionary ecologists to describe host-parasite interactions completely ignore the observed biological realities. "These people wouldn't know a parasite if it bit them," fumed one researcher, who wished to remain anonymous. Conversely, evolutionary ecologists contend that many parasitologists take a naive view of how natural selection works.

Much of the argument centers on a long-standing article of faith among parasitologists: as hosts and parasites coevolve and adapt to one another, their mutual antagonism should diminish. The standard rationale, Brooks summarizes, is that "if you're a parasite and you kill your host, you're dead, too." According to that line of thought, natural selection would favor the survival of less virulent parasites and more resistant hosts. Parasites could gradually become commensal, or harmless to the

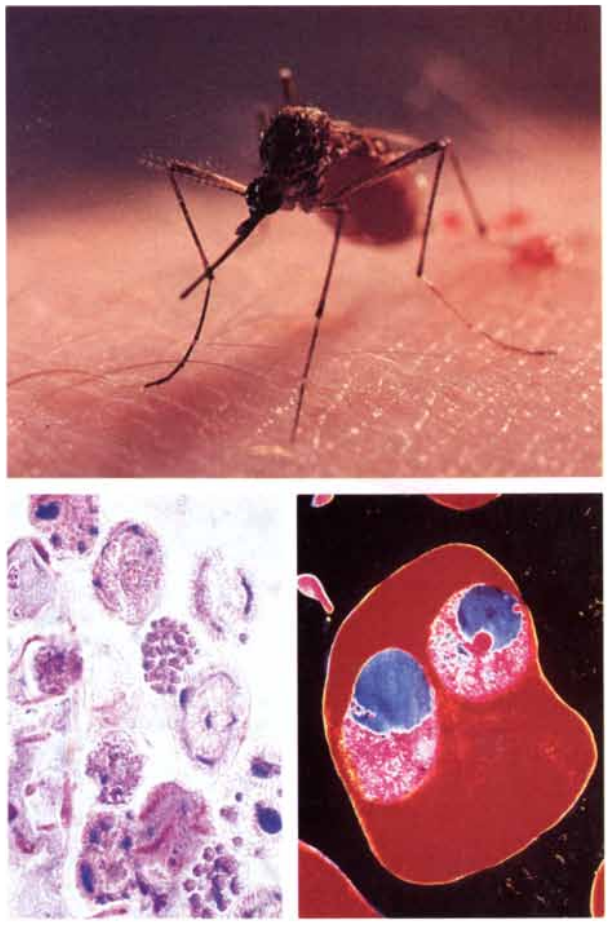


PARASITES OF HUMANS vary in their harmfulness. *Escherichia coli* (*left*), a bacteria that lives in the intestines, is usually benign. In contrast, trypanosomes (*center*), a type of protozoan transmitted by insect bites, cause sleeping sickness and Chagas' disease. Cholera microorganisms (*right*) cause their host to dehydrate and are sometimes highly virulent.

Malaria: A Case Study of Coevolution

Worldwide, more than 100 million people are infected with malaria every year, and about 1.5 million of them die. With human hosts and malaria parasites competing in a "coevolutionary arms race," such a scourge would be expected to have shaped the evolution of both. In the past year researchers have found more genetic evidence that this indeed is the case.

In February of 1991 at a meeting of the British Society of Parasitology, Adrian V. S. Hill of the Institute of Molecular Medicine of the University of Oxford and an international team of medical researchers announced that they had found two genes that protect people from malaria. Both genes encode major histocompatibility complex (MHC) proteins—molecules that the immune system uses to recognize infected cells. After surveying more than 2,000 patients in western Africa, Hill's group found that people bearing either of those MHC genes suffered fewer severe cases of malaria.



***MALARIA is transmitted by mosquitoes* (top) *that inject one form of the parasite* (left) *into the bloodstream. Later, parasites infect red blood cells* (right).**

The two MHC genes seem to be most common in precisely those populations that are routinely exposed to malaria. According to the researchers, one of the genes is carried by 40 percent of all people in Nigeria, where malaria is endemic, but by only 2 percent of black South Africans and by less than 1 percent of whites and Orientals. These discoveries offer strong evidence that the vast diversity of MHC genes found in the population—humans produce hundreds of types—may have been a response to evolutionary pressures exerted by parasitic diseases.

The only other human gene known to confer resistance to malaria is the gene for sickle cell anemia. People who inherit two copies of that gene eventually die because their red blood cells produce a defective form of the oxygen-carrying hemoglobin molecule. Carriers of the gene usually do not become anemic because they have one normal hemoglobin gene. Sickle cell anemia is fairly rare in most ethnic groups, but it is common among some black Africans and people of African descent. In Gambia, for example, about one quarter of the population carries the gene for sickle cell anemia.

The prevalence of the sickle cell gene in Africa was a mystery until the 1950s, when researchers noticed that carriers are exceptionally resistant to malaria. Because the benefits of malaria resistance more than offset the mortality from sickle cell anemia, natural selection preserved the gene in the African populations rather than eliminating it.

The protective effects of the newly discovered MHC genes seem to be only about half as great as those of the sickle cell gene. Because they are found in more of the population, however, the MHC genes may be protecting more people. Whereas the sickle cell gene may prevent the equivalent of 12 percent of all the serious cases in regions of Africa, the MHC genes may prevent 15 percent, Hill and his co-workers have estimated.

Studies of malaria parasites are also turning up clues to why *Plasmodium falciparum* malaria—which causes 95 percent of all malaria deaths—is far more lethal than other strains. A biomolecular comparison released last April by Thomas F. McCutchan and his co-workers at the National Institutes of Health suggested that *P. falciparum* is more closely related to avian malaria parasites than to human ones. According to McCutchan, people may have acquired *P. falciparum* from birds within only the past 10,000 years. *P. falciparum* may therefore be more virulent than other malaria parasites because humans have not yet devised a good immunologic defense against it.

host, like *Escherichia coli,* a usually benign bacterium that thrives in human intestines. Given enough time, parasites and their hosts might even become mutualists, organisms that contributed to one another's well-being, such as the fungi and photosynthetic bacteria that make up lichens.

That view of coevolution makes intuitive sense—yet to many evolution theorists, it is misguided. "Virtually none of it is consistent with deeper, more rigorous evolutionary thinking," Gill says. He explains why with a hypothetical example involving two strains of tapeworm in a white-tailed deer, one of which is more virulent than the other. (The example involves a great many simplifying assumptions, he cautions.) Conventional wisdom holds that the more benign tapeworm should have the competitive edge. Because its host will live longer, the tapeworm ought to produce more eggs during its host's lifetime than one that kills the deer quickly.

Yet a parasite's virulence often reflects its ability to reproduce success-

fully. If the aggressive tapeworm can transmit more eggs in less time than the benign one, it will always be ahead. Even if the deer host dies immediately, aggressive offspring will be more numerous in the next generation. Instead of diminishing with time, the aggressiveness of the parasites should therefore increase for as long as any deer remain. The deer and the parasites may eventually be driven to extinction by these changes, Gill says, but "no organism alive, including humans, gives any evidence at all of being able to plan wisely for the future."

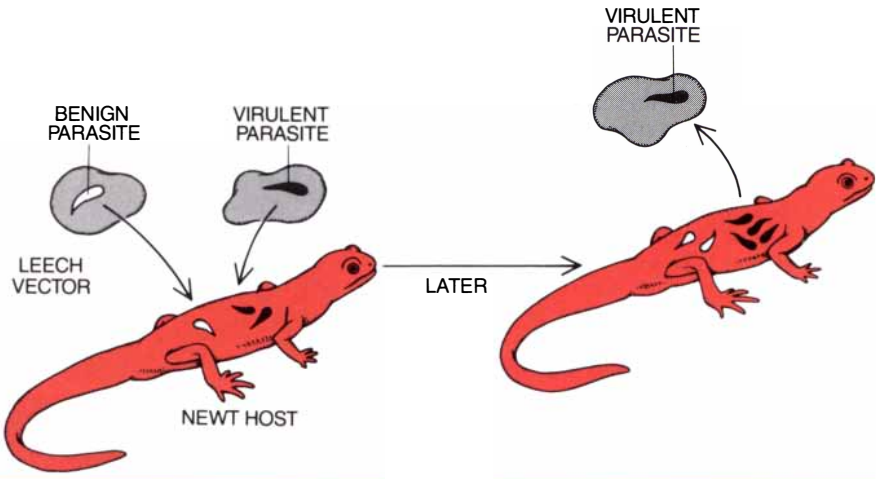
The reason that parasites have not killed everything on the planet is that the dynamics of their interactions are considerably more variable. Population geneticists Roy M. Anderson and Robert W. May of the University of Oxford have shown that the evolutionary end point of host-parasite interactions is highly case dependent. Sometimes parasites get worse; sometimes they become mutualists; sometimes their virulence attenuates to an intermediate level. There is no predisposition toward mutualism in most cases, the evolutionary ecologists conclude.

The guiding metaphor for most biologists looking at parasitism is the coevolutionary arms race. Parasites should be adapting relentlessly to take more resources from their hosts for the purpose of making baby parasites. Hosts should be vigilantly adapting to stop them. If both sides are evenly matched, the result should be a kind of biological détente in which neither parasites nor hosts can afford to relax but neither faces immediate extinction. In 1973 ecologist Leigh Van Valen of the University of Chicago labeled such a situation a Red Queen's race, referring to the character in Lewis Carroll's *Through the Looking Glass* who says, "Now, here, you see, it takes all the running you can do, to keep in the same place."

BRIGHT PLUMAGE on a male red jungle fowl, the ancestor of domesticated chickens, may act as a cue to females seeking mates that are resistant to parasites.

Nice Parasites Finish Last . . .

Relatively benign parasites are often at a competitive disadvantage. Benign parasites in newt hosts should reproduce more slowly than virulent parasites and would therefore be less likely to be transmitted to leech vectors.



Playing to Win

That race seems like one that parasites should win every time. Parasites typically have shorter generations than their hosts, which means that natural selection should groom their population for successful adaptations faster. Long-lived hosts often have immunologic defenses, however. The populations of lymphocytes and other cells that constitute the mammalian immune system, for example, can change rapidly to recognize and attack new parasites. In effect, the immune system constantly redefines the cellular and biochemical landscape that parasites face inside the host.

Still, parasites are free to launch their own counterattack. A particularly cunning ploy was discovered during the late 1970s by George A. M. Cross, now at the Rockefeller University, and other researchers while studying the insect-transmitted microorganisms called trypanosomes, which cause sleeping sickness (African trypanosomiasis). Victims of sleeping sickness cannot rid their bodies of the parasites, because the trypanosomes alter their immunologic features in every generation.

Cross has shown that the trypanosomes carry a library of about 1,000 genes for different surface proteins, out of which only one is expressed randomly. He also found that these surface antigen proteins detach from the trypanosome cells if the cells are damaged, thereby making it harder for the immune system to maintain the focus of its attack.

Parasites can also exploit their hosts without making them sick. Helen M. Alexander of the University of Kansas has discovered that the parasitic fungus *Ustilago violacea* manipulates the reproductive strategy of the weedy plant called catchfly to great advantage. If the host plant is male, the fungus sterilizes it by transforming the pollen-producing stamens in the flowers into organs that shed fungal spores. If the host plant is female, the fungus somehow forces it to grow infertile malelike flowers and then repeats its spores-for-pollen swap. Insects attracted to the infected catchfly's blooms pick up a cargo of spores and innocently carry them to other catchfly plants.

Some parasites can even manipulate the behavior of their hosts in self-serving ways—usually as a means of reaching the next host. Wilhelm Hohorst, then at Hoechst A.G. in Frankfurt, and his colleagues have shown that ants infested with the lancet fluke *Dicrocoelium dendriticum* shackle themselves to blades of grass with their own mandibles. The ants are then eaten by grazing sheep—the next host in the fluke's life cycle. Studies by Janice Moore of Colorado State University have demonstrated that pill bugs carrying parasites known as acanthocephalan (thorny-headed) worms behave in ways that make them easy prey for songbirds.

Faced with such Machiavellian tactics by parasites, hosts competing in the

. . . But Sometimes They Win Anyway

The six-year period during which juvenile newts live outside ponds introduces selection pressure against virulent parasites. Only hosts carrying benign parasites live long enough to reenter ponds, where more hosts can be infected.

HIGHLY VIRULENT PARASITES KILL THEIR HOSTS QUICKLY

LESS VIRULENT PARASITES KILL THEIR HOSTS MORE SLOWLY

ONLY BENIGN PARASITES AND THEIR HOSTS SURVIVE TO REENTER PONDS

coevolutionary arms race may have had to devise secret weapons of their own. Some evolutionary biologists suspect that one of the weapons may be a phenomenon whose existence has long baffled them: sex.

Evolutionarily speaking, sex is a bad idea. "Asexual reproduction is a more efficient process," explains William D. Hamilton of Oxford, one of the foremost theorists on the significance of sex in evolution. "You don't need to get two mates together. You just go ahead and reproduce."

A still more compelling argument, Hamilton notes, is the twofold cost of sex, which is based on the observation that males do not usually invest as much as females in the creation and rearing of young. "From that point of view, you are throwing away half of your reproductive effort into a gender that will not really contribute to the expansion of your descendant line," he reflects. "That should create an extremely strong selection pressure to get rid of sex. The puzzle is why it doesn't succeed."

For more than a decade, Hamilton has argued that sex survives because it offers unique advantages to hosts in their struggle against parasites. According to his argument, the recombination of large blocks of genetic information resulting from sex helps to diversify the makeup of a host's offspring more rapidly and efficiently than mutation could. Those offspring may therefore be resistant to parasites that thrived in their parents, whereas offspring genetically identical to their asexual parents would not have that safeguard. (Because of their short generation times and extremely rapid evolutionary rates, parasites seem to have less need for sex; most parasites are asexual for all or part of their lives.)

Sex as a Strategy

Hamilton also believes that sex helps a host population retain resistance traits that have temporarily lost their effectiveness but may prove useful again. In his view, a population of parasites will generally be adapted to the most common type of host in the population. As those hosts fall victim, other less common types gradually rise and fall in the same way, leading to what Hamilton calls "nonprogressive seething." "This host-parasite chase is slightly different from the arms race as it is typically conceived," he says, because host resistance does not need to grow continually greater. "The host genotype that was most common 100 years ago may rise in frequency again." In short, sometimes the Red Queen runs in circles.

The idea that parasitism explains sex is not universally accepted. Other explanations have been proposed, most notably one that sex eliminates deleterious mutations from the population. Nevertheless, Hamilton believes he answered many of the objections to the idea in a paper that appeared in 1990 in the *Proceedings of the National Academy of Sciences*. "I think that no one else has met the challenge of the twofold cost of sex with a model that looks realistic," he remarks.

Some parasitological fieldwork also supports the idea. In 1990, for example, Robert C. Vrijenhoek and Clark Craddock of Rutgers University and Curtis M. Lively of Indiana University published a study of sexual and asexual wild minnows in Mexico that seemed to confirm the antiparasitic advantages of sex. They found that the clones of asexual fish were parasitized by trematode worms more often than the sexual fish, except when the genetic diversity of the sexual fish was extremely low because of inbreeding. In the inbred population, the antiparasitic advantage evaporated because even the sexual fish were too much alike. When more sexual individuals entered the inbred population, however, the level of parasitism declined rapidly.

Lively has also observed a similar

WILLIAM D. HAMILTON of the University of Oxford has proposed that sex evolved as a strategic weapon in the coevolutionary arms race between parasites and hosts. He is shown holding the nest of a species of social wasp.

DOUGLAS E. GILL of the University of Maryland at College Park discovered why certain parasites in newts were benign after he studied the life cycles of the organisms.

relation of sex and parasitism in certain New Zealand snails. Asexual female snails seemed to be most abundant in habitats with relatively few trematode (flatworm) parasites; both males and females were common where the parasites were numerous.

In 1982 Hamilton and his graduate student Marlene Zuk, who is now at the University of California at Irvine, further extended the theory that sex is linked to parasites by proposing that the Red Queen's race can affect a female animal's choice of a mate. In many species—peacocks are the best-known example—the females select their mates during a beauty contest of sorts, in which the strutting males show off their brightly colored plumage or other secondary sexual characteristics. Many researchers have suggested that those displays must advertise some valuable quality that the males possess; Hamilton and Zuk theorized that it might be resistance to parasites.

Their first test of the idea involved a survey of some North American birds to determine whether species with brightly colored males tended to be more heavily parasitized than dowdier species. That survey buttressed their hypothesis, although other studies have found that the trend breaks down among birds more generally.

Zuk found more supportive evidence while investigating the connection between parasitism levels and the prominence of male characteristics within single species. While working at the University of New Mexico, she and her colleagues studied red jungle fowl from Southeast Asia, which are the colorful ancestors of domestic chickens. "They look kind of like gaudy chickens," she remarks. The researchers observed that the body and beak sizes of the infected red jungle fowls seemed normal, but their ornamental plumage was smaller and more drab.

"It's not just that if you're sick, you have trouble getting mates," she emphasizes. "It's that the parasites seem to be reflected in exactly those traits that females use to make mating decisions." Other researchers have found additional examples that seem to connect parasites with sex and mating behavior. Critics of the idea, however, point to their own counterexamples that favor alternative theories.

Have Germs, Will Travel

The coevolutionary arms race—even one fought with sex—is evidently a useful image for explaining instances in which parasites and hosts seem to intensify their struggle against one another, such as when diseases become more virulent. Less obvious, however, is how the metaphor can explain the tendency for some parasites to become less aggressive over time. One researcher who believes he has found part of the answer is Douglas Gill.

Gill may be the only person in history to know 9,000 newts on virtually a first-name basis. Beginning in 1974, twice a week for 10 years, he and his students rose before dawn to drive from their Maryland laboratory to the Shenandoah Mountains in West Virginia, where a population of red spotted newts lived. The researchers captured new specimens, returned old ones to the wild, took various measurements, then went home at nightfall. Because the pattern of spots on each newt's back was distinctive, Gill was able to track the newts' individual histories throughout the long experiment.

In 1981 he and Beverly Mock, then his graduate student, focused on the effects of trypanosome parasites on the fitness of specific newts. "To our astonishment, we could detect no impact at all," Gill says. "Some newts were able to tolerate infection levels of a million trypanosomes per milliliter of blood—there were almost as many parasites as red blood cells. You would think that would be dreadfully debilitating. But our long-term measurements showed no signs of sickness, no signs of early mortality, no signs of worse reproductive performance."

Puzzled by the benignity of the trypanosomes, Gill began to search for some explanation. The answer, he eventually concluded, hinged on the life histories of the trypanosomes and the newts. The trypanosomes were transmitted from one newt to another by the bites of amphibious leeches. Consequently, they could be transmitted only in ponds. The newts, however, were not purely aquatic. "At the end of every summer, juvenile newts crawl out of the ponds where the adults swim, go out into the forests and spend about six years growing up there," Gill remarks.

That interval introduced selection pressure against harmful trypanosomes, he reasoned. Newts carrying even marginally virulent trypanosomes would probably die before they matured, returned to a pond and passed on their infection. As a result, only benign trypanosomes recycle into the parasite population and breed.

Working from cost-benefit models, evolutionary ecologist Paul W. Ewald of Amherst College independently arrived at a similar broad principle about the critical role of transmission in parasite evolution. While nursing a bout of intestinal distress 15 years ago, he began to wonder whether conditions such as diarrhea were sometimes a disease-causing organism's method of spreading to other hosts. "I started to wonder what kinds of transmission would most favor virulent strains and what kinds would favor benign strains," he recalls.

Ewald's conclusion was that if a parasite can be carried from an incapacitated host to other susceptible ones by an intermediate vector—a biting fly or mosquito, for instance—then the parasite can reproduce aggressively, even at the price of killing its host. Conversely, if a parasite relies on its host to bring it into contact with other susceptible individuals, then natural selection will

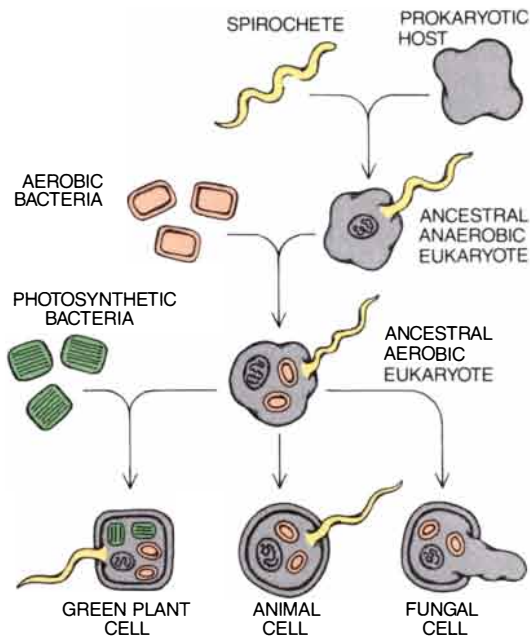
The Creativity of Symbiosis

To Lynn Margulis, symbiotic associations such as parasitism are not merely one influence in evolution. Instead they are among the most important creative forces in the process. A biologist at the University of Massachusetts at Amherst, Margulis believes that through symbiosis, organisms pool their genetic resources to accomplish more than either partner could separately.

That idea is one few evolutionary theorists seem to dispute as a general principle. Margulis nonetheless maintains that by relying on mathematical models based on competition between organisms, most of her colleagues ignore the effects of other biological influences. "These people are trying to claim that natural selection is responsible for the creative novelty one sees in evolution," Margulis says. "Of course, natural selection may select the symbionts over the individual partners or an animal with one genotype over another. It's an intrinsic part of the evolutionary process. But natural selection is the editor, not the author."

Perhaps the best illustration of the idea is the serial endosymbiotic origin of eukaryotic cells. Margulis was not the first scientist to suggest that eukaryotic cells, those with internal organelles, descended from symbiotic unions of simpler, unnucleated prokaryotic cells. During the 1960s, however, she did propose ways to test the hypothesis.

As she predicted, organelles such as mitochondria and chloroplasts do contain genes unrelated to those in the nucleus of eukaryotic cells but similar to those in some bacteria. The evolutionary significance of the finding was that it showed eukaryotic cells did not have to reinvent respiration and photosynthesis through genetic trial and error. The first eukaryotes simply acquired the skills from unrelated bacteria by incorporating those cells as endosymbionts (internal symbiotic partners).



COMPLEX CELLS may have evolved through a series of symbioses between simpler organisms.

Evidence continues to accumulate that a series of endosymbiotic events has added to the complexity of many organisms. It also shows that such endosymbioses are not restricted to prokaryotes. Last March, Susan E. Douglas of the Institute of Marine Biosciences in Halifax and her colleagues found the first proof that two eukaryotes had joined symbiotically to create a species of freshwater alga called a cryptomonad.

Cryptomonads contain an unusual membranous structure known as a nucleosome, which previous investigators have found holds both DNA and RNA, the molecular blueprints of life. A decade ago Sally Gibbs of McGill University proposed that the nucleosome is the remnant of a red alga that parasitized a eukaryotic host long ago. Douglas's group has confirmed that idea by showing that the DNA in the nucleosome is more similar to that of red algae than to that in the cryptomonad's nucleus. Apparently, the ancestral cryptomonad became photosynthetic by incorporating red algae containing chloroplasts.

What seems to irritate Margulis is that evolutionary biologists accept that symbiosis created early eukaryotic cells yet still question its role in creating more familiar lifeforms. "People take symbiosis seriously in lichens," she says, because lichens are undeniably a community of fungi and photosynthetic bacteria or algae, "but then they dismiss lichens as unimportant. They don't take it seriously in the organisms that are dear to them—seed plants and animals."

Symbiosis is clearly integral to most organisms. Botanists generally acknowledge that 90 percent of all land plants are mycorrhizal—that is, fungi associated with their roots are essential to the plants' ability to draw nutrients from the soil. Most herbivorous animals and insects depend on microorganisms in their guts to digest the cellulose they eat. "How can you talk about the evolution of the cow without discussing its cellulose-digesting microbes?" Margulis asks.

Peter W. Price of Northern Arizona University, whom many parasitologists credit with having drawn other biologists' attention to the field in recent years, outlines an evolutionary scheme for how herbivores could arise from symbioses between animals and microscopic plant parasites. The parasite, he says, would have already evolved enzymes for digesting the materials of its host plant.

If an animal host were to establish a symbiosis with the parasite, it could thereafter share in the nutrients derived from the vegetable matter. The herbivorous partnership could then spread out to wherever the plant grew. Its success in finding new food resources would favor the natural selection of more animals capable of similar symbioses.

The nagging question about such a scheme is why an animal would be able to establish a symbiosis with a plant parasite. Price suspects that "parasites are preadapted for living in close associations with hosts" and that these adaptations lend parasites a predisposition for establishing new mutualistic associations. The nature of those preadaptations remains to be clarified, however.

"Selection will always favor a parasite moving toward a beneficial impact on the host," Price remarks. Evolutionary modelers generally reach diametrically different conclusions, he says, but "they treat the mutualism as composed of two independent organisms. As soon as you get this tight linkage of a parasite with its host, the model isn't interesting, because the two species evolve as one. The modelers avoid that." Until the mechanisms that predispose organisms for symbiosis can be quantified, that situation is unlikely to change.

Cybernetic Parasites

During field trips to Costa Rica, Thomas S. Ray was surrounded by parasitic plants, fungi, insects and microorganisms. The ones that concern the evolutionary ecologist most these days, however, live in a computer terminal in his laboratory at the University of Delaware.

For the past two years, Ray has been exploring the world of artificial life—computer simulations of simple organisms competing for survival in cyberspace. His brainchild Tierra, which has been hailed as the most sophisticated artificial-life program yet developed, has independently confirmed what parasitologists have always known: parasites are an inevitable, ubiquitous part of any ecosystem.

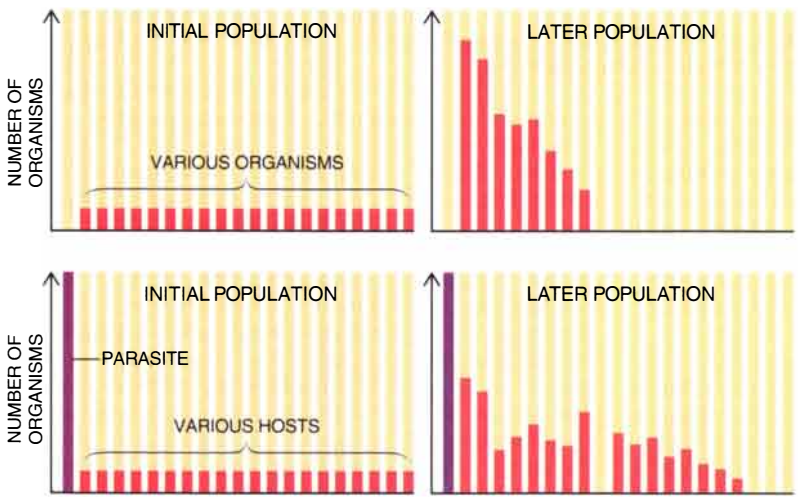
With Tierra, Ray was able to create an imaginary ecosystem inside his computer. Organisms, in the form of short programs, competed for processing time and bred copies of themselves that were occasionally flawed. Competition and mutation then caused further evolution in the system.

To Ray's surprise, parasites evolved spontaneously within the first five minutes of the simulation. "Generally right away, as the result of a mutation, you get the deletion of a major chunk of code that affects the replication of a creature," Ray explains. Although he had not programmed the creatures to do so, they then borrowed the necessary code from their complete neighbors, thus becoming parasites. The host programs subsequently evolved to block the incursions of the parasites, but they, too, continued to change.

The result was a perfect example of a coevolutionary arms race. Even after all the parasites were exterminated by particularly successful hosts, new types of parasites eventually evolved out of the host population. "Anything that's successful attracts parasites," Ray says. "They find a way of exploiting it."

Some of Ray's observations show that parasites can foster greater diversity within an ecosystem. He conducted community ecology experiments with Tierra in which he began with 20 kinds of organisms, none of which were parasites. (He deliberately turned off the ability to mutate to prevent parasites from arising.) By the end of the run, only eight kinds were left. When he reran the simulation with 20 kinds of hosts and one form of parasite, 16 varieties of host survived. The parasites apparently prevented any one species of host from driving many of the others to extinction.

Ray says he was perhaps most astonished by his creatures' discovery of sex. Even when he prevented mutation, the creatures began swapping bits of their genetic code. "I didn't even think that was possible," he swears. "I wouldn't go so far as to say that [beating parasites] is the selective force that maintains sex in the system," he goes on to say, "but that is clearly an advantage that sex provides."



***ARTIFICIAL ECOSYSTEMS remain more diverse when parasites are present. In the Tierra simulations, only eight out of 20 unparasitized species survived* (top). *With one type of parasite, twice as many host species persisted* (bottom).**

favor the benign strains of parasite, which let their hosts socialize.

According to Ewald, that principle accounts for the trends in virulence seen in the agents of most human diseases. "About half of the vector-borne pathogens fall above the criterion for severity, which is death for about 1 percent of the untreated patients," he says. "Only about 10 percent of the nonvector-borne diseases do."

Most evolutionary biologists studying parasitism seem to embrace Ewald's idea that a parasite's mode of transmission will determine whether its virulence will gradually increase or decrease. "I think his work is very beautiful and very convincing," Hamilton praises. A few researchers have at least mild reservations. "My own view is that there may be such broad generalizations, but they're not likely to be very helpful in any one instance," Robert May cautions. "Ultimately, the direction in which evolution will take a [symbiotic] association depends on the life history details and is constrained by them."

Listening to the predictions that fall out of the mathematical models—for patterns of virulence, for the emergence of sex, for the importance of host immunity—one can easily believe that the modelers have captured the full evolutionary essence of host-parasite interactions. Many parasitologists, however, say they have a long way to go.

One outspoken critic of the evolutionary ecologists and their natural selection models for host-parasite interactions is Lynn Margulis of the University of Massachusetts at Amherst. "They are superficially mathematizing without an understanding of the biology," she insists. "They're so far removed from the genetics, biochemistry, and physiology of the organisms that there's almost no basis for their discussions." She notes that the modelers often lump viruses in with parasites that metabolize and reproduce themselves. Virulence is also not an intrinsic property of parasites: changing the amount of water or sunlight in the environment can sometimes make parasites seem more or less harmful, she says.

Margulis has become famous over the past decade as a proponent of the Gaia hypothesis, which holds that the web of interdependent life on Earth causes the planet to act as a self-regulating, living (she prefers the term "autopoietic") system. In the 1960s Margulis proposed that eukaryotic cells—those with internal structures called organelles—evolved through the symbiotic union of simpler prokaryotic cells, such as bacteria.

She suggested, for example, that mitochondria, the organelles that derive energy from oxygen and carbohydrates, originated as aerobic bacteria; chloroplasts were originally photosynthetic bacteria. Most evolutionary biologists initially rejected her ideas about the endosymbiotic origin of eukaryotes—"ridiculed" is how Margulis puts it—but many lines of evidence have since bolstered her argument.

Nevertheless, Margulis feels their acceptance is halfhearted. "I think it's accepted and then trivialized," she says. "The serious genetic implications of symbiosis have not been taken. People keep on doing the same sorts of population modeling and drawing evolutionary trees that only branch. Branches should also come together to represent new symbiotic alliances."

In her opinion, a simplistic emphasis on competition and cooperation in many natural selection models obscure the more complex interactions in symbiotic associations. "What does competition mean in these cases?" she asks. "It's a term that's perfectly appropriate for the Boston Celtics but totally inappropriate for evolutionary analysis."

PAUL W. EWALD of Amherst College believes that how a parasite is transmitted to new hosts strongly influences whether it will evolve toward virulence.

Silent Partners

"I think comparing the importance of symbiosis with that of natural selection is comparing apples and oranges," Hamilton retorts. "The problem is that of trying to understand how natural selection goes on in the presence of symbiosis. And there I would agree that symbiosis is one of the most creative kinds of association in evolution."

Hamilton says he is currently exploring the idea that the presence of parasites in a host organism's population may help foster macroevolutionary changes in the hosts. Differing resistances to parasites may effectively divide a population into smaller reproductive groups, just as geographic barriers can, he explains. The late evolutionary biologist Sewall Wright proposed in 1931 that such fragmented populations may be able to expand into new ecological niches more efficiently than unified populations can.

The modelers must also face a different criticism based on parasitologists' fieldwork. "People involved in modeling parasites in evolutionary ecology are not parasitologists, and they don't collaborate with parasitologists," Brooks explains. "As a result, they have made some pretty silly mistakes that parasitologists would not make."

He points out that the modelers' assumption that parasites hurt their hosts is flawed. In reality, "the number of organisms that we call parasites for which a negative impact on the host's fitness has been demonstrated is vanishingly small." Some parasites do represent serious health problems, Brooks acknowledges, but they are in the minority, and most of them seem to be relative newcomers to the species they kill. "Look at the parasites in human beings that are most closely related to those in the great apes, like pinworms," he says. "Pinworms are all over the world. They cause a lot of itching and they're a real cosmetic problem, but they cause no pathology at all."

The snail-sabotaging parasite *Leucochloridium* is another example of a parasite that appears to perturb its host's fitness far less than observers might expect. According to Lewis, the masses of parasites in a snail frequently occupy one half or more of the volume inside its shell, not to mention completely distorting its eyestalks. Yet infected snails, he says, continue to feed, crawl and copulate without apparent difficulty. (He does note, however, that no one actually knows the relative fertility or fitness of the snails.)

There are two ways of interpreting such cases, Brooks says. "One is that the organisms have beaten one another up in the past and that now they either have an uneasy truce or are still beating one another up. The alternative is something less violent; something that says, in effect, that competition is a mistake."

Whichever interpretation they favor, many parasitologists and evolutionary biologists now believe that terms such as parasite, mutualist and commensalist are too subjective and simplistic to capture the truth of the interactions to which they refer. In a sense, only symbiosis is real: the amount of harm or good that organisms seem to do one another often depends on what the experimentalist hopes to measure. "I would say that all those terms could be dumped in the hopper and we wouldn't lose anything," Brooks says.

"It may be that evolution is not just 'Nature red in tooth and claw,'" he muses. "Studying the coevolution of hosts and parasites may tell us something about the coevolution of all organisms. It may be a guide to how things get along rather than how they compete."

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Growing Strong

Biotechnology's new wave hopes that being first will pay off

"It's biology's turn now," Peter J. Farley, a founder and then president of Cetus Corporation, trumpeted during the biotechnology rush of the early 1980s. White-coated research scientists were piling breakthrough on breakthrough, venture capital was flowing in torrents, and initial public offerings were being snapped up by eager investors. Robert Swanson, the thirty-something-year-old founder of Genentech, became a role model for more than one executive when he swore that he would build "a $1-billion company by 1990."

Instead Genentech, which cloned the first gene-spliced drug to reach the market (human insulin) and followed that with a cardiovascular clot buster (t-PA), marked the new decade by selling a controlling interest to Hoffman–La Roche. Cetus, which developed an important technique for making DNA haystacks out of single-strand needles, never managed to bring a drug to market in the U.S. The whale was swallowed in the summer of 1991 by quiet Chiron, a firm 10 years its junior. Genetics Institute, Inc., respected by many for the best product pipeline in the business, lost a patent battle to a competitor and then surrendered wholly to American Home Products in the fall of 1991.

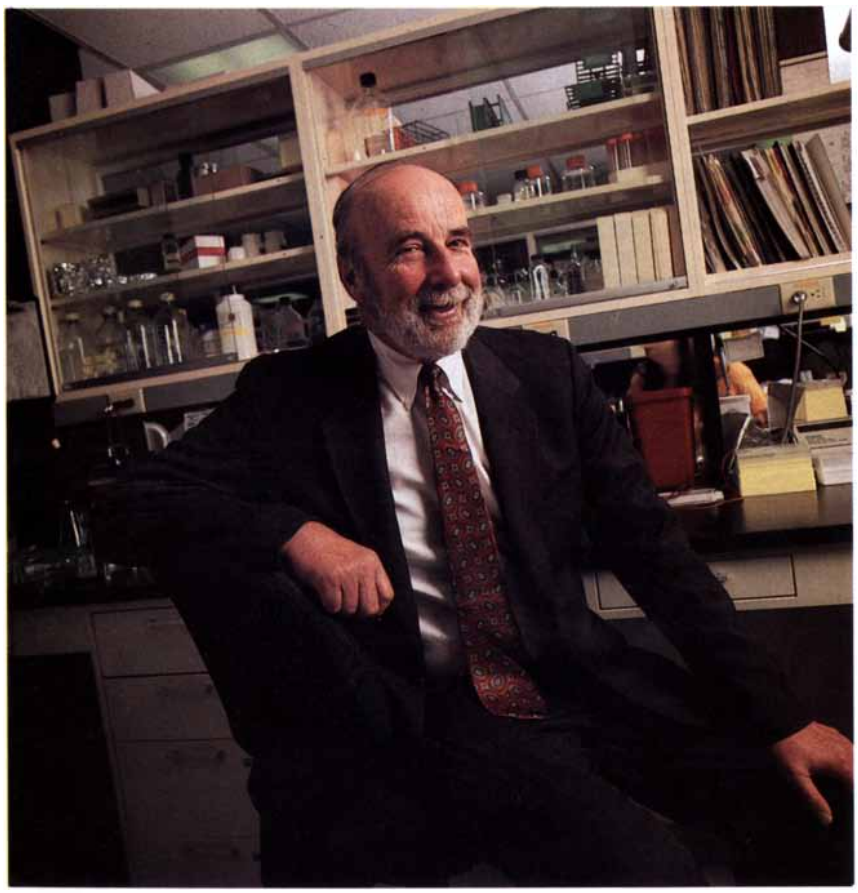
The list goes on, but don't write biotechnology off yet. Genentech's t-PA (tissue plasminogen activator) brought in $210 million in 1990, and although sales have been falling under criticism that less expensive drugs are just as effective, the drug did kick off a cascade of research into blood clotting. Cetus may not have reaped adequate benefits from the discovery of the polymerase chain reaction, but the technique has revolutionized diagnostic testing and basic research. Since the approval of recombinant human insulin in 1982, the Food and Drug Administration has approved 15 more biopharmaceuticals, and another 120 are cued up for review. More than 800 clinical trials are taking place around the country for drugs produced by biotechnology.

Even with the dips and wobbles, there have been outstanding successes among the first generation of start-ups. Consider Amgen: with a corporate valuation of $7.7 million, it is already bigger than Schering-Plough, an old-line pharmaceutical house. Financial analysts expect the firm to climb into the Fortune 500 by the end of 1991, primarily on the strength of revenues from a red blood cell stimulating protein called erythropoietin (EPO) and a granulocyte colony-stimulating factor trade-named Neupogen.

Amgen committed itself to developing EPO when other biotechnology companies were concentrating on genetically engineered versions of hormones already known to be useful in treating disease, such as growth hormone. EPO has earned Amgen more than $660 million since its approval in 1989 for treatment of the anemia caused by kidney dialysis. The only other way of relieving the condition is blood transfusion. "You have to be willing to do something new in a different way than anyone else," emphasizes George B. Rathmann, Amgen's chairman emeritus and former chief executive officer (CEO). "Being first will pay off."

Rathmann took his own "get out and innovate" advice to heart in September 1989, when he helped to co-found ICOS Corporation. Duplicating a key tactic from Amgen—raising plenty of money early—the firm amassed $33 million from high-net-worth individuals before the full team assembled for work a year later. The public offering in June 1991 brought in another $36 million. This financial muscle, and a set of human genes involved in relaying cellular messages, strengthened the company's bargaining position with potential partners. Glaxo has joined ICOS to develop drugs for inflammatory diseases such as arthritis, asthma and multiple sclerosis. The two will co-market products.

ICOS is just one example of a new



GEORGE RATHMANN made Amgen a success with blood cell stimulators. He plans to do the same for ICOS with anti-inflammatory drugs. Photo: Raymond Gendreau.

SCIENCE/SCOPE®

The U.S. Army may soon have improved nighttime visibility and target detection capability, in battle and in bad weather, as a result of an infrared sensor array developed by Hughes Aircraft Company. This second-generation focal plane array provides an infrared image with higher resolution and enhanced thermal sensitivity. It contains a detector chip bearing thousands of heat-sensitive detecting elements. Developed initially for the Army's Headstart Project, these arrays will eventually be common units for military sensors in systems from Army tanks to rescue helicopters.

The Navy's "Top Gun" Training System will have a new level of realism and value, now that Hughes is producing a digital computer to link it with the F-14's Hughes-built radar. The computer link will improve real-time interface for F-14 aircraft used in this "Top Gun" Tactical Aircrew Combat Training System (TACTS). The system allows pilots to fly air combat missions against one another without ever firing a shot, as ground instructors monitor their moves in real time, from any angle, on large multicolor computer graphic displays.

Germany has upgraded portions of its air traffic control systems with a new state-of-the-art system built by Hughes. These TracView systems give air traffic controllers a real-time, full-color digitized display of aircraft detected by multiple radars that feed into air towers and centers. Installed in former West and East German sites, TracView provides automated identification and beacon code correlation and networked beacon code allocation. The systems draw sensor data from a wide range of old and new radars built by Western and Eastern Bloc companies.

Improvements in the Advanced Medium Range Air-to-Air Missile (AMRAAM) are now underway. They incorporate technological advances in aerodynamics, aircraft carriage, and guidance and signal processing, to counter future threats. AMRAAM's state-of-the-art radar enables pilots to launch and maneuver out of danger, while achieving multiple strikes per engagement. The 12-foot, 345 pound missile was developed by Hughes to become the mainstay air-to-air missile for the Air Force's F-15 and F-16 fighters and the Navy's F-14 and F/A-18. Its deployment is also planned on the German F-4F and the UK's Sea Harrier and Tornado aircraft. Hughes will lead this product improvement program, with support from Raytheon.

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HUGHES

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generation of biotechnology firms that plan to develop drugs for indications ignored or failed by traditional methods. Last year the initial public offerings of about 35 companies, which analysts are calling "The Class of '91," pulled in more than $1 billion from investors. "It was the biggest year yet for biotechnology financing," marking a halt to the investment drought of the late 1980s, raves Jeffrey Casdin, who analyzes the industry for Oppenheimer & Co. in New York City. This next tier of companies is beginning public life far better funded than its forebears, Casdin points out.

The new firms plan to develop highly specific treatments for such conditions as allergy, neurodegenerative disorders, cancer, viruses and cardiovascular and autoimmune diseases. No longer limited to proteins, firms are exploring peptides, carbohydrates, lipids, enzymes and even drugs made by conventional pharmaceutical chemistry but elucidated via molecular biology techniques. Some companies hope to interfere with disease processes by blocking gene expression with antisense DNA.

The product lineup indicates that the industry is past what James L. Vincent, the CEO of Biogen, refers to as biotechnology's cherry-picking phase, when proteins were hanging on trees waiting to be plucked. "Now we're in the banana-picking phase, where we have to spot drugs long before they are ripe. We pick products when they're green."

The younger firms tend to have more acumen when it comes to selecting potential products than the first wave of companies, observes Peter Drake, executive vice president and director of equity research at Vector Securities. Drake was one of the first financial analysts to recommend investment in biotechnology. Nowadays company choices are informed by an appreciation for manufacturing and scale-up costs, potential means of delivering the drug, whether the production process is patented and whether a compound has optimal therapeutic activity instead of being merely okay. "Generally speaking, none of those issues impacted go-no-go decisions on the first products," Drake notes.

The need to maintain corporate focus has of course meant that certain projects within a company will be put on the back burner—until a frustrated scientist decides to go forth and develop the idea elsewhere. "That's the history of any healthy industry," explains Stephen A. Duzan, CEO of Immunex Corporation in Seattle. He watched Christopher S. Henney, one of the company's co-founders, leave to participate in the start-up of ICOS in nearby Bothell, Wash. "No one is taking ideas to directly compete, but people are saying, 'I like what I thought up here. I'm going to go out and give it a try.' They go with our blessings," Duzan says.

The younger companies are trying a different style of management that has analysts watching intently. There is a new breed of CEO—Jay D. Kranzler of Cytel, Michael Riordan of Gilead Sciences, Richard F. Pops of Alkermes and Michael M. Goldberg of Clinical Technologies Associates, for example—men in their early to mid-30s who boast several years' experience in banking or financial services. Unlike the academic founders of many early start-ups, who lacked any business experience at all, or the CEOs who often replaced them after being drawn away from pharmaceutical companies, the new hybrid executives feel no obligation to develop a traditional organizational culture. But neither can they draw on personal experiences of commercializing science into salable drugs. The FDA is not the Securities Exchange Commission, critics caution.

The criteria that make a drug worthy of approval by the FDA are changing as well. Because of the push for health care reform, "the issues around FDA approval are increasingly driven less on safety and efficacy and more on pharmacoeconomics," observes G. Steven Burrill, Ernst & Young's national director of manufacturing/high technology industry services. The way drugs are delivered and paid for and the quality of life they enable are all coming to play in the agency's decision. Companies that can prove their drugs save money, by reducing hospital stay or returning productive work years, will be able to do well, Burrill says.

What is commonly referred to with a heavy sigh as "the patent situation" will continue to be a thorn in the industry's side. The early disputes over whether a protein altered by a single amino acid is actually a different product should wane somewhat as companies develop smaller, more specific molecules. But conflicting rights promised by patents issued in different countries are sure to provoke nasty, expensive, international battles.

Patents are becoming ever more important as reverse engineering of proteins and other products of high technology becomes commonplace. When information travels around the world to competitors in seconds, trade secrets are little more than delusions. "We should be rewarding innovators," declares George Rathmann, "so that people who hang about being number two and waiting for someone else to do something will start thinking differently. There's not that much wonderful stuff created by people who copy. There's nothing preventing you from innovating." —*Deborah Erickson*

New Targets for Young Companies

Antisense Technology

By acting like molecular Velcro to stick to DNA or messenger RNA, antisense oligonucleotides may block the genes that cause cancer as well as infectious, inflammatory and cardiovascular diseases. Initial targets are viruses, such as herpes.

Developers: Isis, Gilead Sciences, Genetic Medicine, Triplex

Autoimmune Disorders

Instead of suppressing the entire immune system, devising ways to inactivate subsets of cells or block events that elicit antiself responses may result in treatments for diseases such as rheumatoid arthritis, multiple sclerosis, AIDS and allergies.

Developers: Anergen, IDEC, ImmuLogic, Vertex

Cell Adhesion Molecules

Molecules that bind to sites on cell surfaces are key to triggering a range of biological processes such as inflammation. Drugs that block these doors to molecular pathways may treat rheumatoid arthritis, cardiovascular disease, psoriasis and sepsis.

Developers: Icos, COR, Cytel, Glycomed

Central Nervous System Disorders

Companies are developing neuroprotective compounds and growth factors, ideally in forms that can be transported across the blood-brain barrier. These could treat head and spinal injuries and stroke and degenerative diseases such as Alzheimer's.

Developers: Alkermes, Cambridge NeuroScience, Cephalon, Regeneron

Ex Vivo Therapy

Patients' cells from blood or marrow are sorted by specialized equipment, genetically modified or stimulated, cultured, then reintroduced into the body. The technique has the potential to treat cancer, enzymatic deficiencies and hereditary disorders.

Developers: Applied Immune Sciences, CellPro, Genetic Therapy

Explosive Images

The FAA scans technology for airport security systems

Spending a workday watching X-ray images of shaving-cream cans and portable hair dryers is enough to put an airport security officer to sleep. The Federal Aviation Administration (FAA) has been planning for more than a decade to improve airport security by automating baggage screening and finding more effective means of bomb detection than conventional X-ray scanners.

Pressure on the agency from Congress and elsewhere increased dramatically after Pan Am Flight 103 was blown out of the skies over Lockerbie, Scotland, on December 21, 1988. The fear and anger that ensued caused what high-level governmental reports characterized as a rush to judgment to deploy technology to detect plastic explosives.

The FAA claimed in September of 1989 that thermal-neutron analysis (TNA) was the "only existing, proven" system. (TNA bombards baggage with neutrons, causing nitrogen-rich plastic explosives to emit gamma rays of a characteristic energy.) The agency's move opened the way for what could have been a purchase of as many as 860 TNA systems at up to $1 million apiece by the end of the decade.

The FAA's support for the technology now appears to have been premature, and the agency has been backpedaling ever since. TNA has run into difficulty when it has to detect the tiny amounts of plastic explosives equal to what was thought to have been present on Pan Am Flight 103. The machine, when calibrated for small quantities, often has produced an excessive number of false alarms. The Air Transport Association, which represents commercial carriers, commissioned a study that showed that up to 30 percent or more of passengers would be unable to make an international connecting flight because of delays caused by TNA.

In 1990 Congress intervened again by passing the Aviation Security Improvement Act, which effectively put a hold on the FAA's requiring U.S. airlines to buy TNA, while leaving open a loophole. The law directed the agency to develop a testing program in consultation with outside experts before giving its approval to TNA or any other detection system, an apparent response to criticism that the agency had failed to perform adequate testing of TNA. But the bill gave the agency the emergency authority to deploy TNA or other technologies for a period of 18 months after passage of the bill.

Expanding the selection process has triggered a technology slugfest among a variety of imaging or vapor-detection devices that are potential candidates for what could turn into a $1-billion market. The FAA's aviation security research and development service, with about three times the budget and four times the staffing it had before Lockerbie, has awarded more than 25 contracts to research electromagnetic or vapor detection.

Scan-Tech Security, for example, along with Rutgers University, was awarded a recent contract to develop a prototype for a coherent X-ray scattering system, similar to X-ray crystallography, which identifies the spectra produced when a material is illuminated with X rays. A neural network, software used for pattern recognition, can then compare those spectral signatures with a data base of known solid explosives.

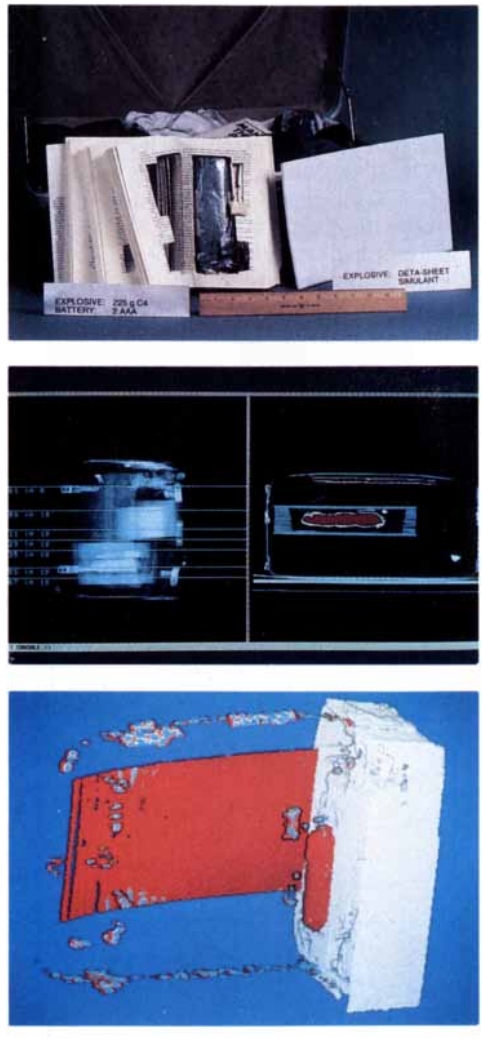
Another contract went to Imatron Federal Systems, a Burke, Va., firm that is developing a high-speed version of a computed tomography (CT) scanner. Like the instruments used in hospitals, the CT scanner can yield cross-sectional images at any depth, enabling a glimpse inside a packed radio or book. The computer compares density and other readings of the material with a data base derived from CT measurements of more than 100 different types of explosives. The FAA, meanwhile, still continues to fund research into TNA, but it has yet to order deployment of the system.

By soliciting and testing more ideas than it can use, the agency may want to avoid another debacle. Eager vendors for this panoply of competing products were given a chance to scan and sniff one another last November at the agency's first symposium on explosives detection at the Sands Hotel and Casino in Atlantic City, near the FAA Technical Center.

Even with the many options, finding the bomb in the bag is no small problem—and no one technology is likely to be completely effective. Lee Grodzins, a physics professor at the Massachusetts Institute of Technology, who is an expert on explosives detection, insists that so far the main benefit from TNA testing has been the realization of how complicated pattern and material recognition can be inside a shut suitcase. "You have to do in six seconds what is difficult to do in two hours in the laboratory," Grodzins says.

That is why whatever technology is finally chosen will probably be combined with the type of psychosocial profiles and baggage identification procedures that are routinely performed by Israel's El Al Airlines. The profile expert might ask whether the passengers are an elderly couple from Dubuque who purchased their tickets two months ago. Or is the traveler a holder of a one-way ticket bought in cash a few hours before departure time? The last passenger's luggage gets the full treatment.

Even with all the technology, any system may have to be altered almost as soon as it is put in place. A neural network might be smart, but no match for an Abu Nidal. —*Gary Stix*



BOMBS IN THE BAG are pinpointed by using conventional two-dimensional X-ray scanning* (middle left), *followed by two-dimensional* (middle right) *and three-dimensional* (bottom) *computed tomography. Photos: Imatron.

Current Event

Bright future for a new photovoltaic cell

Photovoltaic cells are familiar in such applications as calculators, and higher-power versions are increasingly being used to provide electricity in locations beyond the easy reach of transmission lines. Parking lot lights and traffic signs powered by solar cells are also becoming common. But today's systems, which are almost all based on silicon, are still relatively expensive. Photocomm, Inc., the largest U.S. supplier of photovoltaics, quotes a price of $8 to $10 per installed watt for a residential system.

Hence the interest aroused by a new technology for making photovoltaic cells. Based on dye-coated titanium dioxide, the chemistry mimics the role of chlorophyll in photosynthesis. Cells built so far seem to promise improved efficiency at lower cost. That persuasive combination could give photovoltaics a major boost if the device meets expectations. About 50 megawatts of photovoltaic capacity, valued at $700 million, are installed worldwide every year, according to Scott Sklar of the Solar Energy Industries Association.

The cell, the product of almost a decade of work by Michael Grätzel of the Swiss Federal Institute of Technology in Lausanne, is now under investigation by two major European companies. Grätzel recently described in *Nature* a design that is 7 percent efficient in sunlight and as much as 12 percent efficient in diffuse daylight.

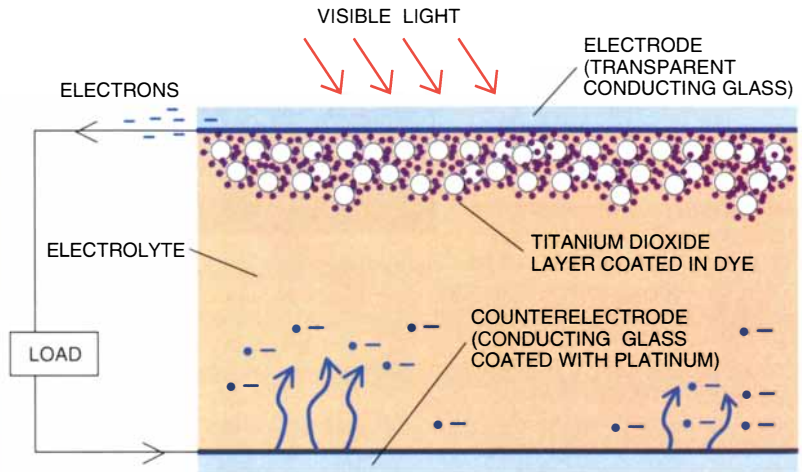
That is already about as good as the best amorphous silicon cells, although complex cells using materials such as gallium arsenide have achieved efficiencies of nearly 30 percent. But theory suggests it should be possible to improve the Grätzel cell even further. "We want to reach 15 percent efficiency," says Roland Entschel of Sandoz Chemicals in Basel, which is developing new dyes for use in the cell.

Moreover, a commercial device based on the design would be easier and cheaper to make than silicon cells, according to Brian O'Regan of the University of Washington. "It's a new ball game," says O'Regan, who has collaborated with Grätzel for the past two years and was a co-author of the *Nature* report.

Grätzel's device is an electrochemical cell—two electrodes in contact with a liquid that contains charge-carrying ions. One of the electrodes is covered with a layer of titanium dioxide particles, which are in turn coated with a special dye. The ruthenium-based dye has intriguing similarities to chlorophyll in that both molecules consist of a metal atom surrounded by rings of carbon and nitrogen that are able to capture the energy of the sun.

The photosensitive dye molecules absorb photons of incoming light, acting like miniature antennas, and release electrons to the titanium dioxide underneath. The electrons flow from

A New Route to Photovoltaics



Dye-coated titanium dioxide particles capture the energy of sunlight. Electrons from the ruthenium-based dye travel through a layer of conducting glass around the external circuit to a counterelectrode. Iodine ions in the electrolyte ferry electrons back to the dye, completing the circuit.

the light-absorbing electrode around an external circuit to a counterelectrode and are returned to the dye by iodine ions in the electrolyte.

Several researchers tried in the 1980s to coat semiconductors with dyes to improve light absorption, Grätzel says, but they all ran up against a problem. A dye layer thick enough to do a good job of absorbing light was too thick to allow efficient transfer of electrons into the underlying semiconductor. In addition, organic dyes were not stable over long periods.

Grätzel made a key discovery in 1985, when he modified a ruthenium-based dye so that it included chemical groups that bound it tightly to titanium dioxide. The current-carrying capacity increased 10,000-fold. Grätzel was awarded patents on the principle in 1988.

The latest advance, which brings the device into the realm of commercial viability, was the contribution of O'Regan. He perfected techniques for depositing fine titanium dioxide particles from a colloidal solution onto a conductive glass substrate. The layer in the Grätzel-O'Regan cell now has a surface area of 780 units for each unit of glass covered. The high surface area permits the dye to absorb most incoming photons and also transfer electrons efficiently to the glass.

Further improvements are expected. Since 1989 Sandoz has been helping Grätzel synthesize and test new dyes, and he has applied for patents covering dyes that absorb light more efficiently. A commercial device would not necessarily be based on a metal-containing dye, Entschel says, and would probably use a mixture of dyes tailored for optimal absorption of sunlight. A critical consideration is that the compounds must be stable enough to perform well over a product lifetime of 10 or 20 years. Asea Brown Boveri in Baden recently joined the effort and is developing commercial fabrication methods. O'Regan says that conducting polymers or other compounds might eliminate the need for a liquid electrolyte.

Sandoz is also dealing with patent applications—if the new cell turns into a commercial success, royalties will flow to the Swiss research institute. "They were kind to us," says Grätzel, who is a consultant to the company. "A venture capitalist would have hesitated."

The firm now has two small laboratories working on the project. Entschel says Sandoz is committed to pursuing the new cell at least until the end of 1992. "We should by then be able to decide if it's useful," he says. If it is, it will add new brightness to Sandoz's expertise in dye chemistry. —*Tim Beardsley*

***SCRAPPED CARS** in Germany number more than two million every year. Now automakers are hoping to recycle them. Photo: Volkswagen.*

Green Machine

Volkswagen gears up to recycle autos

Gerhard Rohlfs has never built a car. Neither has any of the other 28 or so workers at Volkswagen's most unusual plant, located in Leer, in the northwestern tip of Germany. Instead, for the past two years, Rohlfs and his team have ripped apart, shredded and pulverized enough used and new VWs to reduce most automobile dealers to tears.

The Leer plant, or "laboratory," as Rohlfs likes to call it, is at the forefront of an environmental issue that will soon confront the automobile industry worldwide: how to recycle cars. Within Europe, Germany is taking the lead in trying to establish policies that favor recycling and to sort out who will bear the costs.

In the U.S., legislators are monitoring Germany's recycling strategies. And automobile manufacturers are beginning to research different options for making their products more recyclable, says Gary Eaton, who chairs the plastics committee of the Society of Automotive Engineers (SAE). Last September the SAE and the Society of the Plastics Industry issued a standard for labeling the various plastics used in cars.

Such efforts are still a lap or two behind those in Germany. Spurred by public concern for the environment, the German government was widely expected to announce at the end of 1991 regulations that would force manufacturers to take back their aging cars and be responsible for disposing of them.

From the perspective of German automakers, the new rules could translate into a lot of costly trash. Germans scrapped about two million cars in 1990. Even though about 75 percent of that material is already reused, either as scrap metal or as refurbished secondhand parts, the remaining amalgamation of plastics, rubber, glass and other assorted materials amounts to more than 400,000 metric tons of refuse a year. Because Germany has stringent regulations on burning waste and an acute shortage of dumping grounds, disposing of that material will be prohibitively expensive, says Gary S. Stacey, a senior economist at Battelle in Geneva, Switzerland.

As a result, German car makers practically bumped into one another at the Frankfurt auto show last year in a race to prove their greenhood and so shape the emerging government regulations. A convoy of manufacturers, led by VW, announced their intentions to take back new models when they had run their course. Because most of those pledges apply to the latest models, the companies hope to have about 10 years before they have to make good on their promises. And a few companies are dabbling in recycling firsthand.

The Leer plant, which is a cooperative venture between Volkswagen, the East Friesland trade corporation, the Leer labor office and a local metal scrapyard, shows how painstaking recycling must be if it is to make a significant dent in the 25 percent of car materials that are now rubbish. Even the simplest cars use more than 600 different materials, Rohlfs observes. "I don't think 100 percent recycling is possible," he concedes. Instead he is exploring how many parts he and his team can extract and recycle and still enable Volkswagen to break even. "Don't mistake—this project is about making money," Rohlfs says.

VW crew members at the Leer plant consequently look for the swiftest ways to disassemble cars and segregate the parts that will be shipped off to other locations for reprocessing and recycling. So far they need two man-hours to take apart a simple VW car.

The workers begin by draining all fluids—engine and transmission oil, brake fluid and coolant, and so on. These are stored in barrels for recycling or processing. Large units, such as the engine, battery, gearbox and tires, are removed next. These are subsequently either refurbished as secondhand parts or sold for their constituent materials. (The platinum and rhodium in catalytic converters can fetch between 50 and 200 deutsche marks for the recycler.) Then workers rip out large plastic parts such as bumpers, fuel tanks and interior molding.

Volkswagen boasts its greatest successes with bumpers. Once stripped of any decorative metal and trim, plastic bumpers are ground into pellets that are mixed with fresh resin to make new bumpers. "We want to make old bumpers into new ones, not into flower pots," says Jörg Barrenscheen, who directs work on technologies for recycling at the VW Wolfsburg facility.

Since last May about 20 percent of the material in new bumpers destined for Polo cars came from recycled bumpers. The main factor preventing Volkswagen from increasing the proportion of old plastic in its bumpers is a guarantee of a steady stream of material, Barrenscheen says.

Unfortunately for the recyclers, not all bumpers are made alike. VW and Audi produce bumpers based on different recipes of plastic; other manufacturers use still other mixes. Increasingly, however, German car makers are stamping plastic parts with a government standardized code that identifies the material. VW is also beginning to redesign parts to use fewer materials. The plastic fuel tank for the VW Golf, which went into production last summer, has 11 fewer parts than the old

design. "The motivation for environmental protection is so high that all the engineers now want to design for recycling," Barrenscheen declares.

Even so, plastics still remain a recycler's headache. Volkswagen's efforts address only 30 to 40 percent of the 100 kilograms of thermoplastics typically found in its cars. Other car parts continue to defy recyclers' efforts. For instance, the Leer workers have not yet found any use for laminated glass windows and glass embedded with heating strips. Dashboards and steering wheels are also such intricate combinations of materials that separating the constituent parts would be extremely expensive, Rohlfs says. And because they have for the most part tackled simple Volkswagens and Audis, the VW workers have not yet tried to sort out what to do with the electronic components included in more complex autos.

Even tougher than separating materials will be the issue of who will eventually undertake recycling projects, how many different makes and models of cars they will handle and who will bear the costs. Still, observers such as Stacey are optimistic that auto recycling will grow rapidly into a booming business. "Car makers now think they don't know how to make money taking cars apart," he says. But if automakers scale up operations such as that at Leer to an automated "mass-production" level, he says, they may find the economics of recycling cars will shift into drive.

—Elizabeth Corcoran, Leer, Germany

No Tipping, Please

In March the first iron-collar workers joined the legions of blue-collar cleaning and service employees at Marriott Corporation. Avoiding walls and sidestepping obstacles, these service robots, or serbots, trace a sudsy path down the corridors of two Chicago hospitals. They are an attempt by the $7.5-billion company to explore how some jobs might eventually be replaced by machine labor.

Marriott is one of the first institutional service companies to add robots to its work force. They are also being tested by the U.S. Postal Service and are even being used in France to clean floors at the Louvre Museum.

The inspiration for Marriott's experiment was a 1990 study prepared by the company with a consultant, Joseph Engelberger, a robot pioneer. The study concluded that the corporation could automate 8,000 jobs in a single year, achieving an immediate payroll savings of $200 million. Additional savings would follow in each of 10 years afterward. The plan attracted the rapt attention of the top executives, including J. Willard Marriott, Jr., the chairman, and Richard E. Marriott, vice chairman.

The ambitious original scheme was scaled back when the company was forced to slash its annual $1.3-billion capital budget by $650 million. So far it has installed a well-oiled worker at Northwestern Memorial Hospital in downtown Chicago and one more at Rush-Presbyterian-St. Luke's Medical Center a few miles away. Although the first units cost more, Marriott eventually expects to buy robots for $20,000 apiece, about four times more than a manual cleaning machine.

The robots look like any other floor-cleaning machine that workers still push down hospital corridors, except they need no human operator. Training began by moving the robots manually along their route of travel. During these first few trips, the machines, products of the Kent Company, a division of a Swedish firm, Electrolux AB, recorded an internal map of the floor layout. Later they navigated on their own. The robots are also equipped with ultrasonic sensors. If a person or object gets in their way (hospital staff enjoy testing the machines' reactions), the robots stop and wait a few moments to see if the obstacle moves. If not, they skirt to the side of the obstruction.

MILO THE SERBOT does floors at Northwestern Memorial Hospital in Chicago. Photo: Neil MacDonald.

There have been only a few comic mishaps. "One employee ran after a robot because he thought it was a runaway cleaning machine," Scott Knell, who heads the technology advancement group at Marriott's Bethesda, Md., headquarters, told a gathering at a Robotic Industries Association conference held in October. Even so, Marriott's human laborers have accepted their mechanical colleagues. One of the two members of each cleaning detail has been assigned to a new job in the hospitals; the other, now a "Robobuddy," accompanies the machines, one of which has been christened Milo. To help a machine get into corners, the human member of the team has only to switch the machine to a manual setting.

If robots pass probation, some jobs held by humans may be eliminated through attrition. The remaining Robobuddies, Marriott executives hope, will take enough pride in supervising a machine that they will help stem overwhelmingly high turnover rates for these low-paying and unskilled jobs.

Based on early experience with mechanical workers so far, Marriott has ordered 10 more units. Robots might eventually be used for such tasks as cutting the grass on golf courses—or perhaps placing silverware on trays.

For now, management has decided that it does not want robots dealing directly with guests at its hotels. "We're not going to automate room service to the extent that we'll have a mobile vending machine with a microwave oven in the robot's tummy," Knell jokes. Even so, a robot paperboy that delivers *USA Today* to a guest's door and then wheels silently away is a distinct possibility. Tipping will be strictly prohibited. *—Gary Stix*

Coping with Math Anxiety

Economics boasts—or perhaps laments—a lengthy, intimate and not always fruitful affair with mathematics. Its practitioners routinely employ tools from simple algebraic expressions to abstruse differential topology to express theories. (One helpful tract written in 18th-century Italy by Cesare Beccaria relied on algebra to point out the hazards and profits of smuggling.)

Yet increasingly during the past few years, some economists have worried that the explosion of work in high-powered mathematics has outpaced research on fundamental theory. There has evolved the notion that "you can solve great social questions on a blackboard instead of in a library or lab," asserts Donald N. McCloskey, an economist at the University of Iowa. Leaders in the field are more temperate, suggesting that the passion for math has now crested. It is time, they add, to settle down to the less flashy stuff of economic principles.

Enthusiasm for mathematical economics soared after World War II—and for good reason. Mathematics offers the social scientists two advantages: a discipline to help state their theories precisely and the analytical equivalents of picks and shovels for extracting insights from mounds of raw data.

Kenneth J. Arrow, who received a Nobel Prize in 1972 largely for his mathematical expressions of equilibrium theory, recalls that when he worked as a staff economist with the Council of Economic Advisers in the 1960s, even simple mathematical reasoning was applied to economic problems only haphazardly. "The work I did there was only mildly mathematical," he says.

As a specialist in microeconomics, Arrow regarded his skills to be unsuited to the major policy questions facing the council. Instead he devoted himself to cost-benefit analyses and tried to spark other economists' interest in doing similar work. One of the first targets to drift across Arrow's desk was a proposal from the Civil Aviation Administration (the precursor to the Federal Aviation Administration) to build a supersonic transport (SST). The document numbered several hundred pages and "went on and on about how it was man's destiny to travel that fast," Arrow recalls. "Not a word in there that would make sense to any economist."

Tagged to the project was a hefty bill, one "that no one expected would ever be repaid," Arrow says. Although the project was too complex to analyze definitively, for two years he kept peppering officials with questions about the likely costs and benefits. About that time, the SST began attracting opposition because of its environmental hazards, and the project was canceled. "I like to think I saved the country about $4 billion," Arrow says, with a note of satisfaction. "That was pretty primitive stuff. Just a matter of asking the questions that needed to be raised."

Since then, using mathematics to help ask the right questions has given way to building models that demonstrate dizzying mathematical virtuosity but give shorter shrift to underlying economic principles. "Uncritical enthusiasm for mathematical formulation," complained Nobel laureate Wassily Leontief as early as 1970, "tends often to conceal the ephemeral substantive content of the argument behind the formidable front of algebraic signs." Arrow, too, grew concerned. "The math takes on a life of its own because the mathematics pushed toward a tendency to prove theories of mathematical rather than economic interest," observes the Stanford University economist.

Are economic principles simply obscured behind the mathematics—or have they vanished?

The clearest sign of such worries was a two-year critical review published last September in the *Journal of Economic Literature* about the community's own efforts in graduate education. That study by the Commission on Graduate Education in Economics (COGEE) found "a great deal of malaise among graduate students and faculty in economics," says Daniel H. Newlon, senior program director for economics at the National Science Foundation. The resounding complaint: economics education puts too much emphasis on formal tools and devotes surprisingly less attention to tackling practical issues.

The problem is not the excessive use of complex math, argues Anne O. Krueger, an economist at Duke University and chair of the commission. Instead it is the lack of relevance that some of the tools and formulations have to real-world questions. "It is less a problem of overkill in math," Newlon concurs, "and instead reflects the state of empirical and substantive work in economics."

Despite the growing consensus about the imbalance between math formalisms and economic concepts, no one is pushing graduate schools to act on the study's recommendations. "You can't tell anyone what to do," Krueger says. Newlon hopes economics departments will experiment with different teaching approaches. Still, he suggests that the COGEE study may better reflect the ongoing debates in the profession than act as a call to action. "The pendulum is definitely swinging away from what could be argued has been excessive emphasis on math," he contends.

Among the signs of the times, some economists say, is the award of the most recent John Bates Clark Medal for the most promising young economist to Paul R. Krugman of the Massachusetts Institute of Technology. Krugman is no mathematical slouch, but he has gained prominence through his work on economic theories of international trade. The two runners-up for the award, Lawrence H. Summers and Jeffrey D. Sachs of Harvard University, are following even more applied tracks. Summers is now chief economist at the World Bank, and Sachs spends most of his time trying to help countries—notably Poland—find the road to capitalism.

When asked what areas of economics he would explore if starting his career now, Arrow points to big theoretical questions. "I think I'd be concerned about the role of knowledge in economics," he says, that is, what people know and how they acquire knowledge.

"What do you mean by 'knowing a thing'? I realize that sounds very theoretical," he says, somewhat apologetically. But most economic theories are based on the idea that consumers know—or don't know—something. And what economists don't know, he adds, is "to what extent knowledge matters for economic behavior."

—Elizabeth Corcoran and Paul Wallich

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THE POWER IS ON

How to Generate Chaos at Home

Most people try to avoid chaos. After all, who wants to be stuck in an airport on a snowy afternoon before Christmas? But I find chaos relaxing, particularly when I can observe and control it. Chaos is part of the beauty of nature. It can be observed in the flow of a river, the swing of a pendulum or the dynamics of a cloud [see "Quantum Chaos," by Martin C. Gutzwiller, page 78].

One of the best ways to experiment with chaos is to build an electronic circuit such as the one depicted in the diagram below. The circuit serves as a paradigm for chaotic systems. When the circuit is subjected to certain voltages, it produces a signal that is chaotic.

In 1981 Paul S. Linsay of the Massachusetts Institute of Technology was the first to study rigorously the circuit's behavior. Since then, many physicists have attempted to explain how the circuit generates chaos.

When I learned about Linsay's experiments, I was struck by the fact that a simple circuit could produce such complicated and interesting behavior. I had seen computer simulations of chaotic systems, but here was a chance to study the chaotic dynamics of nature firsthand. As an amateur scientist, I decided I wanted to see chaos for myself. And with a little bit of effort, I even found a way to listen to it.

To construct the circuit, all you need is some basic electronic components—a resistor, an inductor and a diode. I recommend that you start with a resistor of 200 ohms and an inductor of 100 millionths of a henry, the unit of inductance. I have found that many different diodes will work, including 1N4001, 1N4004, 1N4005 and 1N4007.

You can buy a handful of resistors, inductors and diodes for less than $20. I purchased the components from a mail-order company. You can also try a hobby store that carries electronics.

The circuit can be assembled on a breadboard, which is a plastic block with rows of holes to accommodate components. The board costs about $10. To supply the input signal, you will need a function generator, which can be bought for around $200. To measure and view the output of the circuit, you are best off using an oscilloscope. If you do not own an oscilloscope and a function generator, you can probably arrange to use them at a department of physics or engineering at a local college.

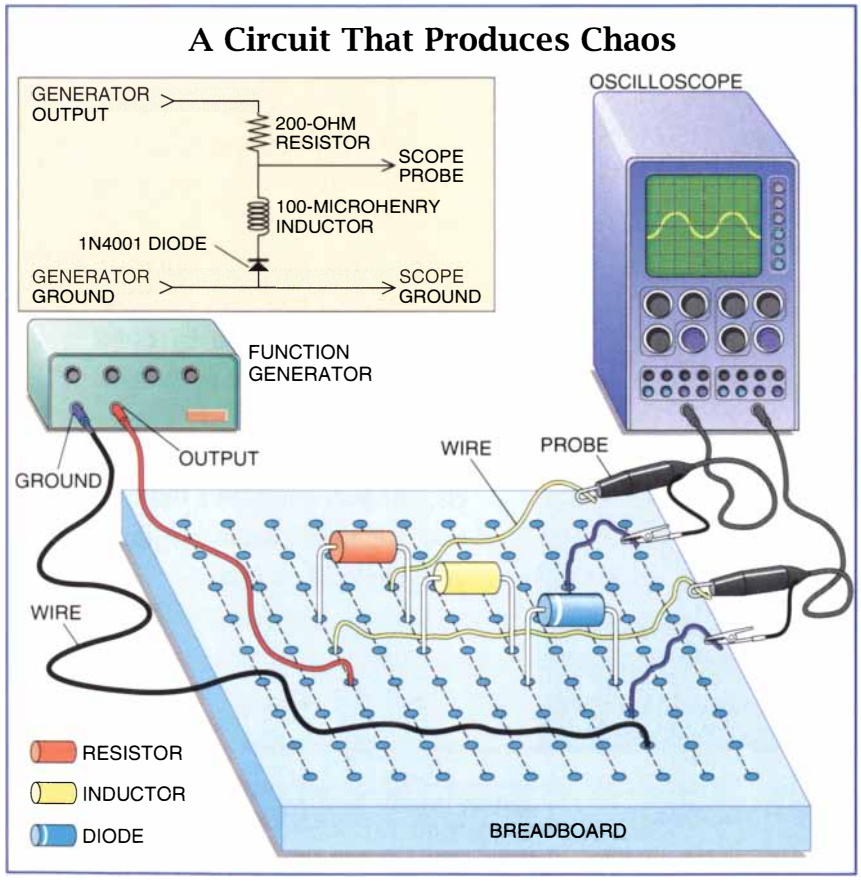
I wanted to have a scope of my own so that I could perform experiments at home, but I could not afford to pay the $1,000 for a new one. Hoping to buy a used scope, I posted a notice on a bulletin board at Argonne National Laboratory. A week later I was contacted by someone who repairs fire alarms and happened to have an oscilloscope for sale. He invited me to his workshop to take a look. The room was filled with electronic parts: dismantled computers, old antennas, disassembled radios, stacks of power supplies. I knew I was in the right place. He sold me a 15-year-old oscilloscope for $100.

Once you have obtained all the equipment, it will not take long to assemble the circuit. The components are connected in series: first the function generator, then the resistor, then the inductor and finally the diode.

You might be aware that the orientation of a diode is an important consideration when building a circuit. A diode has two terminals, known as the cathode and the anode. The cathode terminal is almost always marked by a band on the diode. Ideally, a diode allows current to flow only from cathode to the anode and not the other way.

When you build the chaos circuit for the first time, I recommend that you connect the cathode terminal to the inductor and the anode to ground. But if you do insert the diode the other way, you will find that it makes very little difference.

A Circuit That Produces Chaos



DOUGLAS SMITH is a research assistant at NEC Research Institute, where he is investigating the dynamics of actin and myosin filaments. In the fall he plans to complete a bachelor's degree in physics at the University of Chicago.

To monitor the output of the circuit, clip an oscilloscope probe between the resistor and the inductor. If your scope has a second probe, use it to measure the input. Check all connections and make sure that all components are firmly seated in the breadboard.

You are now ready to explore chaos. Set the function generator so that it produces sine waves whose frequency is about two million cycles per second (hertz) and whose amplitude varies from 0.1 to −0.1 volt. The output signal should have a lower amplitude than the input but the same frequency. Slowly increase the amplitude of the input signal. At a certain amplitude between one and two volts, the circuit will suddenly produce an output signal with peaks of two different heights. The signal actually consists of two components, each having a different frequency. The point at which new components are introduced is known as a bifurcation.

As you continue to increase the amplitude by small discrete amounts, the signal bifurcates again and again. If you record the amplitude at which each bifurcation occurs, you will notice that change in amplitude between bifurcations decreases geometrically. At a certain amplitude, the system will have bifurcated an infinite number of times, thereby achieving chaos. The signal is not random but a complicated mixture of components.

By increasing the amplitude beyond the onset of chaos, you should be able to produce an output signal with three or even five frequency components. This effect is typical of chaotic systems.

If your circuit is not generating chaos, tune the function generator to a different frequency and try again. If you still don't see it and if you are sure everything else is working properly, you should try a different kind of diode. I have learned that the diodes that work best are ones that have a high capacitance. You can find out the capacitance of the diode by calling the manufacturer or by obtaining a copy of the diode's "data sheet."

You might also find it difficult to experiment at frequencies of a few million hertz because of the limitations of your function generator or oscilloscope. By changing the basic components, you can work at lower frequencies. If you use a 1N2858 diode, a resistor of 25 ohms and an inductor of 0.1 henry, you can drive the circuit into chaos around 75,000 hertz. You may be forced to order the 0.1-henry inductor from a catalogue since they are rarely used by hobbyists.

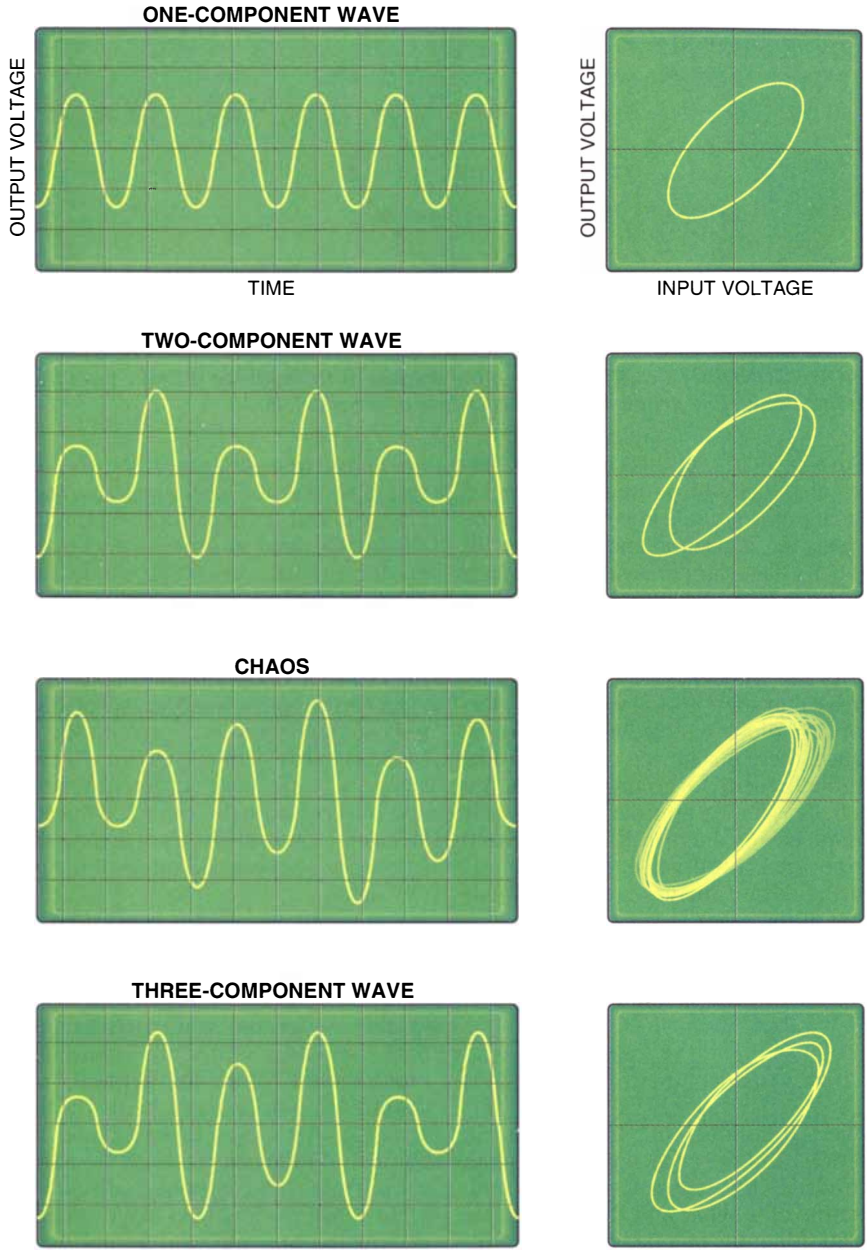
The source of the chaotic behavior in the circuit is the diode. Ideally, a diode would conduct current in only one direction. Current will flow through the diode only if the voltage at the cathode is lower than that at the anode. In the circuit the anode is connected to ground (zero volts); therefore, if the cathode has a negative voltage with respect to ground, the diode will conduct.

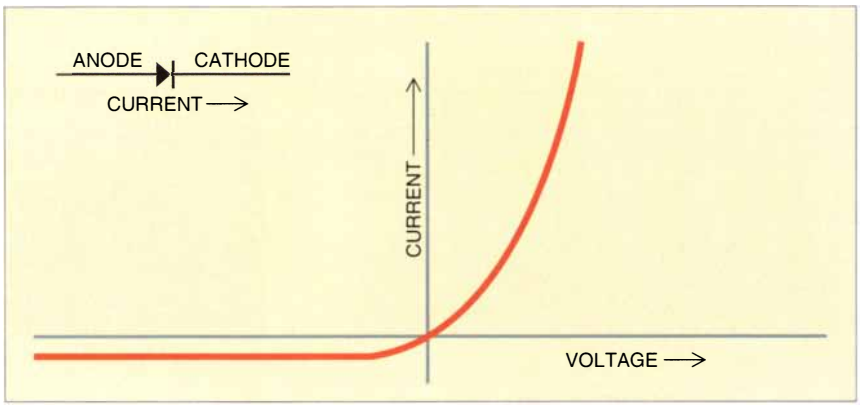
Real diodes differ from the ideal. If the voltage at the cathode is positive, the diode acts somewhat like a capacitor, that is, the voltage across the capacitor is proportional to the rate of change of the current. It will continue to act in this manner until the voltage at the cathode reaches about −0.5 volt. Then it will freely conduct current, but it will still resist the flow somewhat, maintaining the voltage at about −0.5 volt. If the voltage at the cathode then drops below zero volts, it does not shut off immediately. For a short time, the diode allows the current to flow and then acts like a capacitor again.

Circuits that require diodes are usually designed so that the nonideal properties of the diode are suppressed. But our experimental circuit brings out the full character of the diode.

First consider what happens if the input of the circuit is a sine wave whose amplitude varies from 0.1 to −0.1 volt. Under these conditions, the voltage at the cathode does not go below −0.5 volt, and therefore the diode behaves

Response of Chaos Circuit





***DIODE CONDUCTS CURRENT** when the voltage at the cathode is lower than that at the anode. The graph shows the response of a typical diode.*

like a capacitor. In this case, the behavior of the circuit is predictable. When the input is set to a low-frequency sine wave, the capacitor and the inductor will act like a large resistor, preventing current from flowing through them. The amplitude of the input wave will thus equal that of the output wave.

As the frequency of the input is increased to some critical value, the inductor and diode will provide little resistance, thereby allowing current to flow through them to ground. The output voltage will then approach zero. As the frequency is increased or decreased from the critical value, the amplitude of the output increases until it equals that of the input.

The critical frequency depends on the capacitance of the diode and the inductance of the circuit. It equals

$$\frac{1}{2\pi\sqrt{(\text{inductance} \times \text{capacitance})}}$$

where the inductance is measured in henries and the capacitance is given in farads. If the inductance is 100 millionths of a henry and the capacitance is 50 trillionths of a farad, then the critical frequency equals about 2.3 million hertz.

Now if the amplitude varies from +2 to −2 volts, the diode may be behaving in one of two ways. It may allow current through. Or it may behave like a capacitor. Which behavior it chooses now depends on the voltage at its cathode and how long that voltage has been applied. In turn, the applied voltage at the cathode is related to how the inductor reacts to the input voltage. Then again, how the inductor reacts also depends on whether the diode is charging up like a capacitor or is holding at −0.5 volt.

In simple terms, the inductor is receiving one set of instructions from the input signal and another set from the diode. If the sequence and timing of the instructions are just right, the circuit may continue to produce a periodic signal. But if the natural rhythm of the instructions is broken, the circuit produces chaos. During the past decade, Roger W. Rollins and Earle R. Hunt of Ohio University have been working on a computer simulation that describes the behavior of the circuit exactly.

After you get a good grasp of how the components work, I encourage you to experiment with the circuit. For instance, you can insert different diodes and observe how the chaotic behavior changes. Or you might try changing the frequency, shape or DC offset of the input signal.

You might also find it interesting to visualize the output signal in a different way. You can plot the input signal versus the output by using the oscilloscope in the *x*-*y* mode. (One oscilloscope probe should monitor the input; the other should record the output.) You should see one or more loops on the screen of the scope. In this mode the number of loops increases as the number of frequency components rises.

For those readers who like dramatic demonstrations and who do not have an oscilloscope at hand, I recommend a different sort of experiment. It is possible to listen to chaos by hooking the circuit up to your stereo system. Before you do so, you should think about whether the input to your receiver can handle the output of the circuit. You don't want to blast too much current or voltage into the receiver.

You should first confirm that your function generator is producing the voltages that you desire. If the input voltage to the circuit is five volts and the resistor is 200 ohms, the maximum current should be 25 milliamps. (The current equals voltage divided by resistance.) By consulting the owner's manual to your stereo, you should be able to discover whether the input channels can handle five volts and 25 milliamps. If not, you can increase the resistance of the circuit.

To connect the circuit to the stereo, use a patch cord. If you cut off an end of the cord and strip it, you will see a wire and either a metallic shielding or a second wire. Connect the first wire to the output of the circuit. Then attach a wire from the shielding to the ground of the circuit, or connect the second wire to ground. Make sure the stereo is turned off and then insert the plug into an input channel of the stereo.

First, set the function generator to sine waves of one volt at about 1,000 hertz. Turn the volume to a low setting and then switch on the stereo. You should hear a tone about two octaves above middle C. As you increase the frequency, the tone should rise in pitch. But when you reach about 20,000 hertz, the tone will be out of your hearing range. Next turn the frequency up to two million hertz. You should not hear a tone.

To drive the circuit into chaos, increase the amplitude of the input slowly. Do not turn up the voltage beyond five volts unless your stereo can handle more than 25 milliamps. As the amplitude increases, the circuit will produce a signal with two frequency components, then four, then eight and so on. You should still hear no sound. When the amplitude increases beyond the onset of chaos, however, the stereo should hiss loudly. When the circuit behaves chaotically, it generates a wide range of frequency components, including some that you can hear.

You can now explore chaos with your ears. In general, the greater the amplitude of the input signal, the more frequency components you will hear. At certain amplitudes, however, the circuit will generate a signal with only three or five frequency components, and the noise will stop.

I do not think the chaotic circuit has much of a future as a musical instrument. But who knows? Composers have written symphonies using electronic synthesizers. Why not a concerto for chaotic circuit in C major?

FURTHER READING

PERIOD DOUBLING AND CHAOTIC BEHAVIOR IN A DRIVEN ANHARMONIC OSCILLATOR. Paul A. Linsay in *Physical Review Letters,* Vol. 47, No. 19, pages 1349–1352; November 9, 1981.

CHAOS: MAKING A NEW SCIENCE. James Gleick. Viking Penguin, 1987.

THE ART OF ELECTRONICS. Paul Horowitz and Winfield Hill. Cambridge University Press, 1989.

BOOK REVIEWS by Philip Morrison

An Eye on the Sky

THE OBSERVER'S SKY ATLAS, WITH 50 STAR CHARTS COVERING THE ENTIRE SKY, by Erich Karkoschka. Springer-Verlag, 1990 (paperbound, $14.95). **HOW THE SHAMAN STOLE THE MOON: IN SEARCH OF ANCIENT PROPHET-SCIENTISTS FROM STONEHENGE TO THE GRAND CANYON,** by William H. Calvin. Bantam Books, 1991 ($21.50).

You may streak along the interstates with no more aid than a small map of the whole country, but if you want to visit Meteor Crater or Monticello you will long for maps state by state. To find, say, the Morgan Library requires an inset map of Manhattan. This attractive compact atlas by a very knowing observer from Stuttgart has organized the sky at two scales like the highway maps: the entire sphere appears in some 50 small takes, constellation by constellation, augmented by inset maps of starry cities. Wider maps have dwindled to four index charts.

Cygnus, the Swan, for instance, is highlighted on two successive spreads at a scale to suit viewers by unaided eye. Star names and deep-sky objects are labeled for each half bird, although all naked-eye stars are plotted in both maps. Inset charts magnified fourfold hide the constellations nearby. Of course, any area hidden under an inset is displayed on some other chart at unaided-eye scale. The insets are rich, pinpointing many more stars, binaries, variables, clusters and nebular objects, down an order of magnitude fainter. Their match is with the star-crowded view given by binoculars or small telescopes. The inset maps are especially well annotated, including surface brightness of extended objects, one valued but unusual help to the observer.

A tenth of the whole sky is chosen for the insets, finder charts that take up half the total area of the atlas. Overall about 900 of the thousands of marked stars are catalogued, including such data as coordinates, distances, magnitudes and spectral types. All the 110 nonstellar objects named by untiring Charles Messier from Paris, now so dear to the amateurs, are also described. Another 141 similar objects from the New General Catalogue continue the lists all the way south. A few celestial showplaces, like Orion and the Large Magellanic Cloud, enjoy special treatment.

Showpiece 3C 273, the brightest of quasars, is carefully pointed out to the fortunate amateur able to gaze into a dark sky through a six- or eight-inch telescope, to seek that "very faint stellar dot" a cool two billion light-years behind the Virgo Cluster of galaxies (also well mapped here).

This original hybrid atlas includes a shrewd text, an overview with some instructive graphs to analyze this very catalogue. Concise tables, notably of rough planetary positions over two decades, complement the charts of the fixed sky. Although it is much too terse a treatment for most beginners, its firsthand approach and compact form commend it to all who star-watch with lenses and to travelers who know their home skies well but want guidance to new latitudes.

William Calvin's brief and lively book on astroarchaeology is, he says, the "neurobiologists' revenge" for astronomer Carl Sagan's best-seller on neurobiology, which still "sets a high standard for would-be interlopers." Calvin writes with grace, wit and insight. He aims to display how scientists work during the creative process itself, between the first spark of interest and the long validations. His title reveals even more: the pursuit of his own reflective archaeoastronomy led him to the plausible conclusion that some skywatching shaman was the first scientist, able to forecast—at first by no means infallibly—events as important as seasonal changes and as startling as eclipses of the sun or the moon.

Calvin's methods do not call much on tradition. He establishes them with drawings but without formulas, in a disarming personal style of intellectual trial and error, often right amidst the evidence at Delicate Arch or deep in the icy Grand Canyon on the day of winter solstice. (There in the canyon the clues added up to an unlikely conclusion; something is amiss, an experience shared by all who try the delightful task of looking at the sky through the eyes of those who looked long before.) "We want something as unequivocal as a suit of armor, but what we typically get ... is a situation about as flexible as a bolt of *stretch* fabric, which fits anything."

Calvin outlines 10 ways to steal the moon, without the arsenal of calculators, atlases, watches or spherical trigonometry. Some ways carry out his sensible idea that any little gain might have been of real value when this art was new. The odd bit of mica would show a reflected solar crescent early on during a partial solar eclipse. The moon high at sunset excludes a lunar eclipse, even when repeated eclipses have alerted the shaman's flock (or her competitors) to the wandering eclipse seasons. More advanced methods involve shadows at sunset that touch the direction of full moonrise or the use of differences between sight-line directions that take advantage of an artificially leveled horizon, such as the author saw on Salisbury Plain.

If you attend to the ideas here, there are surely many more to be worked—you can learn how to steal the moon out of your own skyscape. Calvin writes with a gentle iconoclasm that appeals to all who dislike pride and pedantry. A pleased reviewer suspects the author of underestimating modern skygazers, amateurs and pros alike, among whom are many who manifestly could have stolen moon and sun alike with flair, absent any modern data bases.

The Fragrance of Almonds

FRACTALS: ENDLESSLY REPEATED GEOMETRICAL FIGURES, by Hans Lauwerier. Princeton University Press, 1991 ($49.50; paperbound, $14.95). **AN EYE FOR FRACTALS: A GRAPHIC AND PHOTOGRAPHIC ESSAY,** by Michael McGuire. Addison-Wesley Publishing Company, 1991 ($29.75). **FRACTAL FORMS,** edited by Etienne Guyon and H. Eugene Stanley. Elsevier/North-Holland, 1991 (P.O. Box 103, 1000 AC Amsterdam, the Netherlands) (paperbound, Dfl. 200 per packet of 10 copies).

Books on fractals stream by for expert and beginner. Three first-rate openers are here, bringing a pleasant fragrance of almonds. Lauwerier is a Dutch mathematician with talent in simple exposition. His subtitle is a bit truncated; fractals are indeed figures with an endlessly repeated motif, but the repeats are at ever changing scale. The computerwise can start with the final chapters (almost any personal computer will be adequate; DOS machines with 80,286 chips are fine) and work back for more insight. Others should go with the book's flow.

The first few chapters take a mathematically inclined reader smoothly from a fractal built solely of the letter H, through the ideas of number, past fractals built on the innumerable—nicely treated—to intricate coastlines, delightful dragon curves, realistic trees. Next comes the fundamental analysis of dimensionality. Chance enters with a flourish, to simulate the noisy natural world. The last chapter climbs to fractal peaks, Mounts Poincaré, Julia and Mandelbrot in color. The final action chapter lists about 50 programs for any who can use a compiled BASIC.

Michael McGuire has come along less steep portions of the route. He has made or found 100 and more quite beautiful black-and-white photographs from nature, mostly roots and waterfalls, to which he adds a brief, relevant account of computed fractals. "This book," he says, "is about a way to *see*." In a foreword Professor Mandelbrot himself concurs: fractals for him, too, are not merely a chapter of mathematics but a way to "see the same old world differently." An eye-opening few pages tell about the sense of "scaling self-similarity," evident in Leonardo's old drawings of water and widespread in classical Chinese and Japanese painting. This is a book that will help assuage the fear of mathematics.

The third book records a fine exhibition about fractals that was shown in the Palais de la Découverte in Paris. These are large, attractive, glossy photographs, first made available as a gift from the publishers to their friends. They have agreed to sell the book to the public at a bargain for packets of 10 copies. The text consists of brief captions, plus a page from Mandelbrot that welcomes the eye back to science. Some 50 computer and natural examples fill the colorful, thin brochure; the final one is the famous Lick mosaic map of the galaxies. These three books differ widely in their audiences: choice among them depends on the reader's background and inclination.

Centuries of Science

THE TIMETABLES OF SCIENCE: A CHRONOLOGY OF THE MOST IMPORTANT PEOPLE AND EVENTS IN THE HISTORY OF SCIENCE, by Alexander Hellemans and Bryan Bunch. Simon and Schuster, 1991 (paperbound, $19.95).

Drag a net with 100-year mesh through the 10,000 dated entries of this thick volume. Here is a sample of what you catch over the centuries: In 1892 a new cholera vaccine saved thousands of lives in India, and water filtration controlled a cholera epidemic in Germany. In 1792 the inventor of coal gas first used it to illuminate his home. In 1692 the mathematician Gottfried Leibniz introduced the terms "coordinate" and "ordinate." In 1592 Korean astronomers observed the appearance and subsequent development of a nova in the constellation Cetus. In 1492 Leonardo da Vinci drew his conception of a flying machine. Roger Bacon, the English philosopher-scientist, died in 1292. And in 1092 the emperor Su Sung built a celebrated giant water clock and armillary sphere.

Listed events are categorized under up to 10 headings, from general interest through a gamut of the sciences, on to technology. A lengthy topic index offers some 5,000 headings; about half as many personal names are indexed as well. In early times the listings do not march by annually. The tempo of science is signaled by the gaps, first only decades, then centuries and millennia, and near the beginning bigger still. The grand parade opens with "science before there were scientists," when in 2,400,000 B.C. African hominids made stone tools. It closes in 1988, when one among many entries reports the claim that the missing proof of Fermat's last teasing theorem had after three centuries been found! (Those old stone tools work, but flaws were soon found in the new "proof.")

This book is open to any reader nimble enough to follow a terse text and an intricate tabular layout. There are no images at all, not one diagram or figure. (What an opportunity to work up your own maps, graphs and family trees of ideas out of all this ready lumber.) The two science writers from England and New York whose partnership produced the adroit book are well read in the modern scholarship of China, so that we are spared the dubious innovations of the Yellow Emperor, nor do we read that printing was a European invention. The integrated-circuit chip did not make the chronological listing, but the drama that led to what is arguably the most important technological invention of the 20th century is well described, complete with its players, Robert Noyce, Gordon Moore and Intel.

A hundred varied introductory essays and single-topic boxes deepen our understanding of all these staccato-timed events. Those pieces treat such matters as mathematical notation; Galileo's focus on instrumentation; the nonsensical but prevalent Victorian "scientific" view of women (not, alas, vanished along with its main postulate,

the long-ago exploded idea that brain weight meant intelligence); and the nature of the vacuum, addressed here both as the matter-of-fact vacuum of siphons and air pumps and also as the active "vacuums" of today's microcosmic physics. The big bargain work is not error free, a standard probably unreachable across so wide and varied a landscape, but it is a careful, usable resource for all, for school library and book-loving home.

From Dog-Power to Turbines

A HISTORY OF INDUSTRIAL POWER IN THE UNITED STATES, 1780–1930, Vol. 3: THE TRANSMISSION OF POWER, by Louis C. Hunter and Lynwood Bryant. The MIT Press, 1991 ($50).

An engraving shows a "modern dog-power" of 1877, 30-watt Rover walking along the endless-chain track to drive the farmhouse butter churn (double dog-powers were recommended for corn shelling). New dog-powers were noticed repeatedly in *Scientific American* from 1848 on; they were certainly always marginal. The prolonged interest in such faintly risible contrivances is deeply diagnostic. Waterpower demanded a nearby stream or a whole river's worth of canalization. The smoky steam engines of urban industry worked cranes and forges well, but at a power of five or 10 kilowatts and up.

In 1860 almost half the value of all manufactured goods still came from small establishments employing fewer than 10 hands, power under one kilowatt. Almost all the mechanical power they used came from human muscles applied to the hand cranks, wheels and levers that drove clever mechanisms in wide variety, turning, grinding, pressing, cutting. No other handy source of fractional horsepower, up to a few hundred watts, was there to help "a couple of craftsmen" at the bench. "Standing out among all... machinery like a monadnock above the plain was the sewing machine," driven then by foot treadle. Over one million of this "first consumer appliance" were sold during the decade of the 1870s alone; their main prime mover was womanpower, well under 100 watts per machine.

Once again the *Scientific American* spoke. Long an advocate of workshop steam engines, it conceded in 1875 that there were on the market none cheap and practical enough for the family-size enterprise. There were "power buildings" in some cities, where you could rent both work space and belt-

delivered horsepower, just as thousands of spindles were fed from a central engine or waterwheel in the big mills of the big firms. A photograph of Thomas Edison's machine shop in 1878 clarifies the issue: whirring pulleys overhead and belts and ropes that slither quickly past give the shop the look of a teeming canopy forest. Such millwork was always surprisingly lossy, expensive, dripping with oil, dangerous. Steam could not serve well at either end of the power spectrum, neither the few biggest establishments that spread over many acres nor the many more that occupied a single workroom.

Other prime movers appeared. The first real winner was the Silent Otto of 1876; its single horizontal cylinder burned gas made from coal. We all knew what became of four-stroke Otto, once the inventors learned to wean it from its pipeline, to live on liquid hydrocarbons and soon to roll free. The Otto engine transports the 20th century under the open sky, and its tiniest hand-held progeny pop and snarl now in every woodlot. But it was subtle, always stubbornly hard to start, slow to develop; by 1890 gas and oil supplied only a thousandth of American stationary manufacturing power. In America the windmill also developed late, finally to take its place by the million as the very symbol of the Great Plains, the rancher's steel tower and windwheel that mostly pumped water to storage, with about one unsteady horsepower.

The idea of power as a commodity for sale was clearly voiced before the technology that enabled it. Forerunners of electric power transmission found important but limited use, employing transmission media lighter and faster than shafts and belts. As early as 1802 Joseph Bramah planned the use of hydraulic lines at high pressure to supply "all the cranage of the London wet dock." Centralized hydraulics did not reach this side of the Atlantic, although half a dozen large ports in Britain depended on just such power into the 1920s. Low-pressure public water supplies offer all city folk a potential for modest power, but the idea caught on only as the hydraulic elevator. Compressed-air power transmission to the rock drill became a boon to miners underground (although it was a direct steam hammer that stout John Henry challenged in some open-air quarry). Central-station urban power delivery by compressed air began in Paris in 1881 and remained successful there even beyond the turn of the century.

It was in 1882 that Edison opened his Pearl Street power station, six 200-horsepower, 110-volt, direct-current dynamos driven by reciprocating steam engines. What he offered was subdivided electric power, not mechanical power for the craftsman, but subdivided light from vacuum incandescent lamps, safer and more convenient than the arcs or the gas flame. Within two years he had lighted 10,000 Edison lamps across the Manhattan financial district and had modest profits to show for it. Public electric power distribution had begun for lighting alone.

By the 1890s, electric power had found its uses beyond lighting. The pioneer streetcar system of Richmond, Va. (the car we see in the book looks very like the Toonerville Trolley), was a success in 1888, and street electric railways then multiplied almost as rapidly as had electric lights, "a quick and complete revolution in urban transportation." By 1893, 55 of the 58 largest American cities had electric cars. In that same year the crowds at the World's Columbian Exposition in Chicago enjoyed moving sidewalks, electric launches, an Intramural Railway, and "myriads of electric lights…shed their opalescent rays upon the sapphire waters of the lagoons," to cite a contemporary stylist. By 1900, the great Niagara Falls hydroplant and the big coal-burning plant at Deptford Station south of London were on line, sending overland at high voltage with alternating current the power they generated from turbines, all the basic elements of the modern system.

But the wheels of American industry did not yet spin by electric power. Consumers of electric light began to use "iceberg" electric fans, the first electrical appliances, during the hot summers of the 1890s. Direct industrial machines driven by belt and shaft from steam engines on the site gave way only slowly. It was not so much the utilities as it was consulting engineers and electrical manufacturers who pushed the change. At first, industries converted from belt-spread steam power to electric power generated in-house. Not until 1919 did the power delivered in U.S. manufacturing by electric motors, mostly of the AC-induction type, exceed that of all other motive sources.

The modern net of giant utilities serving as distributors of power was in place by the time of the New Deal. Most industrial power had become cheap purchased kilowatts. The net connects a myriad of users to a less numerous but still diverse set of economically coordinated power sources; a user hardly knows whether his next kilowatt-hour comes from steam, falling water or hot jet gases. The abstract nexus of energy is like the abstraction of money: its odor is noticed only locally. Steady incremental growth in technological scale and efficiency of generation was behind the change. No less necessary was the formation of bigger utility firms to manage all the power sources in sight, a load-sharing, peak-reducing economics of profitable centralization on large scale, pioneered by the notorious Samuel Insull of Chicago.

Will photovoltaics decentralize us? Without economical local energy stores, that seems unlikely. The great grid will still dominate, although its capacity will surely plateau. Indeed, the turnover has begun, not yet by competition from sunshine but driven by the cost of energy and of its all too mobile wastes.

It is five years since this column noted the first two big volumes of Hunter's study of stationary power sources, the one on waterpower, the other on steam. The devoted author had not lived to complete the third volume he planned. "It is to be hoped that his admirable work will find its continuator." That hope was not vain. This final volume on power transmission, a little less ample, was happily completed from Hunter's draft materials by Lynwood Bryant of M.I.T., himself a senior historian who writes wisely in Hunter's own way, full of empathy, close to the technology, yet always attentive to much more.

ESSAY: AN INNER-CITY EDUCATION by Michael C. Lach

I left Carleton College in the spring of 1990 with a B.A. in physics, an acceptance letter to graduate school and little desire to go. I had a strong science background; my father is a physicist, and I had completed internships at Fermilab and Brookhaven. But I was not comfortable with being a scientist. Not just yet. Other ideas were running in my head.

In my senior year, I had heard of a program called Teach for America that was looking for talented college graduates to send to areas with severe shortages of teachers. I deferred graduate school and through Teach for America was assigned to teach physical science and biology in an inner-city high school in New Orleans.

I thought I was aware of the difficulties an inner-city school faces: education is a prevalent theme on the evening news. I had heard George Bush flaunting his "education president" title and had seen the "stay in school" advertisements on television. The jingles pretend to address the schools' financial instability, decaying infrastructure, declining science and mathematics test scores and lack of teacher motivation. But these slogans have done little to change education in America. Making matters in the classroom worse, gang violence has spilled off the streets into schools, teenage pregnancy rates continue to climb despite improved awareness and the risk of AIDS, and the socioeconomic disparity of our population increases.

By some accounts, I am supposed to be the savior. I am bright, motivated and ambitious; I love science and children. With a few more years' experience, they say, I'll be the kind of master teacher who will solve the problems of inner-city youths by improving the nation's schools. After spending a year in the blackboard jungle, I realize that I and others like me are not the solution. My first year was arduous, exhausting and disillusioning. The progress my class made was not sufficient. To improve science education, we need more than committed and energetic teachers.

My students' environment was the first obstacle I encountered. Poverty dominated their lives: almost all were on welfare, lived in public housing projects and came from single-parent homes. All were African American, with little pride in or knowledge about their heritage. Most witnessed violence and drug use in their neighborhoods daily. In each of my four ninth-grade classes, I taught at least one mother. These problems powerfully affected the children; they came to school angry, upset and scared, physical and emotional anguish carved into their persons.

In many instances, the students I worked with had already given up. On the third day of school, I was told, "It doesn't matter—if we was smart we'd be at McMain" (the nearby magnet school, which has entrance requirements). Almost all had never been out of the Louisiana-Mississippi region, and many had never ventured out of the New Orleans ghettos. They knew that a more desirable life existed for some people, like sports stars and drug kingpins, but by ninth grade most had resigned themselves to poverty.

The whole school reflects the defeatist attitude of its children. The walls are covered with chipping paint, graffiti and dark smears. Windows have narrow grills or plywood coverings. The staff, too, are worn down. I was very impressed with the caliber of my fellow teachers, but they were all overworked. Classes were large, and discipline was an ongoing problem; repairs were seldom made.

The materials provided were minimal as well. I had to supply almost all the equipment for my laboratory experiments—scissors, ramps, pulleys, balls, Slinkies, specimens—as well as regular office supplies—paper for copies, chalk, staples. By a conservative estimate, I spent $800 of my salary on materials. Safety equipment was nonexistent.

Also holding back my students' progress was their educational history. Most were one or two grade levels below the national average. I had to teach decimals before starting the metric system. I taught long division in order to teach density. Few students could write a paragraph or read a page of a textbook without difficulty.

Trying to cram several years of science into one is exhausting. I had expected the long hours. It was unexpectedly demoralizing, however, to find that my paycheck specified a 30-hour week—not even a full-time job. The time I spent each week was closer to 60 hours: mornings before school setting up laboratory experiments; late afternoons for detentions and make-up examinations; weekends for grading papers, making lesson plans and preparing bulletin boards. There are no breaks when teaching. I could not leave my class for a cup of coffee or bathroom break until my 27-minute lunch period.

The demoralizing environment, decrepit building and minimal materials make the high school experience for these children an uphill battle. Merely graduating from such a high school is difficult, much less becoming a high-caliber science or engineering student. Schools with a student population from a higher socioeconomic level would not tolerate the obstacles I encountered daily. Improvements need to be made efficiently and made soon, or the divisions among people in this country will only become more extreme.

Of course, there are things that concerned citizens can do to help. Get involved with a school, especially one in a poor area. Volunteer to give a presentation or just to spend time with the children. My students were thrilled to talk to an insurance salesman who came to give a career exploration lecture. They not only were genuinely interested in the opportunities he described but also were amazed that such a person would donate an afternoon to them.

These measures can help, but they are not enough. For teaching to be effective, the entire environment of the inner city needs to be changed. Teaching someone the difference between velocity and acceleration is irrelevant if that person is hungry and scared. Programs that educate parents in child-rearing, organize low-income groups into cooperative units, fight drug trafficking and help to clean up the ghettos physically will enhance the life in the community.

The small alterations and "new" proposals currently filling the newspapers are certainly not strong enough to transform a decaying and demoralized school structure that has been disintegrating for decades. Inner-city schools need so much more, and the children deserve so much more, than our society is willing to give. Like many other men and women, I entered the teaching profession eager to instigate change and found many institutionalized obstacles in my way. It should not be so difficult to make a difference.

MICHAEL C. LACH teaches physics and biology at Alcee Fortier High School in New Orleans.

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