SCIENTIFIC AMERICAN

MAY 1992
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Predicting the spread of the AIDS pandemic.

Binary optics: lenses for the computer age.

Seeking DNA in the dry bones of Neanderthals.

***Luminous nebula** forms when a dying star spews its matter into space. Our sun will meet the same fate.*

A Car Of Such Diplomacy Even
And Transmission Have An Ongo

The Engine ing Dialogue.

Allow us to interpret.

In the split second before every shift, the automatic transmission, via the Electronic Control Unit (pictured here in the top right corner), sends a signal to the engine telling it to delay ignition timing. This momentarily reduces engine torque, enabling the transmission to shift smoothly through each of the four gears.

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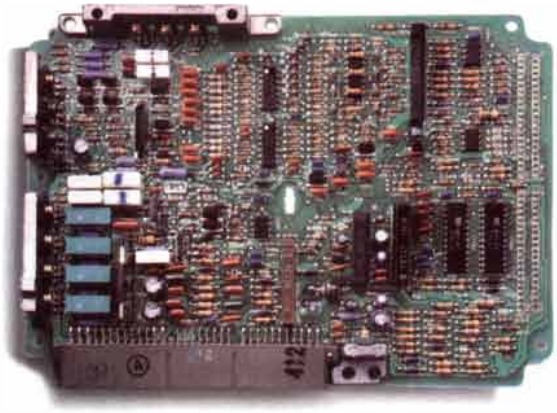
In layman's terms, this simply means that every shift is executed with impeccable manners to minimize any lurching or slips. All you feel is the silken transition from sitting at a standstill to cruising comfortably at freeway speeds. And vice versa.



For life in the fast lane (pardon the cliché), just switch the transmission to power mode. The all-aluminum, 32-valve V8 is then allowed to wind out the revs, taking full advantage of the LS400's

wide powerband. Perfect for passing semi-trucks, city buses and, lest we forget, those little red sports cars.

At this point you might want to ask, while all this emphasis on transmissions conversing with engines is fine for improving performance, what about efficiency? We're glad you asked. Because with 4.0 liters and all, the LS 400 still enjoys respectable gas mileage.*

So now that we've brought you completely up to speed on all the benefits of a car that talks with itself, you're probably more prepared than ever to talk with your Lexus dealer. Where, we hope, further negotiations will transpire.

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The Relentless Pursuit Of Perfection.

*nformation, call 800-872-5398 (800-USA-LEXUS). *1992 EPA estimated mileage 18/23 City/Highway. See your Lexus dealer for details.*

Only in God's country could you

While Canada's Pacific coast is still undiscovered by many of this world, our native peoples have been entertaining visitors for centuries.

The Raven beat his wings, in perfect rhythm, until he had formed our world out of nothing at all. And marked the beginning of life as we know it.

The most revered of spirits and master of ceremonies, the Raven embodies what this land is today. Magic.

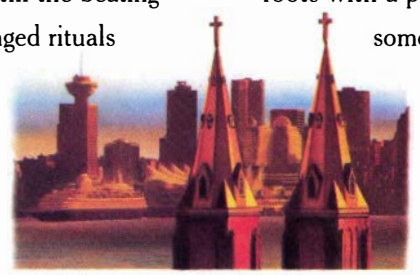
For here the supernatural abides in all that is living.

The mountaintops and salmon streams. The mighty rainforests. The towering cedars, clover meadows and subtle scent of blossoms. The deer, the bear, the seal—the creatures that are the Animal People.

And our link to another realm.

Taking wing with what seemed to be a small berry in his beak, Raven ascended into the thick black sky. With but a quick flick of his head he cast out the sun, unveiling all he had created in a wave of daylight.

Surely, it's for these very good reasons so many of our native peoples, like the Tsimshian, the Tlingit, the Haida, all chose to settle here. And still the beating rhythms of unchanged rituals pay tribute to everything that made it a reality.



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Or in museums and galleries thousands of years in the making.

Vancouver, Canada's third largest urban centre, stakes its roots with a park the size of some cities. Architectural designs—like 'Canada Place'—echo its mountainous backdrop. While our many cultures add their own variations on the performing arts.

And thank heaven for the

meet such interesting souls.

ocean. Yes, the Whale, the Sea Otter and the like still play. But in harmony with cruise ships, ferries, sailboats, seaplanes—and one floating symphony.

On Canada's west coast. Because, when life itself is inspiration, you never know whom you might meet.

And from high overhead, the Raven smiles.

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Canada

The World Next Door

SCIENTIFIC AMERICAN

May 1992 Volume 266 Number 5

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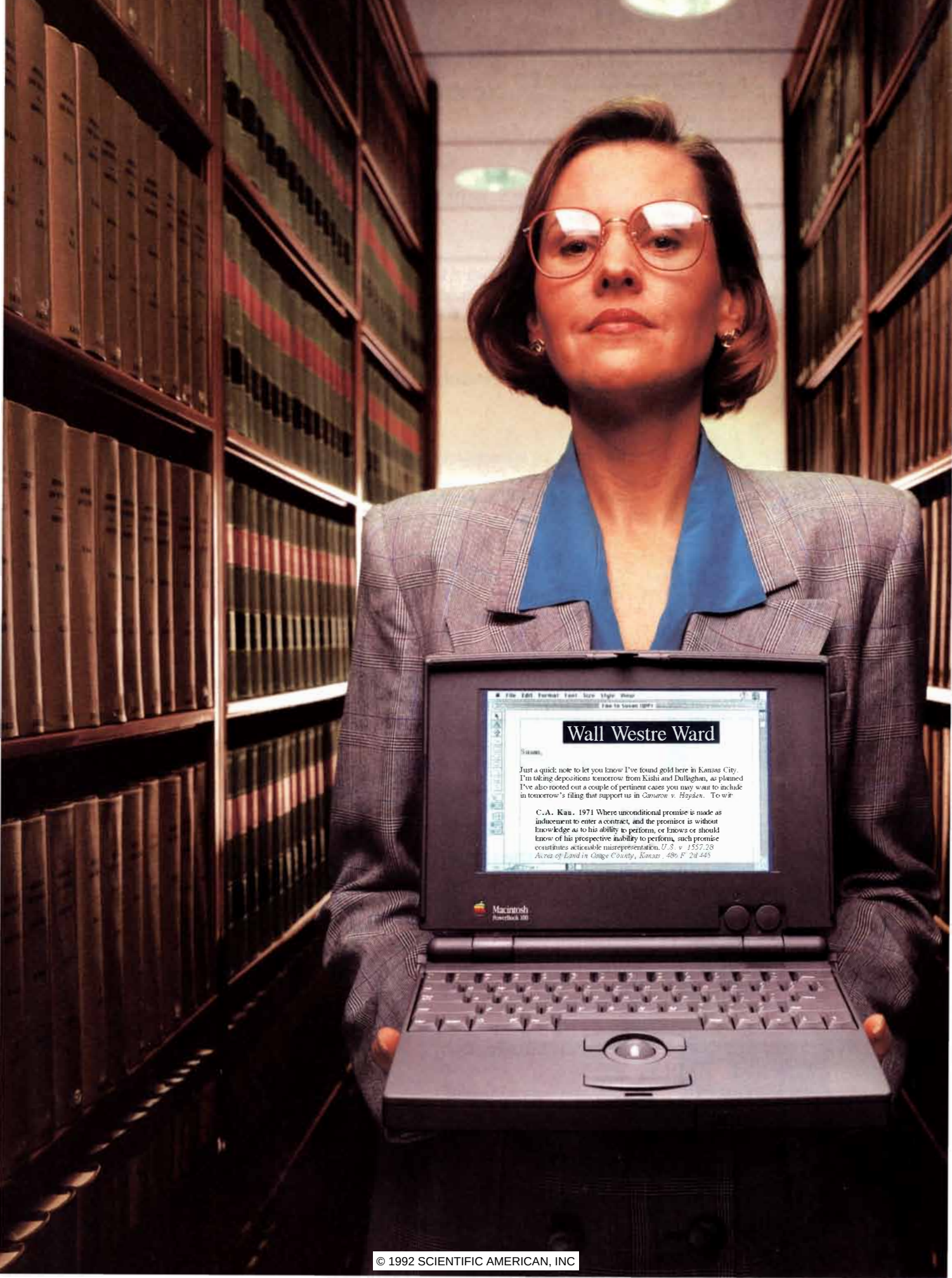
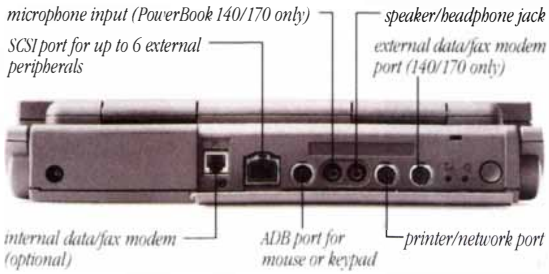
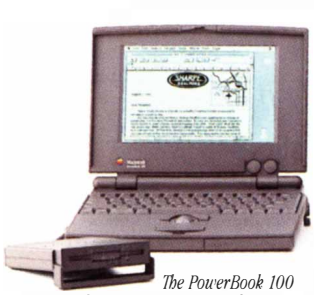
DEPARTMENTS



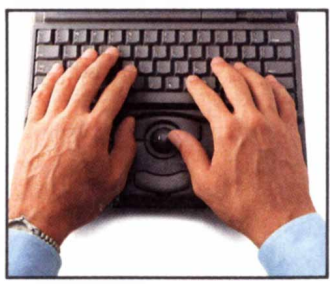




The PowerBook 100 outperforms comparably configured 286 PCs running Windows 3.0.**

The PowerBook 140 outperforms co rably configured 16MHz and 20M 386sx PCs running Windows 3.0.**

The AppleTalk® Remote Access software (included) gives you access to your Macintosh personal computer via phone line – so you can use all your files or e-mail, or an entire AppleTalk network, from wherever you are.



A trackball and palm rests make the PowerBook extraordinarily comfortable for both left- and right-handed people to use.

PowerBook offers a new level of compatibility – its built-in Apple® SuperDrive™ disk drive reads from and writes to Macintosh and MS-DOS formatted disks. Add SoftPC and you can run MS-DOS programs, too. (You can even run MS-DOS and Macintosh programs at the same time.)

PowerBook	Weight	Memory	Hard Disk	SuperDrive	Processor	Internal Modem
100	5.1 lb.	2/4MB	20/40MB	Optional ext.	16 MHz 68000	Optional
140	6.8 lb.	2/4MB	40/80MB	Internal	16 MHz 68030	Optional
170	6.8 lb.	4MB	40/80MB	Internal	25 MHz 68030/ 68882 coprocessor	Optional

All PowerBook models expandable to 8MB RAM.

For the name of your nearest authorized Apple reseller, call 800-446-3000, ext. 700. *To run MS-DOS, all you need is a program like SoftPC and an Apple Si 1991 independent research study conducted by Ingram Laboratories that tested a variety of personal computers running applications available for both the registered trademarks, and PowerBook and SuperDrive are trademarks of Apple Computer, Inc. MS-DOS is a registered trademark and Windows is a tradem

THE COVER PAINTING depicts an idealized version of the Helix Nebula, a bright planetary nebula located 500 light-years from the earth. The nebula consists of an expanding globe of gas, now five light-years across, that formed when a dying star expelled its outer layers (see "Planetary Nebulae," by Noam Soker, page 78). Ultraviolet radiation from the hot stellar remnant at the center causes the gas to glow. All intermediate mass stars, including the sun, produce planetary nebulae before settling into their final phase as collapsed, white dwarf stars.

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Creating borders in Word for Windows was easy for test participants—they simply chose the easy-to-locate "Border" command.

Exotic Excursions
23 Cajun Court
New Orleans, LA 36857

May 15, 1992

Steve Sullivan
8762 W. 180th Pl.
San Diego, CA 98034

Dear Steve:

During the past two years **Exotic Excursions** has seen a record 200% growth in revenues. This success has been exciting, but we now must adjust for our very fast growth. The size of our office impedes proper customer service and is inadequate for the increased level of store traffic.

Creating a bulleted list was two steps in Word for Windows and 12 steps in WordPerfect for Windows.

- I propose that we open another **Exotic Excursions** office, since our phenomenal growth of the past three years is likely to continue.
- ***Thousands of potential clients will attend the grand opening of the new Exotic Excursions office.***

Bold or italics? It was easy with on click of the mouse.

My staff are currently inspecting some potential locations in the Bay Court Plaza. Rental agents have told us that almost 10,000 people pass through this retail space weekly on their way to offices, restaurants, and shops. The table below shows cost projections for three different space configurations.

Word for Windows has an on-screen "Tables" function that lets you add rows almost instantly.

Location	Floor	Meeting	Bath	Street	Cost/Sq.
Court A	4500	N	Y	Main	$2100
Court B	2100	N	N	Main	$590
Court C	3400	Y	Y	52nd	$1000

I recommend that we lease the Court C location. This
It is substantially

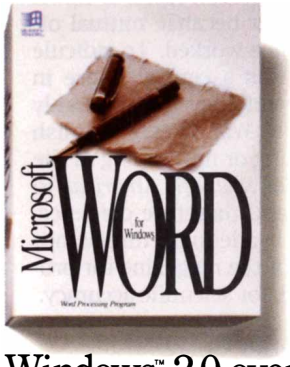
Exotic Excursions
23 Cajun Court
New Orleans, LA 36857

Steve Sullivan
8762 W. 180th Pl.
San Diego, CA 90834

Printing envelopes? Easy. We mean REAL easy. There's an envelope command right on the scree that addresses and prints automatically.

When given this simple letter to revise, WordPerfect for DOS users were impressed at how easy it was to perform everyday word processing tasks using Microsoft Word for Windows 2.0.

No wonder WordPerfect users prefer Word for Windows. It has easy written all over it.



In a recent test conducted by the National Software Testing Labs (NSTL), nearly eight out of 10 WordPerfect® for DOS users preferred Microsoft® Word for Windows™ 2.0 over WordPerfect for Windows. The reasons were plenty.

They were amazed at how Word for Windows put them one step away from accomplishing everyday word processing tasks with, in many cases, one simple click of the mouse. Which may have surprised them. But it didn't surprise us. After all, we designed Word for Windows around them.

Every week during the development of Word for Windows, we invited WordPerfect users to bring in their letters, memos, or whatever business documents they use in their own jobs, and try them out using Word for Windows. Our Product Development people at Microsoft called these sessions "usability studies." Which is just a fancy, shorter way of saying "what-do-people-use-a-word-processor-for-and-how-can-we-make-it-easier-for-them-to-use-it."

These studies not only helped us to design features that make everyday tasks easier, but helped us to make the more advanced word processing features like grammar checking, drawing and charting, easier to use as well.

See for yourself why nearly eight out of 10 WordPerfect users preferred Word for Windows, and take advantage of our special $129 offer,* by calling (800) 323-3577, Dept. Y80. If, for any reason, you're not completely satisfied with Word for Windows 2.0, we'll gladly return your purchase in full.** If you'd like, we'll also send you the files you need to test Word yourself. Then you, too, can have the last word on ease.

Microsoft®

*Offer good for current licensees of WordPerfect, MultiMate,® WordStar,® MS® Word for MS-DOS® and DisplayWrite.® Please allow 2-4 weeks for delivery upon receipt of order by Microsoft. Offer expires 6/30/92. Limit one per customer. Reseller prices may vary. Call for system requirements. **If you're not satisfied with Word for any reason, return the product to Microsoft within 90 days with proof of purchase for a full refund. Offer good only in the 50 United States. To receive only the NSTL test results: In the United States, call (800) 323-3577, Dept. Y80. For information only: In Canada, call (800) 563-9048; outside the U.S. and Canada, call (206) 936-8661.*

LETTERS TO THE EDITORS

Ancient Horsemen

I was surprised to read in "The Origin of Horseback Riding," by David Anthony, Dimitri Y. Telegin and Dorcas Brown [SCIENTIFIC AMERICAN, December 1991], the statement that horseback riding began 6,000 years ago and that this date was much earlier than had previously been thought. At no point do they mention the engravings of horses' heads wearing bridles that appear on bone artifacts from the Upper Paleolithic period of 20,000 years ago. Chisel marks on horse teeth that suggest the use of a bridle and bit or some other restraining device have also been found from that time.

DAVID SHANDER
Denver, Colo.

Anthony replies:

The horses of the Paleolithic lived in an intensely cold climate and were much shaggier than most of today's horses. First, if you examine a Przewalski horse in its winter coat, you will see lines of tufted hair along the cheek and around the nose, exactly where the lines of the "bridle" are depicted on the Paleolithic engravings. Second, it is possible that Paleolithic hunters did trap and restrain mares in heat for use as hunting lures. Neither interpretation of the engravings (which are closer to 15,000 years old) implies riding.

The wear on the incisor teeth of a few Paleolithic horses has been interpreted as evidence of crib-biting (gnawing on a stall), not riding. No evidence has been established to distinguish such wear from other types of natural gnawing or tooth damage; it remains a controversial interpretation.

An Illusion of Balance

"Plant Life in a CO_2-Rich World," by Fakhri A. Bazzaz and Eric D. Fajer [SCIENTIFIC AMERICAN, January], brings to mind the limitations of the unwarranted comfort we take in the belief that nature will seek out a new balance when disturbed. The pervasive thought is that the earth has safety valves that will allow it to survive catastrophe.

Although we may have an abundance of some forms of plant life consuming carbon dioxide as if it were junk food—at the expense of other nutrients—will a CO_2-rich world be suitable for human survival? Will it provide an adequate food supply? We have been asking too many simplistic questions about rising CO_2 levels and consequently formulating only simplistic answers.

GREGORY T. SARAFIN
Mastic, N.Y.

Minding the Teacher

Apparently, the program Teach for America intends to save education by providing "bright, motivated and ambitious" fresh college graduates for the pool of practicing educators. Please be advised that certified teachers all started out as college graduates of some variety. Michael C. Lach's essay [SCIENTIFIC AMERICAN, January] demonstrates poignantly that what bureaucrats consider the "teacher problem" is just a smoke screen. The teacher is simply delivering the policies, practices and curricula generated by administrators and politicians who have no notion of what is relevant to the modern classroom. We need to stop wasting the valuable education and experience of our teachers and once again listen to what they may have to say.

JAMES T. GARSIK
North Palm Beach, Fla.

The real enemy of tax-supported education is the taxpayer, seemingly happy to let politicians line their pockets while neglecting to provide adequate funds for schools. When I was last teaching, my son's baby-sitter earned more per child in her home than I did in my elementary classroom.

D. R. LANE
Vallejo, Calif.

Ig Nobel Fallout

I read with some amusement your account of the Ig Nobel Prize Ceremony ["Science and the Citizen," SCIENTIFIC AMERICAN, December 1991]. I fail to understand, though, why such notable figures as Immanuel Velikovsky, the author of *Worlds in Collision,* and Trofim Denisovich Lysenko were omitted. The first tried to reconcile astronomy with fundamentalism. The second made an equally heroic effort to reconcile evolution with Soviet philosophy.

ARTHUR L. SENTZ
Dallas, Tex.

I was amused by *Scientific American*'s report on the Ig Nobel Prizes. Nevertheless, I was profoundly disturbed by the lampooning of Edward Teller, apparently because he fathered the hydrogen bomb (not the atom bomb, as John Rennie reported) and because he has promoted the development of defensive military systems. Most of us who lived through the cold war realize it never became a hot war because mutual offensive deterrence worked. To ridicule the man who was a central figure in creating the technology that probably prevented World War III is a childish misunderstanding or misreading of the past 45 years. For *Scientific American* to give publicity, and therefore credence, to such wrong-headedness diminishes the reputation of the magazine for probity and, indeed, for scientific accuracy.

ALVIN M. WEINBERG
Oak Ridge Associated Universities

Rennie replies:

Our reputation would suffer had we chosen *not* to do a story because it was controversial. As for ridicule, if Teller can survive *Dr. Strangelove,* he can survive anything.

ERRATA

The profile of Francis H. C. Crick in the February issue erroneously stated that Crick and Leslie E. Orgel co-authored *Life Itself.* Crick is the book's sole author.

In the box on page 96 of "Picture Perfect," by Elizabeth Corcoran [February], the rates associated with various transmission standards are described in terms of frames per second. The correct unit is fields per second.

On page 17 of "Early Arrivals," by John Horgan ["Science and the Citizen," February], one sentence should read: "... the *ancestors* of all modern Native Americans arrived in three distinct waves."

Credit for the painting on pages 122–123 of the January issue neglected to mention that it was based on a drawing by Michael Rothman for the *New York Times.*

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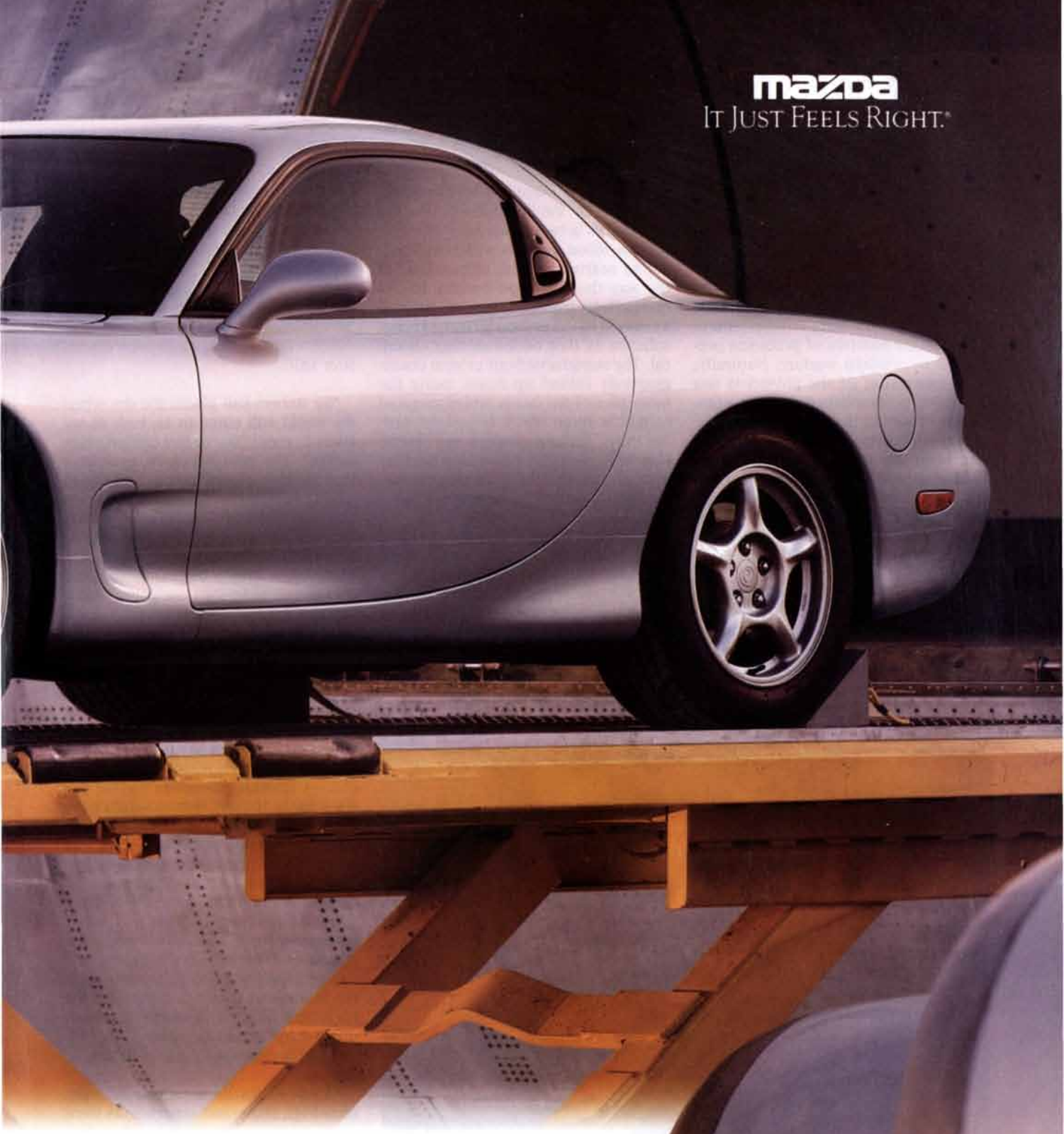
ANNOUNCING THE RETURN OF THE PURE SPORTS CAR. This is the kind of sports car manufacturers stopped making years ago. The all-new 1993 Mazda RX-7 is specially designed for a handful of uncompromising individuals. Those who believe in the simple thrill that only comes from driving a lightweight car with a lot of power. What makes the RX-7 lightweight is also what makes it powerful. The world's only sequential twin-turbo rotary engine. More compact, and hundreds of pounds lighter than a comparable piston engine, it powers the RX-7 from 0-60 in 4.9 seconds and offers unique design



advantages including perfect weight distribution. It even inspires the car's fluid shape. No gimmicks. No gadgets. No compromises. The all-new Mazda RX-7. Unless you race, you've never felt anything like it.

THE 1993 MAZDA RX-7

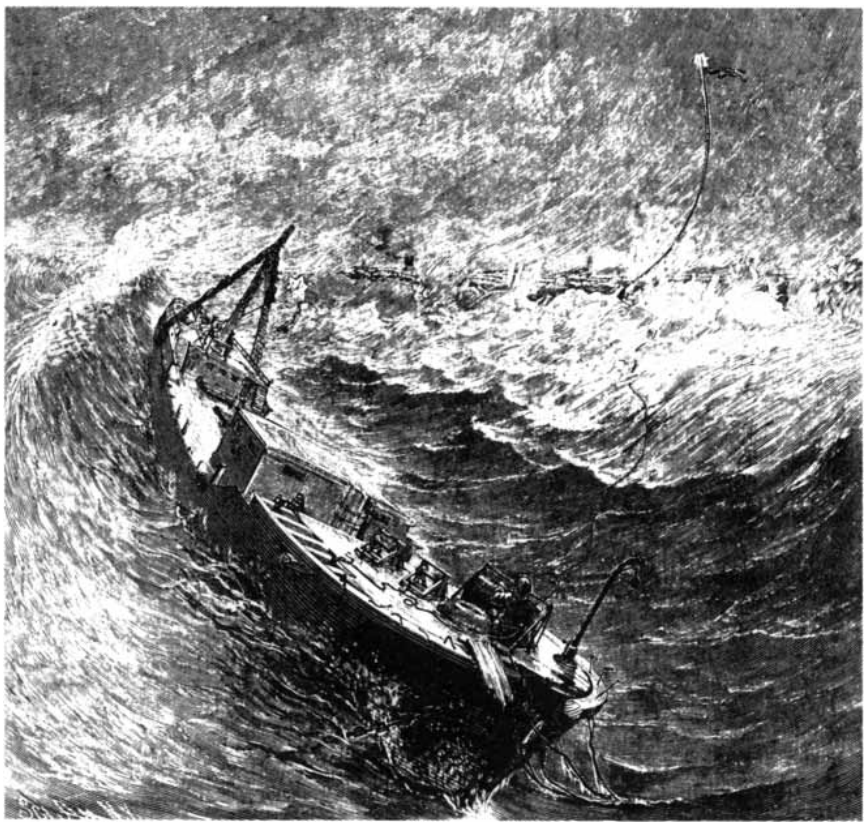
Sequential twin-turbo rotary engine. 255 horsepower. Independent double-wishbone suspension. 11.6-inch, ventilated 4-wheel disc brakes with ABS. Torsen® limited-slip differential. 36-month/50,000-mile, no-deductible, "bumper-to-bumper" warranty. Free roadside assistance. See dealer for limited-warranty details. For a free RX-7 brochure call 1-800-639-1000.

MAY 1942

"By early autumn of 1940 the National Defense Research Committee had decided on its main plan of action. Soon the best physicists of the country were put to work applying the latest discoveries of the pure science laboratories to the solution of problems presented by modern warfare. Naturally, this 'conversion' of the physicists has not been accomplished without completely upsetting their 'business as usual.' Up until recently their main concern had been the study of the great new field of atom-smashing or nuclear physics. Even a year ago nearly all of this fundamental research had come to a stop because of the demand for trained physicists to do war work."

"Dr. Linus Pauling of the California Institute of Technology has developed preliminary tests in an attempt to do what has never been done before—synthesize disease-curbing antibodies in the laboratory. The work is based on the scientist's important studies of protein structure. Dr. Pauling believes that the differences between various antibodies and the blood proteins with which they are so nearly identical, consist only in the way the chain has become folded on itself. He uncoiled the molecules of a selected blood protein by using known substances, then added another chemical. The straightened-out protein chains gradually folded up again, using the molecules of the newly added material as molds about which to coil. According to Dr. Pauling, this process resembles what happens when normal body proteins are formed in blood contaminated by diphtheria-germ poisons."

"Ghosts of ice lurk in water that had been frozen, and other liquids have some slight residual structure which is like a vague recollection of a former crystalline solid state. This finding of science was reported by Dr. John G. Kirkwood, professor of chemistry at Cornell University. When a solid melts, Dr. Kirkwood explained, some trace of the short-range local organization persists. Each molecule in the liquid tends to retain a smaller or larger group of its former neighbors around it."



Kite-borne life line

SCIENTIFIC AMERICAN

MAY 1892

"Sir Robert Ball places the day when the world will come to an end, as we know it, about four or five million years distant. The heat which he estimates that the sun originally contained would supply its radiation for 18,000,000 years at the present rate. It is believed that the sun has already dissipated about four-fifths of the energy with which it may have originally been endowed, and this brings us to the conclusion that it will last 5,000,000 years longer."

"The first explorers of Africa, following the dry beds of rivers to obviate the necessity of cutting their way through heavy jungles, paid no attention to the thousands of balls of hardened mud which were strewed about in profusion. One day, however, when a detachment of the Cameron expedition was exploring what in the wet season would have been a tributary of the Nile, a woodman cracked one of the balls and was surprised beyond measure to see a live fish-like animal fall out of the center of the ball and flounder in the sand. These spherical mud dwellings are perforated with many small holes and lined with a mucus from the animal's body, the mucus keeping the dried ball damp upon the inside, and the holes being used for breathing. This queer animal has been dubbed the 'mudfish,' which is expressive of the creature's curious habits."

"A few weeks since, on two different occasions, successful experiments were made on some islands in the East River, near New York City, to test a new method of carrying a life line ashore from a vessel in distress. The trials, however, were not made from a vessel actually in need, as portrayed here by the artist, but the kite was made to carry the buoy, with the life line attached, across a strip of water five-eighths of a mile wide, in which the current was running at the rate of two and a half miles an hour."

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At the forefront of advances like these is the pharmaceutical industry which will invest close to $11 billion dollars in drug research this year alone. While these efforts hold hope for breakthroughs, the process is long and difficult, with only a few of the thousands of compounds developed ever achieving success.

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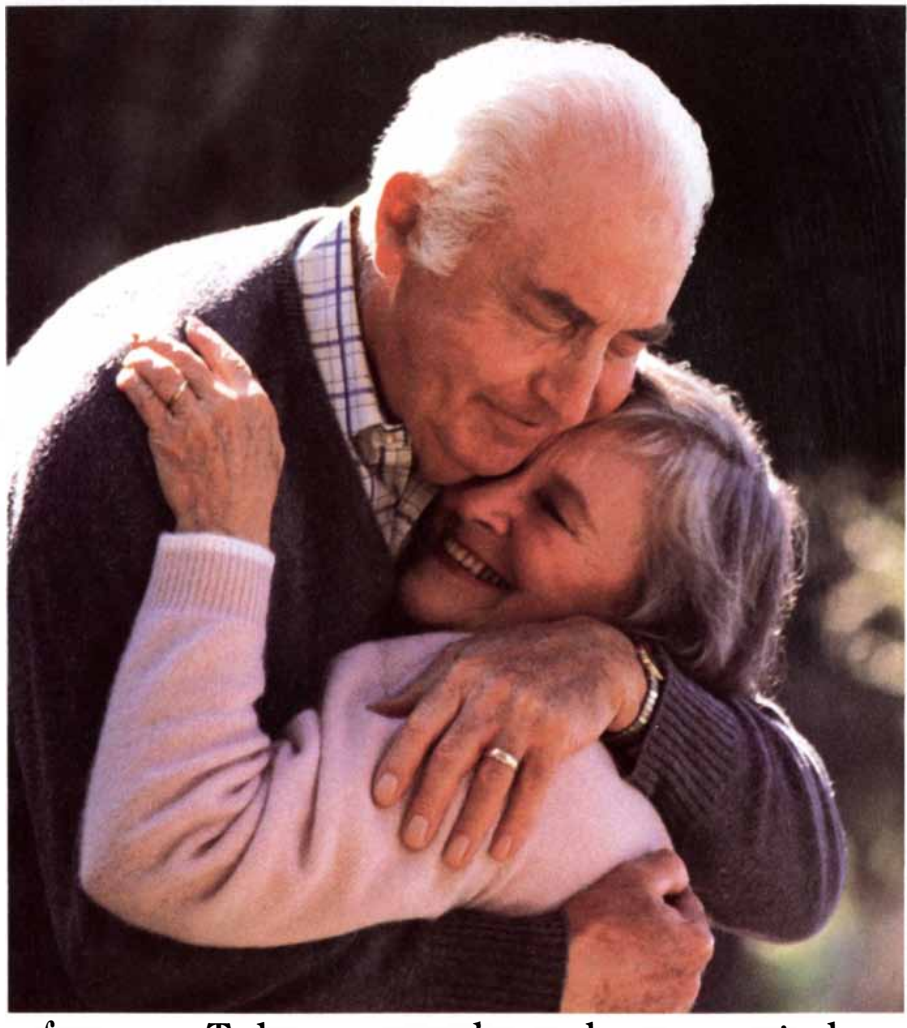

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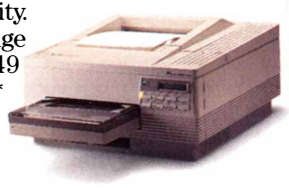

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Better Care, Less Care

Can rationing cure the ailing U.S. health care system?

ESSENTIAL SURGERY? Nearly 50 percent of the heart bypass operations in the U.S. may not benefit patients. Photo: Lawrence Migdale/Photo Researchers.

There is very little disagreement that the U.S. health care system is ailing. Consider the symptoms: It is now the most expensive in the world. Between 1970 and 1990, health care expenditures shot from 7.3 percent of the gross national product to 12.3 percent. Costs are now 40 percent higher per capita than they are in Canada, which has the second most expensive health system. Yet the U.S. system is burdened by tragic inequities. More than 35 million Americans, including 10 million children, have no health insurance, and they die at a higher rate from a given illness than do people with coverage.

What policy treatment should be prescribed? The Bush administration now promises to reform the medical insurance business and to provide tax subsidies for families with incomes below 150 percent of the poverty level. But health economists say the plan is little more than a Band-Aid. Judith Feder of Georgetown University School of Medicine argues the proposal would allow only one half of the uninsured to obtain insurance. And few researchers think insurance reform will do much to slow the escalating costs.

In the opinion of a growing number of economists, radical surgery is needed. A long-term solution will require facing a reality that many physicians, as well as patients, prefer to ignore: many expensive medical procedures that are frequently performed bring little benefit for most patients. Reducing the number of those procedures might be a more effective way of reducing costs. "I think ultimately it's going to be the case that we have to do less medicine," says Joshua M. Wiener of the Brookings Institution.

Wiener argues that efforts to make procedures individually less expensive have been thwarted. Factors ranging from economic gain to the threat of malpractice litigation induce physicians to order additional, more profitable ones. The spread of "managed care" and "utilization review"—checks to prevent blatantly wasteful practices—has cut costs, but many believe the improvement is likely to remain small. "Utilization review criteria exclude almost no one, because they are written by the physicians," says David C. Hadorn of RAND in Santa Monica, Calif. RAND studies show that health maintenance organizations can limit costs, but their reach is short. Requiring insured patients to pay a greater share of their bills also has had only a modest impact.

Hadorn and many other health economists now believe private insurance companies as well as government plans will eventually have to adopt guidelines that effectively ration care. That will put pressure on physicians not to order procedures that are not covered. "We inevitably will have to rely on physicians and other health professionals to do much of the rationing," concludes Victor R. Fuchs of Stanford University.

Proponents argue that a form of rationing—albeit an unfair one—already exists: those lacking insurance simply get less care. But trying to decide how to ration more equitably is a challenge because there is little information on the number of years of improved life that various interventions can be expected to provide. One recent study, for example, showed that 30 percent of heart bypass operations were equivocal, 14 percent were inappropriate, while 56 percent were judged appropriate. "It is remarkable how little we know about the efficacy of many procedures," says Robert M. Kaplan of the University of California at San Diego.

Oregon has blazed a trail by attempting to introduce rationing into its Medicaid system, and many other states are watching to see what will become of the plan. The state intends to make Medicaid benefits available to all Oregonians whose income falls below the federal poverty line, provided the medical procedure in question falls above a thresh-

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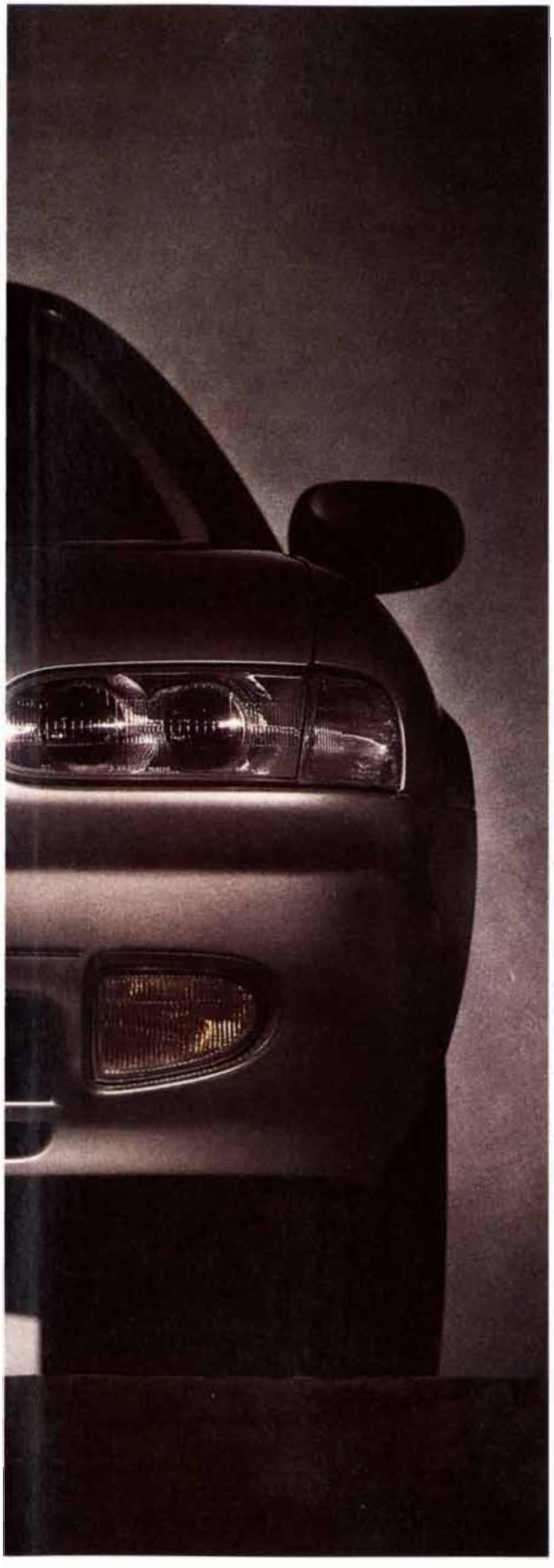

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old on a ranked list produced by the state's Health Services Commission. In the first draft list, issued in 1990, the state ranked health services according to a crude cost-effectiveness measure.

The principle seems rational. "If you stop doing things that don't work and do things that do work to more people, the average health of the population should go up," says Kaplan, one of the originators of the scheme. "The Oregon plan for the first time sees the outcome as part of the solution and says, 'We want to get health for our money.'"

But any kind of rationing is controversial, and the draft was widely criticized. According to Hadorn, it failed to allow for the "rule of rescue": the physician's moral obligation to save life. Thus, appendectomy, which usually saves lives, fell below splints for jaw disorders on the list. Dental caps for pulp exposure were assigned almost as high a priority as life-saving surgery for ectopic pregnancy.

In response to the criticism, the state revised its priority list last year. The new version ranks procedures, grouped into categories, according to benefit alone. Cost was not considered, except in some "by hand" adjustments made at the end. As before, only treatments above a cutoff point would be funded through Medicaid.

Oregon is now waiting for a bureaucratic thumbs-up for its plan—technically, a waiver of Medicaid rules—from the federal Health Care Financing Administration. But in an election year the White House is fearful of appearing insensitive, especially as congressional Democrats oppose the Oregon experiment. The Washington rumor mill has it that the waiver request will be denied and the Oregon plan shot down.

Even the revised list is being criticized. Oregon held numerous community meetings while it was developing its proposal, but "although the commissioners felt constrained to reflect community values, it is not clear they succeeded," says Wiener, who is wary of the approach. Physicians on the Oregon commission often had to guess at the benefits of procedures, he charges. And Wiener questions whether the approach would be politically workable in a "culturally more diverse state."

Others are more optimistic. "Oregon tried to do the right thing," says David M. Eddy, an authority on health care assessment, who is based in Jackson, Wyo. Eddy favors cost-effectiveness analysis, but he acknowledges there are insufficient data to compare all medical services. Eddy now advocates building on a list similar to that in Oregon but refining it by performing cost-effectiveness analyses on narrow categories of treatments that are near the cutoff threshold or suspected of falling on the wrong side of the threshold.

Other ways to ration care are also being developed. According to Hadorn, the key question is: "What sort of treatments benefit what sort of patients?" Hadorn insists that doctors make such judgments every day. "It does not need to be a long, complicated process," he says. Hadorn favors using a "jury" of experts and consumer representatives to evaluate formally evidence for efficacy. With a federal grant, he is putting the idea into practice by assessing treatments for congestive heart failure.

Eventually, Hadorn believes, both Medicaid and private insurance will have to develop a "basic benefits plan" of treatments that have proved cost-effective. "Clearly, there's a need to separate the wheat from the chaff," he says. "The days when insurers would pay for everything are over." —*Tim Beardsley*

Is It History or Just E-Mail?

Computers can act in microseconds, but the law takes a little longer. So the nonprofit National Security Archive in Washington, D.C., discovered when they filed suit in early 1989 to protect from destruction megabytes of data compiled by the Reagan White House staff. A federal judge was expected to issue a ruling in April ordering the current administration to provide an inventory and samples of backed-up data to the archive's lawyers, who contend that the information must be protected under the Federal Records Act. At issue is whether electronic mail constitutes official government records or whether it is simply digital doodling.

The archive, a private group that helps make government information dealing with national security available to scholars, discovered on the eve of George Bush's inauguration that dozens of computer backup tapes—among them ones containing memos from the Iran-Contra fiasco—were about to be erased. Citing federal law that prohibits the wholesale destruction of records, the archive obtained a temporary order preserving the material. The fate of the tapes has been in litigation ever since.

If these memos and E-mail messages were on paper, explains archive general counsel Sheryl Walter, there would be no question that most of them should be preserved. The White House, however, has argued that the documents have no substantive value and fall into the same "nonrecord" category as telephone message slips.

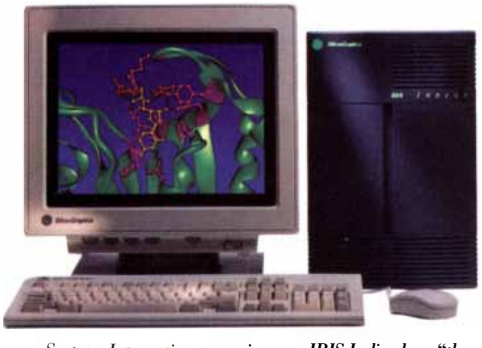
In support of its position, the government cites a policy statement, first committed to paper after the lawsuit was filed, instructing officials that any electronic document attaining "record" status should be printed out on paper and filed for archiving. By implication, anything not printed would be considered ephemeral.

Michael Tankersley, a lawyer at Public Citizen, an advocacy group involved in the case, argues that such a policy leaves individuals with enormous latitude to deny their deliberations to posterity simply by failing to print them out. Furthermore, he points out, the National Security Council allocated only two printers to more than 150 people.

Although high-profile operatives such as Oliver North provide the juiciest potential electronic tidbits, E-mail inhabits a similar limbo at other federal agencies, Tankersley says. At the Department of Energy, for example, the electronic version of officials' personal calendars is considered a record, but E-mail conversations are explicitly unofficial.

Indeed, according to David Bearman of the University of Pittsburgh, the problem goes far beyond the federal government. As business is increasingly transacted by computer, the status of digital documents waxes problematic. Some heavy users of E-mail save everything they send or receive; others discard it all. Managers everywhere, Bearman says, have yet to come to grips with the issue. E-mail and other computerized data are "just out there," he comments. "Managers don't know how they're structured, how they're managed or what happens after they use them."

If Tankersley and Walter get their way, a judge might rule by the end of the year that at least some White House E-mail merits the same preservation as the administration's voluminous paper files. In general, Bearman observes, the official or unofficial status of electronic messages will have to be decided by "a larger cultural consensus rather than a narrow legal ruling." —*Paul Wallich*



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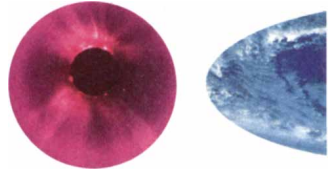

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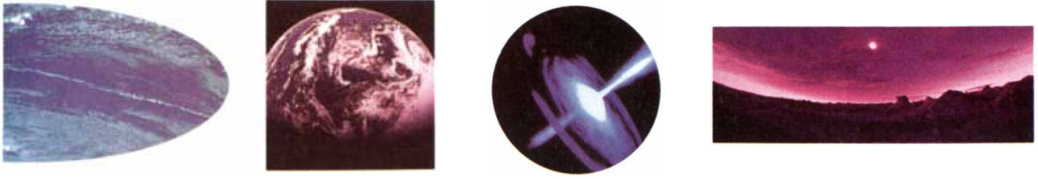

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World Space Congress will feature over 25 concurrent technical and scientific sessions daily, with more than 3,000 invited and contributed papers; and a series of distinguished lecture panels and presentations, featuring the space community's most notable experts. In addition, an International Space Exhibition will simultaneously bring exhibitors face to face with key decisionmakers and publics from every space-faring nation. The World Space Congress will be the most significant event of its kind in history.

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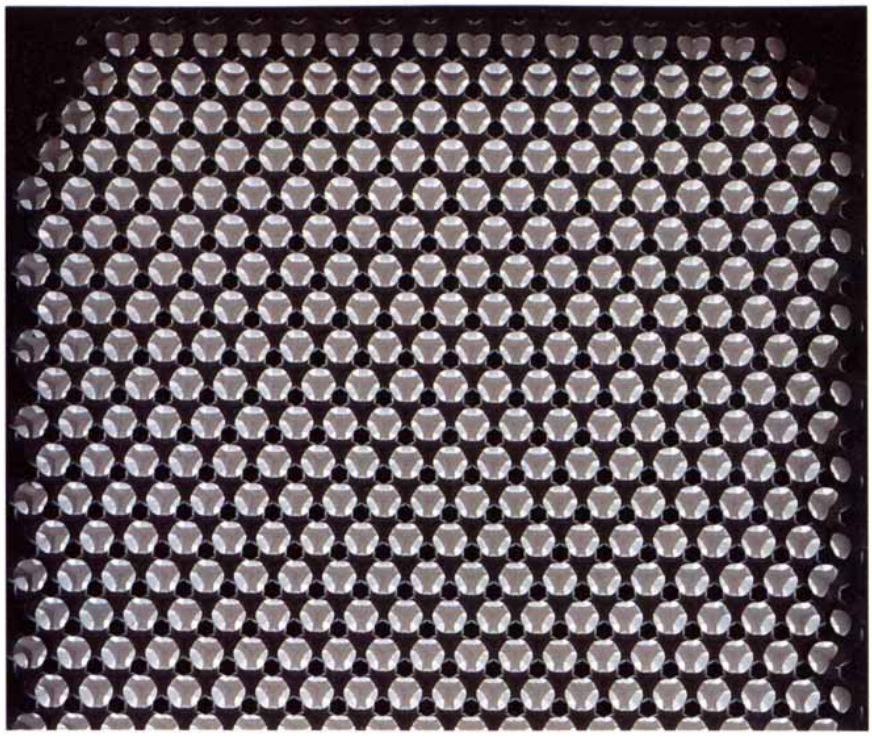


PHOTONIC CRYSTAL designed for microwave frequencies consists of a dielectric with holes drilled from three different angles. Photo: Axel Scherer.

Forbidden Light

Researchers design band-gap structures for photons

A chunk of plastic-ceramic with tiny holes drilled into it hardly seems likely to be the next leap forward in high technology. Yet these and related structures may prove to be an extremely important development in communications, laser technology—in fact, in anything that relies on the microwave and visible end of the electromagnetic spectrum. "What we're trying to do," explains Eli Yablonovitch of Bell Communications Research in Red Bank, N.J., "is to make an artificial crystal that does to photons what semiconductors do to electrons."

The crucial property of semiconducting materials is that they impede but do not completely block the movement of electrons in a solid. Unlike metals, semiconductors have band gaps, or missing energy levels. The gaps separate the electrons in the valence (outermost) band from a higher-energy state, called the conduction band. By introducing specific impurities—or dopants—that provide electrons, engineers can tailor a material's conductivity.

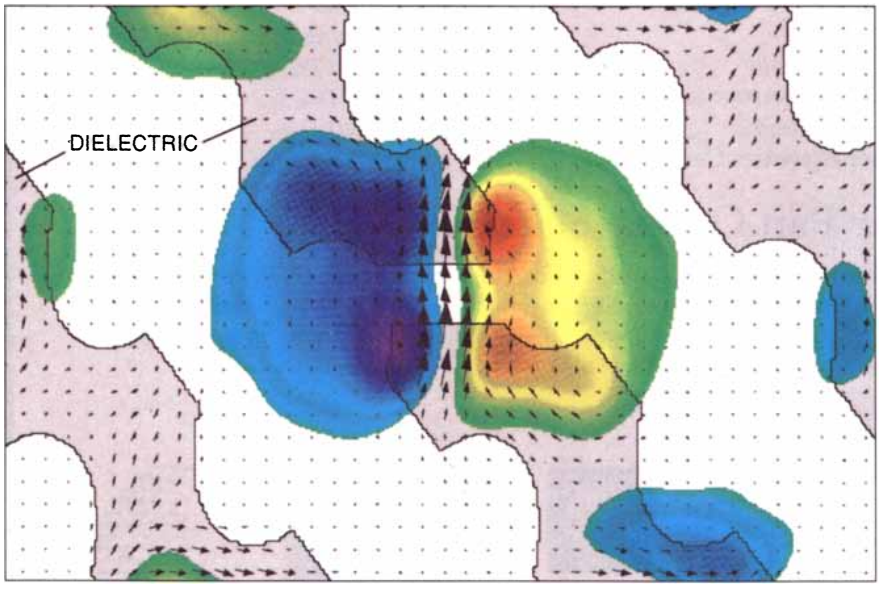
In 1987 Yablonovitch decided to extend the ideas to the photon. He reasoned that there should be structures for photons that are analogous to semiconductors, complete with band gaps. Many false starts and unsuccessful trials later, Yablonovitch and his colleagues announced that they had created a photonic "crystal" that works in the microwave region.

The photonic crystal is simply a dielectric (electrically insulating) substance in which holes about 45 millimeters in diameter have been drilled at three different intersecting angles. When these crystals were probed with microwave radiation, they prevented frequencies between 13 and 16 gigahertz from passing through. That is, the pattern of holes creates a band gap: the microwave photons could not propagate internally in any direction. Photons of other frequencies could pass through.

This March, Yablonovitch and his Bellcore colleague Axel Scherer reported progress toward a photonic crystal that works near the optical wavelengths. Making such a crystal is a much tougher challenge than making one that functions in the microwave region because the holes have to be 13,000 times smaller, about 3,500 angstroms in diameter. The drilling must be done with ion beams.

Like their silicon counterparts, photonic crystals can be doped. The impurities are simply defects in the lattice structure—either extra air or extra dielectric material. Yablonovitch, along with physicists Robert D. Meade, John D. Joannopoulos and their colleagues at the Massachusetts Institute of Technology, showed that the size and kind of defect determine the frequencies that will pass through the crystal.

Doped photonic crystals can also be made to emit a directional beam of coherent light. An electric current, Scherer says, would boost the electrons in a photonic crystal to a higher-energy state. When they dropped to their



ELECTROMAGNETIC FIELD in a photonic crystal becomes localized on a defect, represented by a break in the dielectric. In this computer-generated, cross-sectional image, the electric field* (arrows) *circulates through the defect in the plane of the page. The magnetic field circles in a perpendicular direction* (blue represents the field coming out of the page; red-yellow-green is in). *Diagram: Robert D. Meade et al.

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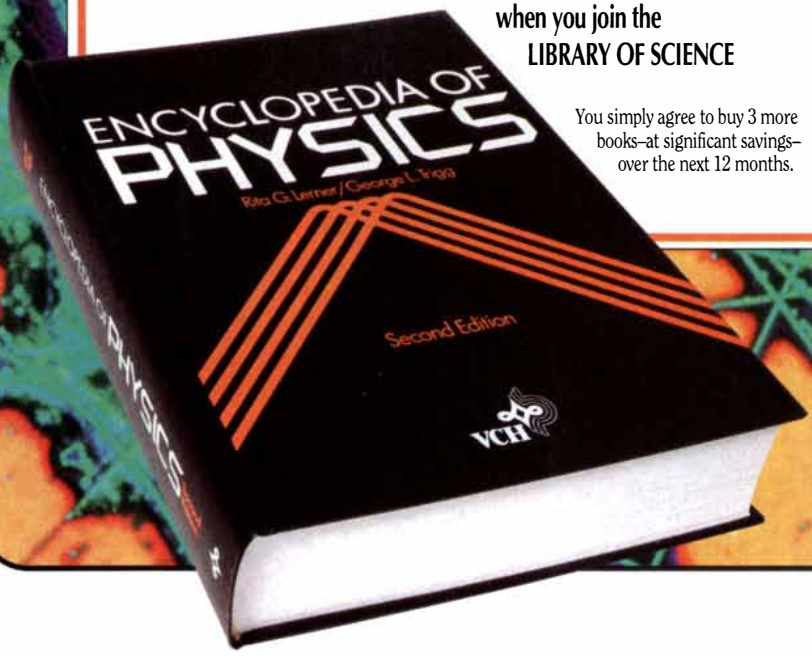
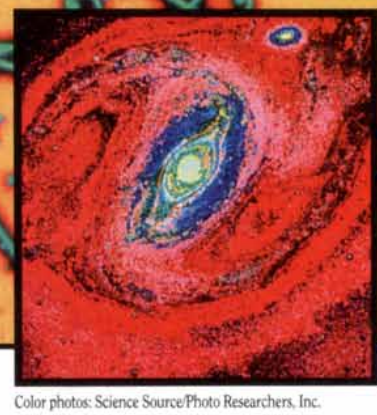


Mandelbrot fractal

Crystalline semiconductor



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- GRAVITATIONAL LENSES
- HIGH FIELD ATOMIC STATES
- JAN-TELLER EFFECT
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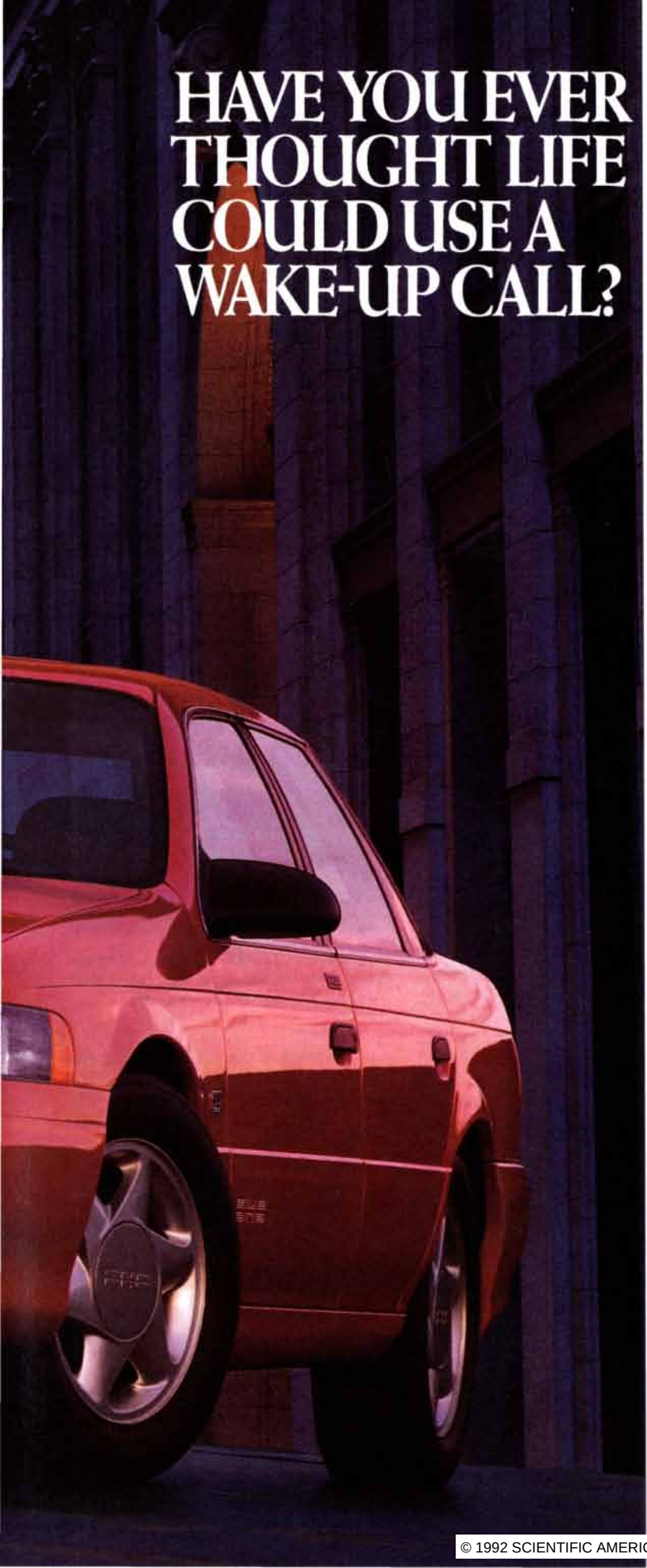

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ground state, they would emit photons. But the defects in the crystal would limit those emissions to a particular frequency. By rounding up all the emitted photons into single mode, each defect would function like the resonant cavity of a laser and would produce a directional, coherent beam. A surface, such as a fiber-optic cable, situated a few photonic lattice spacings away would draw out the radiation.

Yablonovitch hopes to make such a device, which would fall somewhere between a standard light-emitting diode (LED) and an ordinary laser and would combine the best attributes of both. Yablonovitch refers to it as a zero-threshold laser or a single-mode LED. Like an ordinary LED, the zero-threshold laser would be very reliable, insensitive to ambient temperatures and would not require a threshold current to start operating (hence the name). Like an ordinary laser, it would emit a directional beam of coherent light.

Meanwhile Nabil M. Lawandy, a physicist at Brown University, took another approach to creating photonic band-gap structures. Instead of drilling holes, he built a crystalline structure in a colloidal solution of 100-nanometer-wide polystyrene spheres. Because the tiny spheres are electrically charged, they organize themselves into highly ordered crystals. Lawandy then embedded light-emitting and light-absorbing dye molecules in the suspension.

Normally, the dye molecules will emit light after they have been excited by laser light. But the structure of the colloidal crystal blocked their spontaneous emission. After being excited by laser light, the molecules in the suspension did not drop to a lower-energy level and emit photons. Instead the dye molecules remained excited. Lawandy believes this property will prove useful in photocatalysis. In this process, reaction rates are increased through radiation, which excites the catalyst material. But the efficiency of most such processes is often limited by the spontaneous emission of the excited catalyst, Lawandy says. He thinks that photonic band-gap structures, created from or coated with photocatalytic material, would make the reaction more efficient.

Meade and his colleagues have already begun exploiting the microwave photonic crystal. "They can act as microwave filters, isolators, antennas," Meade says. Essentially much of the communications industry (cable converters and cellular telephones, for example) might benefit from the easily manufactured material. Joannopoulos adds: "Within a year, we're sure we'll have something." —*Philip Yam*

Born Yesterday

A younger universe may spell trouble for cosmology

To people who grow antsy just waiting for the teapot to boil, eight billion years may sound like a lot of time. Cosmologists take a slightly longer view of things. They are gravely concerned by recent measurements implying that the universe is no more than 12 billion, and perhaps as little as eight billion, years old.

The most popular cosmological hypothesis points toward the low end of the range. According to models of stellar evolution, however, a class of dense stellar groupings, known as globular clusters, appear to be 12 to 14 billion years old. Clearly, the universe cannot be younger than the objects it contains.

GLOBULAR CLUSTERS such as M13 appear to be older than the latest estimates of the age of the universe.

But where does the error lie—with the theories or with the observations? "It's one of the modern dilemmas in science," reflects David Roberts of Brandeis University.

The dilemma arises from efforts to determine the rate at which the universe is expanding, a figure called the Hubble constant. Knowing the value of this number makes it possible to run the picture backward and infer how long ago the present expansion began. The Hubble constant is calculated by dividing the velocities of remote galaxies by their distances from the earth.

Velocities can be unambiguously determined by analyzing galactic spectra, but finding distances is a notoriously tricky business. In recent years, researchers have refined methods for measuring distance. The results increas-

ingly indicate that the Hubble constant is high and hence that the universe is surprisingly young.

One particularly promising distance-measurement technique makes use of planetary nebulae, glowing shells of gas that surround aged stars. A team led by George H. Jacoby of Kitt Peak National Observatory found that the brightest planetary nebulae are all nearly equally luminous. By comparing the true, intrinsic luminosity of an object with its apparent brightness in the sky, astronomers can deduce the distance to the object. Two years ago Jacoby reported finding a Hubble constant indicating a universe eight to 12 billion years old.

At the time, some astronomers questioned the accuracy of using planetary nebulae as yardsticks. Now Jacoby's group has augmented its study of the Virgo Cluster with observations of several additional galaxy clusters and used other distance-scale research to calibrate its estimates. "There are no big errors," Jacoby concludes. "All observational methods are yielding the same distance to Virgo."

Michael J. Pierce of Kitt Peak National Observatory, working with Michael E. Ressler and Mark Shure of the University of Hawaii, derived the Hubble constant by looking at supernova explosions. In the past, distance measurements made using supernovae have tended to yield low values of the Hubble constant and so were often cited by such skeptics as Alan Sandage of the Mount Wilson Observatory.

Pierce's group examined a kind of supernova that seems always to peak at a certain absolute luminosity. Comparing that luminosity with the supernova's apparent brightness reveals its distance. By scrutinizing observations of a supernova that occurred in a nearby galaxy, the group inferred the distances to supernovae in the more distant Virgo Cluster. Pierce admits that these improved measurements are "still not definitive." But he is heartened that the supernova technique now seems to corroborate the view that the universe is at most 12 billion years old.

Wendy L. Freedman of the Carnegie Observatories and Barry F. Madore of the California Institute of Technology are developing new, exceptionally precise observations of Cepheid variable stars. These stars serve as distance markers because their period of variability correlates with their intrinsic luminosity. By examining the stars at infrared wavelengths, Freedman and Madore have eliminated much of the distorting effect of interstellar dust. Their observations have been used to calibrate several independent approach-

es to distance determination (in addition to those already mentioned). The results support the conclusion that the universe is between eight and 12 billion years old. Freedman worries, however, that astronomers "still have to demonstrate that there are no systematic errors" in their methodology.

Every measurement technique mentioned so far depends on using cosmic stepping-stones to determine the distances to relatively nearby galaxies. Roberts has been pursuing a completely independent, and particularly intriguing, approach. He and his co-workers have been observing a gravitational lens, in which the light of a distant quasar is bent by the gravity of an intervening galaxy. The degree to which the light is bent reveals the separation of the two objects and thus the rate of the expansion of space between them.

The technique yields "rather different" values for the Hubble constant depending on the assumed structure of the lensing galaxy, Roberts notes. But as it is refined, it should become a powerful tool. For example, gravitational lenses enable astronomers to tell whether the rate of expansion is consistent throughout the universe. Jeremiah P. Ostriker of Princeton University has suggested such inhomogeneous expansion as one way of reconciling observation and theory.

The onslaught of evidence for a fairly young universe places observers and theorists in a polite, but conceptually fierce, conflict. Theorists such as Andrei Linde of Stanford University, who have invested tremendous time and energy in refining and modifying big bang cosmology, are loath to back down. "These reports make good press but bad science," he coments. He remains confident that future research will show the Hubble constant to be comfortably low.

Observational astronomers, on the other hand, put little faith in their theoretical brethren: "I always prefer direct measurements to anything that has to go through a computer," Jacoby confides. Observers readily admit that their own results are far from conclusive. But most of them quietly suspect that the favored version of the big bang or theories of stellar evolution (or both) are in error. As better data pour in, the issue should be settled in the next few years—a mere blink of the eye in cosmic terms. *—Corey S. Powell*

Life in a Test Tube?

The definition of "life" is becoming awfully flexible lately. Some computer scientists think a computer that simulates any living system, from a brain to a colony of algae, is a kind of "artificial life." Julius Rebek, Jr., a chemist at the Massachusetts Institute of Technology, makes a more modest claim. He proposes that any assemblage of chemicals—not just ones consisting of proteins and nucleic acids—is arguably alive if it acts alive.

Rebek began promoting this view two years ago, when he created a simple, synthetic molecule that makes copies of itself much the way DNA does. The molecule consists of two chemical building blocks, an ester and an amine. When mixed in a chloroform solution, the ester and amine form a molecule called an amide. Like DNA, the amide guides its own self-replication by serving as a template on which its components can assemble.

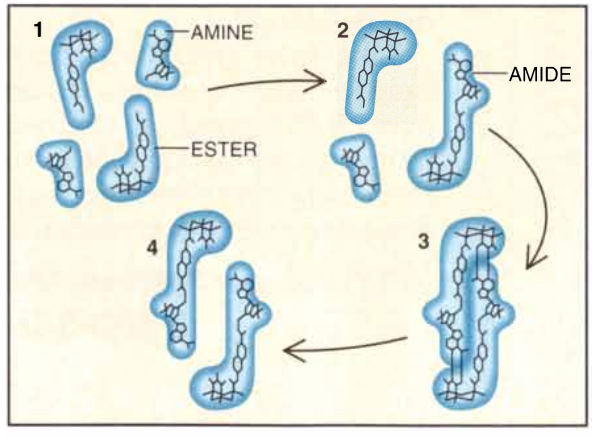
Molecular biologists such as Leslie E. Orgel of the Salk Institute were not terribly impressed. Life involves more than just self-replication, Orgel noted. The process must occasionally allow heritable mistakes, or mutations, leading to more efficient replicators. Only then can natural selection and evolution—the true hallmarks of life—occur.

Chastened, Rebek went back to his laboratory. Early this year he and three M.I.T. colleagues, Jong-In Hong, Qing Feng and Vincent Rotello, unveiled in *Science* a system that evolves, albeit only a little. Their new brew contains three amines, each of which joins with an ester to form a self-replicating amide. These three, slightly different amides replicate at roughly the same rate, but when irradiated with ultraviolet light, one amide mutates into a variant that reproduces much faster than the others.

More recently, Rebek and his colleagues mixed two esters and two amines together to create four different amides, including two created in the earlier experiments and two new "hybrids." One of the hybrid amides is a highly efficient replicator, better even than the mutant spawned by ultraviolet radiation. The other hybrid cannot replicate at all; it is "doomed to the fate of a mule," Rebek says.

These test-tube ecosystems are still wan imitations of the dog-eat-dog Darwinian world. Each of the amide replicators, even the most efficient ones, can serve as a template not only for its own formation but also for that of the other amides. That is like a guppy occasionally spawning a stickleback. Moreover, the replicators have no capacity for change beyond the simple exchange of components and the mutation induced by ultraviolet radiation. "It's a dead end," says Gerald F. Joyce of the Scripps Research Institute.

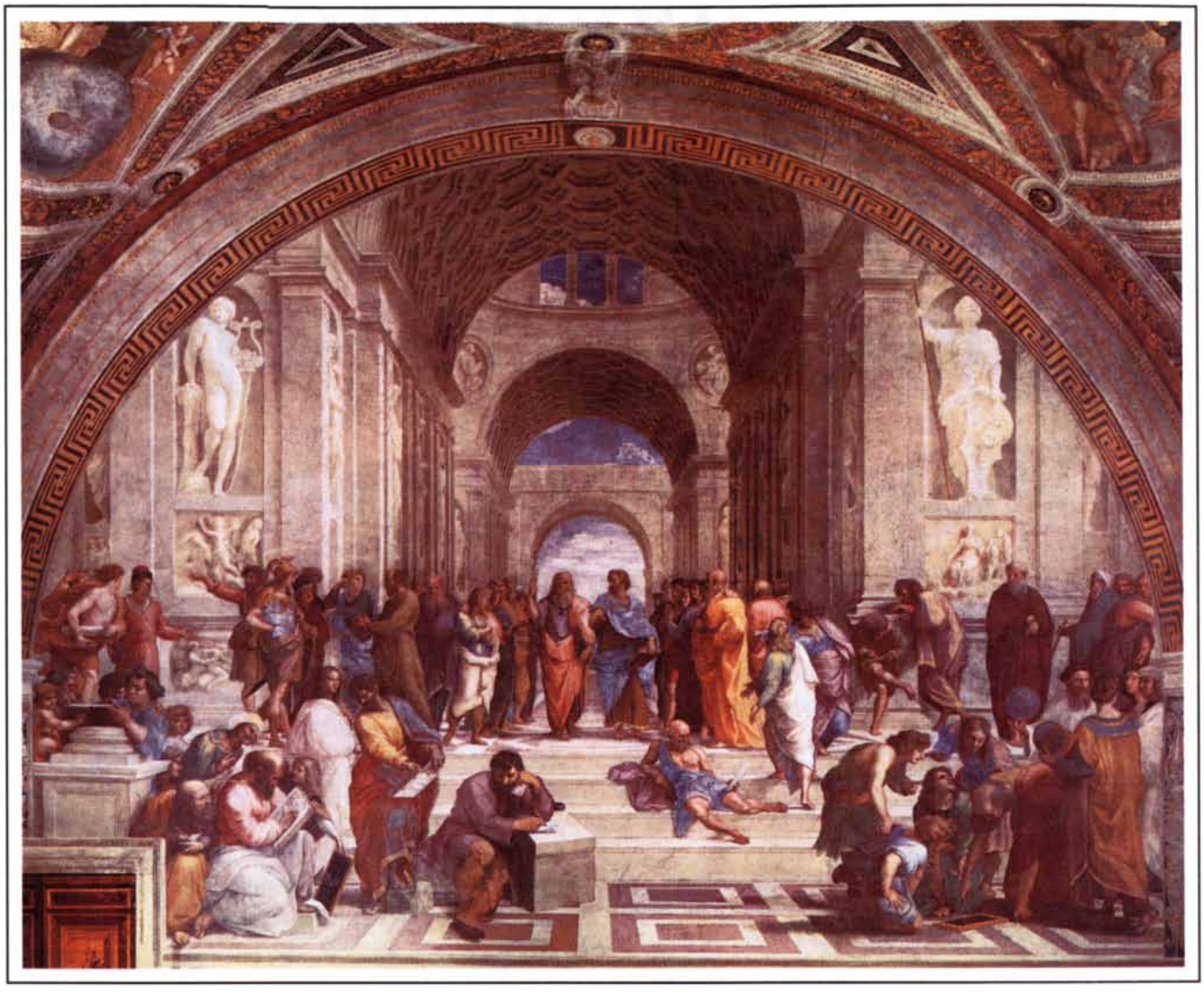
Yet Joyce applauds Rebek's efforts. By the end of the millennium, he predicts, Rebek and researchers doing similar work may well have created a synthetic system that can serve as a useful model of Darwinian evolution. This type of research, according to Joyce, could complement other, more traditional investigations into the origin and fundamental nature of life.



***MOLECULAR SELF-REPLICATION** occurs when an amine and an ester form an amide, which then serves as a template on which another amine and ester can join together much more easily. Thermal jostling separates the two amides after assembly occurs.*

Rebek envisions an even grander future for "extrabiology," a term he has coined to describe the simulation of life in nonbiological systems. "Whether they involve synthetic molecules in vitro or computer constructs in silico," he asserted in a recent issue of the British journal *Chemistry and Industry,* "these studies are intended to extend, then subsume that which is currently considered molecular biology." Watch out. *—John Horgan*

Different Schools Of Thought Thrive In The Same Company



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Mutable Mutation

Some genes cause diseases by growing and growing and....

The stability of the mutations at the heart of most genetic diseases enables them to act with terrible predictability, inflicting consistent misery as they pass from generation to generation. Over the past year, investigators have found another disease-causing genetic pattern, one that clearly bucks the simple rules laid down by Mendel.

At least three illnesses—fragile X syndrome, myotonic dystrophy and spinal and bulbar muscular atrophy (Kennedy's disease)—are caused by parts of genes that grow explosively from one generation to the next. As Pieter J. de Jong of Lawrence Livermore National Laboratory puts it, "Here, the mutation is itself mutable." That clue may help untangle the riddles of many diseases, including cancer.

In the case of fragile X syndrome, the most common cause of inherited mental retardation, all the men who carry the abnormal X chromosome should be affected. Instead 20 percent of them are normal. Their grandchildren, however, are often retarded. Myotonic dystrophy, the most common form of muscular dystrophy in adults, seems to get worse in successive generations: adults with unnoticeable symptoms have typically learned of their own condition only after a child with the severe congenital form of the disease was born. Genetic anticipation, as this progression is called, was often dismissed by geneticists as a diagnostic fluke, recalls Robert G. Korneluk of the Children's Hospital of Eastern Ontario in Ottawa, but clinicians insisted the change was real.

An explanation began to emerge in late May 1991, when groups led by Jean-Louis Mandel of INSERM in Strasbourg, France, Grant R. Sutherland of Adelaide Children's Hospital in Australia and Stephen T. Warren of the Emory University School of Medicine reported the discovery of the defect in fragile X syndrome. They found that a gene containing 30 copies of a certain trinucleotide base sequence—cytosine, guanine, guanine, or CGG in the shorthand of molecular biologists—was altered in people with a fragile X chromosome. Whereas healthy carriers had about twice as many repeats of CGG as did normal individuals, retarded persons had hundreds or thousands of extra copies. In some bizarre way, the fragile X site was expanding rapidly between generations.

Six weeks later Kenneth Fischbeck of the University of Pennsylvania School of Medicine and his team made a similar announcement about Kennedy's disease, which causes a slow degeneration of the motor neurons in adults. Patients with the disease had two or three times too many repeats of a CAG (cytosine, adenine, guanine) sequence in a gene for an androgen hormone receptor. Although it represents a less dramatic expansion than in fragile X, Fischbeck notes, it is still inexplicable through standard mutations.

The clincher consisted of another flurry of papers on myotonic dystrophy, published in recent months by de Jong, Korneluk, Duncan J. Shaw of the University of Wales College of Medicine, Keith Johnson of St. Mary's Hospital Medical School in London and others. They established that the severity of the disorder correlates with the massive duplication of CTG (cytosine, thymine, guanine) repeats at one genetic site.

FRAGILE X CHROMOSOME* (at arrow) *carries an expanding gene that causes mental retardation. Photo: National Fragile X Foundation.

These discoveries provide at least a sketchy basis for genetic anticipation. People with mild or asymptomatic forms of the diseases carry genes that are functional but structurally unstable: they may gain or lose a few copies of a repeated unit with each round of DNA replication. If one such gene reaches a threshold length, a sudden cascade of further duplications takes place, and the disease manifests itself strongly.

"It's not clear what the mechanism is that causes the expansion," Warren admits. Misalignment of the replicating DNA strands could create a few sequence duplications. Explosive copying, Fischbeck offers, might involve "enzymes that polymerize simple sequence repeats in DNA, like the ones that maintain telomeres," the repeat-rich areas at the ends of chromosomes.

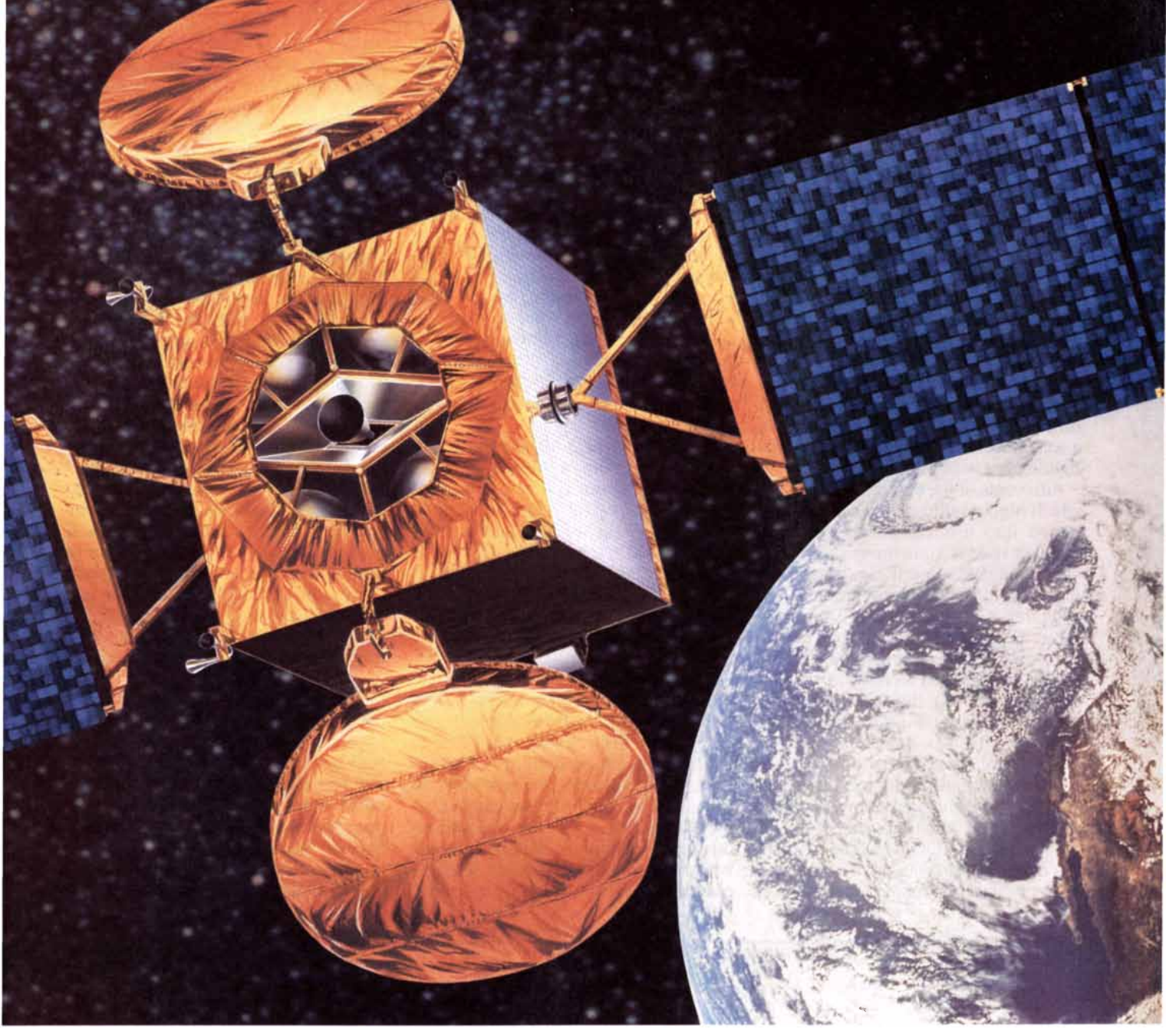
Probes for expanded repeat regions may now serve as highly accurate diagnostic tests for carriers and potential victims of the diseases. Conceivably, the tests could warn people that they and their future children will be healthy but that their descendants two or more generations removed might be at risk. Warren doubts that long-term predictions have much practical value, however. "In 40 years the burden of a disease may not be what it is today," he argues, because new treatments may become available.

Moreover, the expansion phenomenon cannot account for all the peculiarities in the inheritance of these diseases. Although the symptoms of myotonic dystrophy and the expansion of the repeat region within a family are linked, the severity of the disease cannot be predicted from the repeat length alone. Some sick persons, Korneluk says, have repeat regions no larger than those of mildly affected people in other families.

Another issue is the timing of the repeat expansion. Because sick children have more repeats than their parents, at least some expansion probably occurs during meiosis, the production of eggs and sperm. Yet researchers have also found that blood cells in the bodies of some patients with fragile X syndrome and myotonic dystrophy harbor varying numbers of repeats, which means that expansions may occur during mitotic cell divisions throughout the body.

"Is the expansion varied in the tissues of an individual?" Korneluk wonders enthusiastically. If so, he thinks genetic variability may regulate other diseases. Warren offers a scenario in which repeat expansion could be involved in tumor progression: "You start off with a cell that is not very invasive but is still malignant, and then it mitotically divides and becomes more aggressive until you get a full-blown metastatic tumor."

Warren notes there are many conditions, including diabetes and Huntington's disease, that do not follow a clear pattern of inheritance. "Often people have ascribed that to the influence of more than one gene," he says. "At least a subset of those, to my mind, may be genes that undergo similar repeat expansion." Indeed, he and his colleagues have screened human DNA and found dozens of other genes with repeat regions like those of fragile X and myotonic dystrophy. "So there are other genes like that—we just don't know yet what they do," he says. —*John Rennie*



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Trying Transmutation

Experts debate practicality of a nuclear-waste scheme

Many thousands of tons of so-called high-level radioactive waste, the most lethal legacy of the nuclear age, have piled up at commercial and military nuclear sites around the U.S. Meanwhile technical problems and political opposition have indefinitely stalled construction of repositories in which the waste would be buried for millennia. Inevitably, then, nuclear-energy experts have once again turned their attention to transmutation, a waste-disposal method that calls for fighting fire with fire.

Adherents of the decades-old idea—in which highly radioactive waste is converted into less dangerous elements through what is sometimes called "nuclear alchemy"—say it can greatly reduce and possibly even eliminate the need for repositories. Two years ago James D. Watkins, head of the Department of Energy, reportedly saw merit in this view, and as recently as last fall the prospects for the technology still seemed bright, as favorable articles appeared in the *Los Angeles Times,* the *Washington Post* and other publications.

But transmutation's standing has slipped in recent months, with critics arguing more forcefully that it would be much too costly and would actually increase the total volume of waste. The DOE's official position is neutral, according to Clyde W. Frank, who oversees waste-disposal research. But he emphasizes that transmutation can at best only complement, not replace, burial in repositories. "Transmutation is not the cure-all that one reads about in the newspaper," he says.

The basic mechanism underlying transmutation involves exposing radioactive elements to a stream of neutrons. Fast-moving neutrons can cause elements such as plutonium, which has a half-life of about 24,000 years, to split into lighter, shorter-lived and less poisonous elements. Slower-moving neutrons can also be absorbed by the waste elements, making them heavier and more stable.

Either a particle accelerator or a fission reactor can supply the neutrons for transmutation. The most advanced research on reactor-based transmutation involves the Integral Fast Reactor, or IFR, which is now being developed at Argonne National Laboratory. The IFR is a modified breeder reactor, in which neutrons are harnessed not only for the generation of heat but also for the production of new fuel.

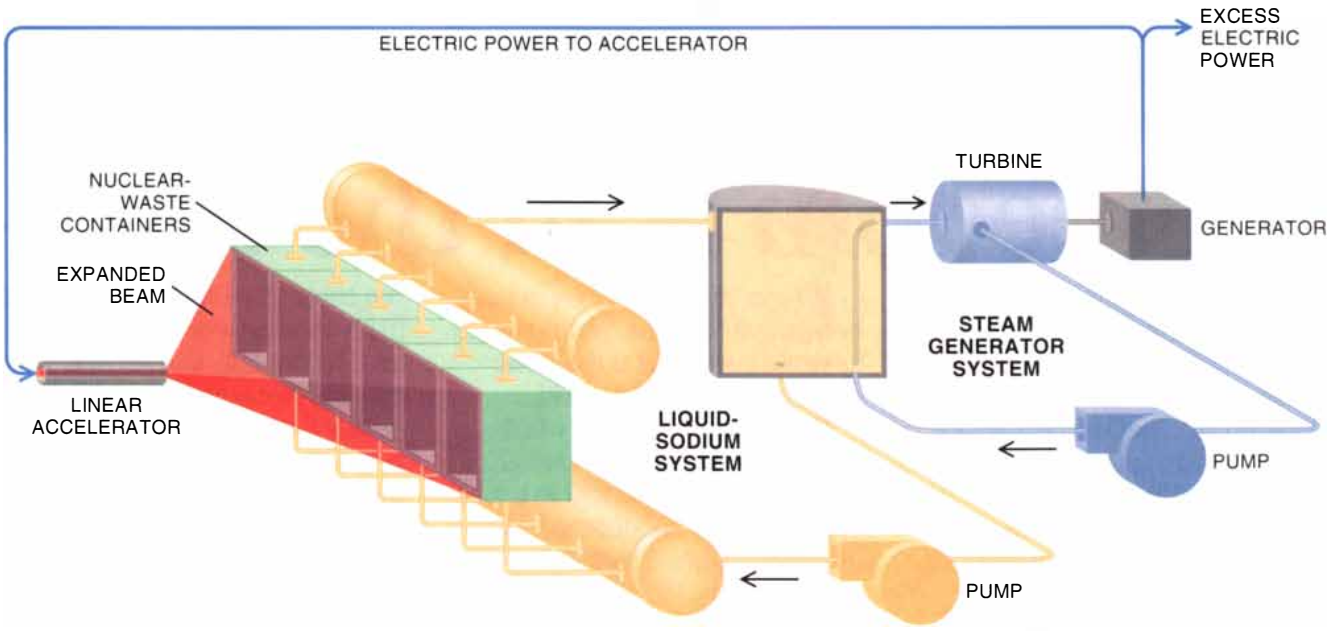
In a standard breeder reactor, neutrons from the reactor irradiate a blanket of uranium and transform it into plutonium, which can be used either in nuclear weapons or in reactors. The IFR is designed to irradiate its own waste so that it can be recycled, thus eliminating the reactor's need for new fuel and reducing its volume of high-level waste. With minor modifications, an IFR-type reactor could also transmute, or "burn," high-level waste from other reactors, according to Yoon I. Chang, manager of the IFR program.

An accelerator-based plan has been devised by workers at Los Alamos National Laboratory. With funds from the Strategic Defense Initiative, also called "Star Wars," the laboratory has already built one of the most powerful proton accelerators in the world, according to Edward D. Arthur, who heads the Los Alamos team investigating transmutation. The plan calls for accelerating protons against a lead target, which in turn spews out a stream of neutrons.

A similar accelerator-based concept has been proposed by workers at Brookhaven National Laboratory. Accelerator-based transmutation "minimizes the concern you'd have with a reactor," contends Michael Todosow of Brookhaven, since the waste never achieves a self-sustaining, or critical, reaction. If problems arise, such as an excess of heat in the transmuting waste, workers can simply turn off the accelerator, and the reactions immediately cease, Todosow explains. The risk of a Chernobyl-style meltdown and explosion is thereby eliminated.

Like the reactor-based approaches, the Los Alamos and Brookhaven designs call for converting the heat generated by transmutation into electricity. The Brookhaven team says its facility could produce enough electricity to keep the accelerator running and still have as much surplus power left over as a midsize commercial reactor.

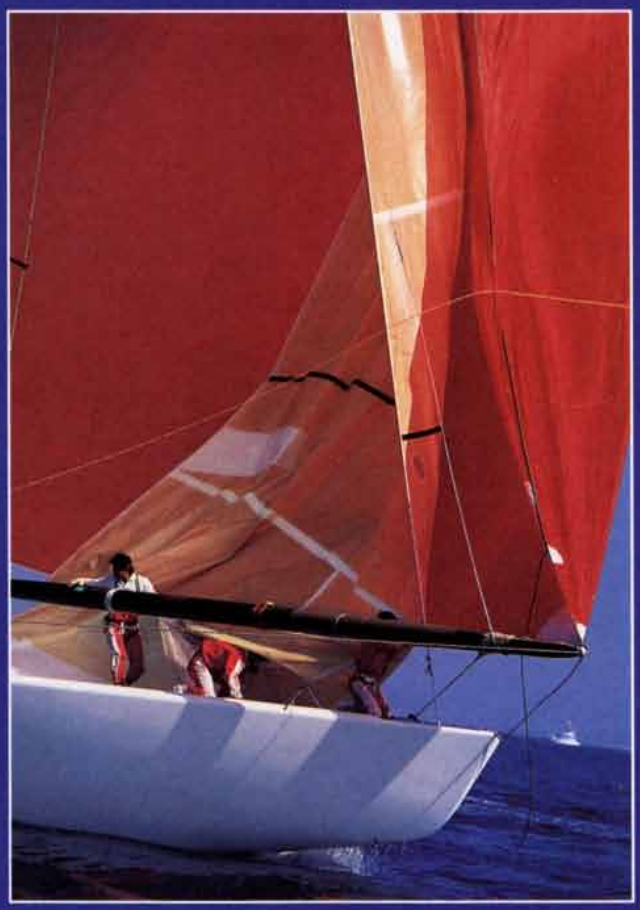
At least in terms of funding, the DOE



***ACCELERATOR-BASED TRANSMUTATION** proposal called Phoenix was developed at Brookhaven National Laboratory. An expanded beam from a linear accelerator irradiates waste stored in separate chambers. The transmuting waste heats the liquid-sodium coolant, which in turn produces high-pressure steam that drives a power-generating turbine.*

ADVERTISING SUPPLEMENT

AN ENTHUSIAST'S GUIDE TO THE TECHNOLOGY OF THE AMERICA'S CUP



BY

CHESTER KYLE & DAVID EGGLESTON

SCIENTIFIC AMERICAN

AMERICA^3 IS JUST A BOAT THE WAY CORVETTE IS JUST A CAR.

Some people dream of winning the America's Cup the way others dream of owning a Corvette. That's why Chevrolet Corvette is the "Official Car of the America^3" as it fights to defend the America's Cup.

You're looking at some of the most sophisticated technology to set sail, along with one of the most sophisticated and powerful production convertibles in the world.

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THE HEARTBEAT OF AMERICA IS WINNING.™

THE AMERICA'S CUP CAN BE VIEWED AS A COLOSSAL HIGH-TECH CONTEST IN WHICH THE BEST TECHNICAL TALENT AND RESOURCES OF EACH COMPETING COUNTRY ARE APPLIED TO A DESIGN PROBLEM WHICH IS RIGIDLY CONSTRAINED BY RULES. ALL OF THE RACE SYNDICATES EMPLOY NAVAL ARCHITECTS, SCIENTISTS, OCEAN ENGINEERS, AERODYNAMICISTS, AND OTHER EXPERTS AS PART OF THE TEAM. AS ALBERTO CALDERON, A DESIGNER FOR TEAM DENNIS CONNER, SAYS: "IT FITS VERY WELL INTO THE STANDARD MISSION ANALYSIS CONCEPT USED IN THE AEROSPACE INDUSTRY." ALL OF THE ELEMENTS ARE HERE: PERT CHARTS, BUDGETS, SCHEDULES, LOGISTICS, STRATEGY, INTELLIGENCE GATHERING, AND TACTICS; THESE GIVE MEANING TO THE WORD "CAMPAIGN" IN DESCRIBING THE PROCESS TO WIN THE CUP.

TEN SYNDICATES HAVE RACED AT LEAST ONE BOAT IN THE 1992 AMERICA'S CUP ELIMINATION SERIES. EACH IS SAILING AN ENTIRELY NEW CLASS OF YACHT CALLED THE INTERNATIONAL AMERICA'S CUP CLASS (IACC), WHICH IS LARGER, FASTER, AND LIGHTER THAN THE OLD 12-METER CLASS. TEAMS FROM AUSTRALIA (TWO SYNDICATES), FRANCE, ITALY, JAPAN, NEW ZEALAND, SPAIN, AND SWEDEN HAVE SAILED IN THE CHALLENGER ROUND ROBINS, WHILE AMERICA CUBED (AMERICA^3) AND TEAM DENNIS CONNER HAVE COMPETED IN THE DEFENDER TRIALS. THE FRENCH, ITALIAN, JAPANESE, AND NEW ZEALAND SYNDICATES ARE MOUNTING THREE OR FOUR-BOAT CAMPAIGNS. AMERICAN MULTIMILLIONAIRE BILL KOCH'S AMERICA^3 PROJECT HAS A FOUR-BOAT PROGRAM. THE SINGLE-BOAT SYNDICATES OF AUSTRALIA (TWO), SPAIN, SWEDEN, AND TEAM DENNIS CONNER ARE AT AN OBVIOUS DISADVANTAGE; THEY HAVE NOT HAD "TRIAL HORSES" TO RACE AGAINST DURING THE DEVELOPMENT STAGES.

ONCE A CHALLENGER DECLARES A BOAT, THEY CANNOT SUBSTITUTE. THEY DO, HOWEVER, HAVE THE OPTION OF CHANGING THE APPENDAGES (KEEL, BALLAST BULB, AND RUDDER) AND THE SAILS BETWEEN ROUNDS. CUP DEFENDERS, ON THE OTHER HAND, CAN SHIFT FASTER BOATS INTO THEIR ALLOTTED RACE SLOTS BETWEEN TRIALS AS WELL AS CHANGE APPENDAGES. WITH FOUR BOATS AND TWO ASSIGNED RACE SLOTS, BILL KOCH HAS TAKEN ADVANTAGE OF BOTH OPTIONS. TEAM DENNIS CONNER, WITH JUST ONE BOAT, CAN ONLY CHANGE APPENDAGES AND SAILS BETWEEN TRIALS.

DESIGNING AN AMERICA'S CUP YACHT

Somewhere within the rules, hidden in the complex region of length, sail area, displacement, and hull shape, lies an optimum boat design. The common problem of all designers is to find it. Naval architects from each team begin the search by laying out the lines of candidate hulls and using a computerized velocity prediction program (VPP) to uncover likely winning combinations.

A great deal of skill and art combines in the VPP process. Computers don't do the synthesis, but they do allow full creativity by the designer. Since the codes display instantly the effects of changing various features on the screen, computers allow naval architects to explore hundreds of combinations in a relatively short time.

Once the designers identify promising hull and keel shapes, the next step is to build scale models for testing in the tow tank and the wind tunnel. When the designers are satisfied with the results–or more commonly when time runs out–a full-scale boat is built and tested on the water. Each stage of the project leads to new ideas and improvements. Multi-boat programs have an obvious advantage in that each succeeding boat is usually faster. An important part of the design process is the interaction between the race crew and the technologists in tuning and revising each boat for maximum speed.

PHOTO: SALLY SAMINS

TEAM DENNIS CONNER'S STARS AND STRIPES, SAILING ON A REACHING LEG WITH MAINSAIL AND GENNAKER.

In 1988, the Science Applications International Corporation (SAIC) organized a high-level research program called the Partnership for America's Cup Technology (PACT), to make available the best in current technical resources to the individual U.S. syndicates. Headed by John Marshall, PACT includes such industrial giants as IBM, Boeing, and Cray Research as well as many smaller organizations.

PACT's basic research programs give American syndicates a head start in building boats to the new IACC class rules.One project was to tow tank test a systematic series of five hull models in order to measure the effect of length, beam, displacement, and shape upon wave drag. This gave the American syndicates benchmark data to update their velocity prediction programs for the new IACC class boats. Other projects were to test keel, rudder, and ballast bulb configurations in the wind tunnel and to determine the effect of sea waves on added resistance.

SAIC and Technology

The Winning Combination

Nothing surpasses the excitement of race day. Each crew member's experience, skill and strength pushed to the limit guiding a massive yacht around the race course. But the thrill of that moment is, in fact, the culmination of an intensive design effort. Since 1984, SAIC has worked hand-in-hand with U.S. America's Cup yacht designers to produce the fastest boats. Performing hydrodynamic calculations, developing race model simulation software, and applying other leading technology, SAIC has helped keep the U.S. one step ahead of its competition.

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WHAT MAKES AN AMERICA'S CUP YACHT GO FAST

Basically, fast boats must have efficient sails and low drag forces, as well as stability and maneuverability. The most time-consuming problem designers face is controlling the drag forces. Primarily, five types of drag can affect boat speed: skin friction, form drag, wave drag, the added resistance in sea waves, and induced drag. Designers control drag in ways that will result in the fastest time around the course.

Skin friction is caused by fluid viscosity which generates a shear force in the boundary layer next to the wetted surface. Up to a point, mirror-smooth, wet-sanded finishes can minimize skin friction, but they cannot eliminate it entirely.

Form drag is the result of pressure being greater on the leading edges of an object than on its trailing edges. It can be a serious problem if fluid separates from the surface, creating a low pressure region at the back of the object. Separation can usually be controlled by streamlining or by avoiding high angles of attack.

PHOTO: DANIEL FORSTER [STOCK NEWPORT]

ITALY'S IL MORO DI VENEZIA. THERE ARE 16 IN THE CREW: THE HELMSMAN, THE TACTICIAN, THE NAVIGATOR, FOUR SAIL TRIMMERS, FOUR GRINDERS AND FIVE WHO CHANGE THE SAILS.

As a boat travels through the water, waves radiate away from the hull, wasting energy. The resulting pattern of crests and troughs along the hull causes a pressure distribution which results in wave drag. For equal displacement, slender hulls have a lower wave drag than wide hulls. But IACC yachts require width to keep the boat upright as it heels under sail pressure. Subtleties in hull shape can minimize wave drag for certain speed ranges.

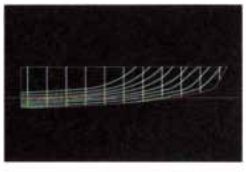
Another type of wave drag is the added resistance caused by sea waves, which is roughly proportional to the square of the wave height. Hull and bow shape can significantly minimize this type of drag. Locating the weight toward the center of the boat (lowering the polar moment of inertia) can help to minimize wave resistance. Also, light displacement boats usually have lower resistance.

The sail, keel, and rudder are designed to develop side force (lift) when traveling at an angle of attack (leeway) to the wind or water. Induced drag is a byproduct of this lift. For example, when a rudder is turned at an angle to the flow, high-pressure fluid curls around the tip, causing a vortex to spin off into the wake. This is wasted energy. Induced drag (often called vortex drag) can be lowered by using long, narrow profiles (high aspect ratios), or, to a lesser extent, by tapering the lifting surface toward the tip. Also, end plates can be effective in cutting induced drag. On a keel, a properly designed ballast bulb or winglets can have the same effect as an end plate.

When underway, the thrust force generated by the sails is exactly balanced by the drag forces on the hull and appendages. The side force on the sails is opposed by the lift forces of the keel, rudder, and hull. When beating to windward in a 12-knot breeze with a mainsail and jib, the forward thrust on an IACC yacht is about 1,200 pounds (5,300 Newtons), while the side force is 4,500 pounds (20,000 Newtons). The appendages generate lift so efficiently that the leeway is only about 2° to 3°.

Jerry Milgram, a Professor of Ocean Engineering at the Massachusetts Institute of Technology and the design director for the America^3 group, estimates that with a boat sailing upright in smooth water, about 45% of the total hydrodynamic drag is skin friction of the hull, 10% is form drag of the hull, 25% is wave making drag, and the remaining 20% is the drag of the appendages. With the boat heeled over sailing to windward, the induced drag can raise the total by about 20%. Typical waves off San Diego are from one- to two-foot wind chop superimposed on a long swell. However, occasionally the seas are much higher. The additional sea wave resistance can add from 10% to 50% or more to the overall drag.

This America's Cup series will see as many design solutions as there are boats. To the average spectator, this is most apparent in the shape of the bows. The most common shape is found in the spoon bow, used by America^3, Team Dennis Conner, and the French,



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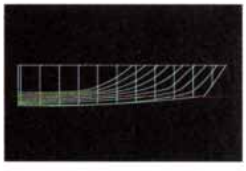

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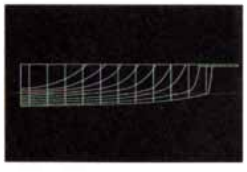


[3]

BOW TYPES

WITH ITS FRONT OVERHANG, THE SPOON BOW [1] GIVES ADDED WATERLINE LENGTH AND LOWER WAVE DRAG, WHEN THE BOAT IS HEELED OVER. SEA WAVES TEND TO GO UNDERNEATH THE BOW. A DESTROYER BOW [2] SLICES CLEANLY THROUGH SEA WAVES, BUT THE WATERLINE LENGTH REMAINS UNCHANGED WHEN HEELED OVER. THE PLUMB BOW [3], USED BY THE NEW ZEALAND CHALLENGE, IS A VARIATION OF THE DESTROYER BOW, AND HAS THE LIGHTEST STRUCTURAL WEIGHT IN COMBINATION WITH THE BOWSPRIT COMPUTER GRAPHICS: DAVID PEDRICK YACHT DESIGNS

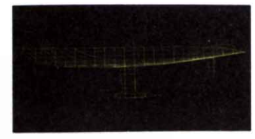
Italian, Japanese and Spanish syndicates. This bow has an overhang above the water: when hitting sea waves, the waves tend to go underneath the bow. When the boat heels over, the overhang rolls into the water, producing a longer effective waterline length. Since longer hulls have lower wave drag, they have an advantage when sailing upwind.

Another solution is the destroyer bow found on both Australian boats and the Swedish syndicate's yacht. This system has no overhang above the water and the sharply raked prow neatly slices through sea waves. The waterline length does not change when the boat heels over. A variant of the destroyer bow is the unique design of the New Zealand Challenge; the plumb bow. This bow comes nearly straight out of the water, and probably has the lowest structural weight of any of the bow types.

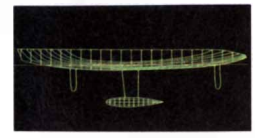
Keel and rudder designs also vary. The common solution seems to be a thin symmetric wing-shaped keel with a trailing edge flap and a rear rudder. The flap provides lift with less drag when the boat sails to windward. When the flap is trimmed at an angle, it simulates a cambered airfoil, which is a more efficient lifting surface than a plain symmetric airfoil. This design permits the boat to sail with less leeway, limiting the induced drag on the hull and also improving the sail efficiency. When sailing to windward, the rudder also produces significant lift by being turned about 2° into the flow. The rules permit only two moveable control surfaces, and the rudder and the keel flap satisfy this requirement.

Another arrangement calls for twin rudders, one in front (a Canard rudder) and one behind. The Japanese syndicate has experimented with the Canard rudder. Fore and aft rudders may have the advantage of a high lift-to-drag ratio and faster turning. However, control could be a problem.

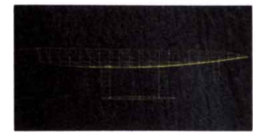
A third scheme, found in Spirit of Australia, the New Zealand Challenge, and in Team Dennis Conner, uses twin keels to support the ballast bulb. The front keel pivots, and a flap on the rear keel also rotates. This allows the two control surfaces to be used for either turning or to develop side force. Apparently, however, both Spirit of Australia and Team Dennis Conner removed the twin keels when they proved to be a slower solution in the typical San Diego sailing conditions. The New Zealand boat probably still uses twin keels. ⚓



[1] KEEL WITH TRIM FLAP AND REAR RUDDER - TRE KRONER [SWEDEN]



[2] CANARD RUDDER - NIPPON CHALLENGE [JAPAN]



[3] TWIN KEEL - NEW ZEALAND CHALLENGE

KEEL TYPES

THE RULES ALLOW TWO CONTROL SURFACES. MOST OF THE BOATS HAVE USED OPTION [1] A KEEL WITH A TRIM FLAP PLUS A REAR RUDDER. RUDDERS ARE USED BOTH FOR TURNING AND TO DEVELOP SIDE FORCE. THE CANARD RUDDER [2] WOULD BE ESPECIALLY EFFICIENT FOR BOTH PURPOSES. THE FORWARD STRUT OF THE TWIN KEEL [3] ROTATES AS DOES THE FLAP ON THE REAR STRUT. ANOTHER OPTION [DEPICTED IN 3] INCLUDES A RUDDER AND TWO STRUTS, ONE OF WHICH IS MOVABLE. COMPUTER GRAPHICS: JIM GRETZKY, GRETZKY & ASSOCIATES; GEORGE HAZEN, DESIGN SYSTEMS.

TOW TANK TESTING

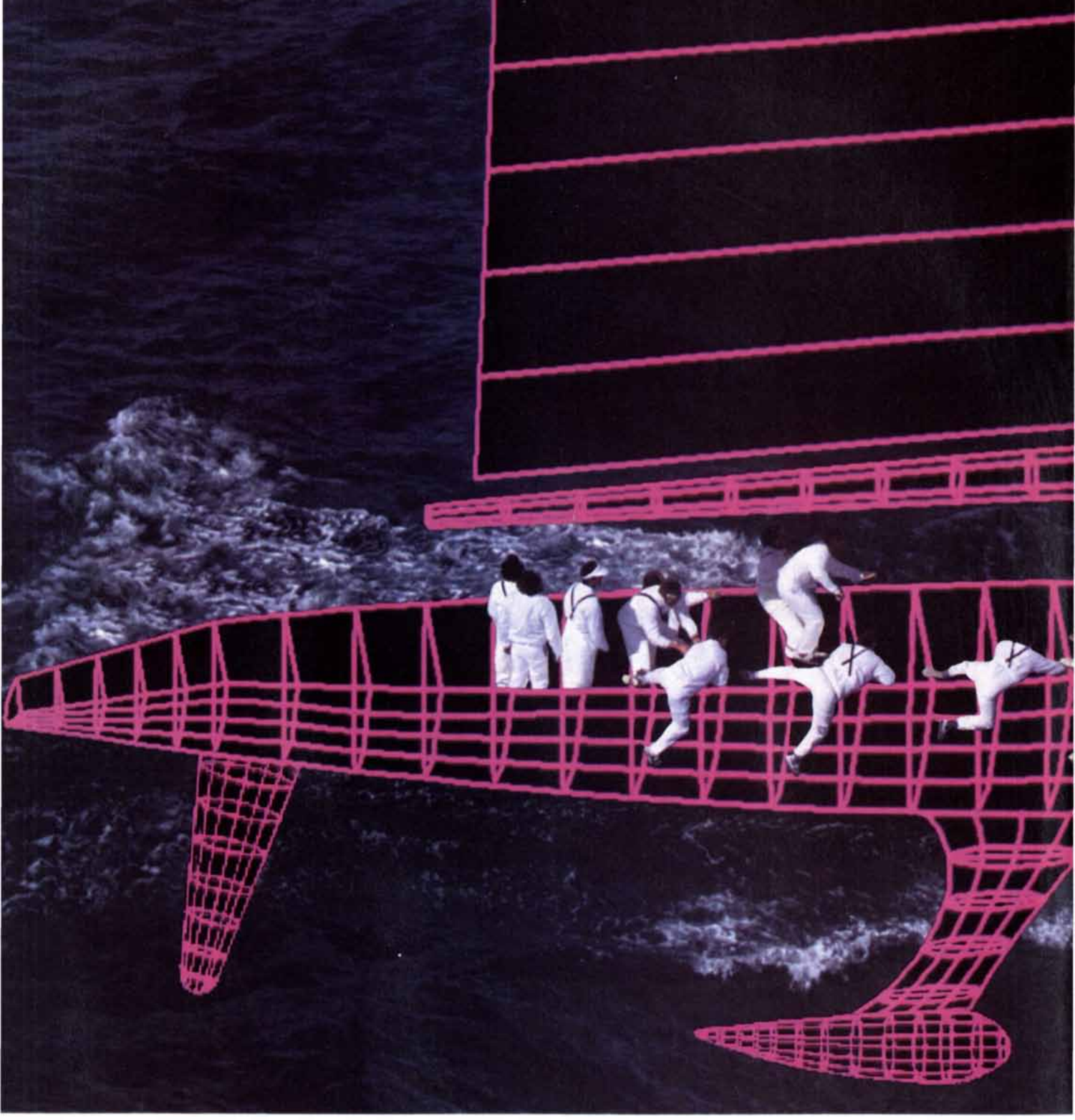
Tow tank tests are costly, but they can be an extremely accurate predictor of full-scale yacht performance. Because of the high cost of tow tank testing, some syndicates run only a few models. Dennis Conner's group has studied seven models in the ARCTEC facility near Escondido, California, while Bill Koch's America^3 group has tested more than 50 at Hydronautics Research near Fulton, Maryland. The teams from New Zealand, Italy, and Japan have run dozens of models during their development program.

The typical tow tank is between 8- and 15-meters wide, about 5-meters deep, and 90-meters long. Although most of the testing is done in smooth water, the tanks have computer controlled wave generators to simulate actual sea conditions. A rolling bridge carriage, which spans the tank, is used to tow the model. Force and velocity data is fed to computer terminals for analysis.

Naval Architect Karl Kirkman, who is a consultant to the tow tank testing program for the America^3 group and for PACT, has shown that the reliability of tank tests in predicting full-scale performance improves as the model size increases. The typical size of IACC models is 1/3.5 scale, or about 6 meters long. The repeatability of tank tests is excellent—from 0.5% to 1%, if tests run consecutively. However, if the model is removed and later retested, the accuracy is about ±1.5%. It so happens that the difference between first and second place finishes in the two-and-a-half hour race is only one to two minutes—or about the same 1.5% differential found in measurements. Since any errors in measurement can hide speed potential, high precision is required in the test procedures.

In the standard U.S. testing method, boat models are bolted to a force dynamometer which fixes the heel (roll angle) and yaw (leeway angle), while leaving the boat free to pitch (rock) and heave (move up and down). The dynamometer measures the drag and side forces as well as the dynamic heel and the yaw moments (torques). The models are ballasted to have the same static water line and center of gravity as the full-scale boat. Adjustable weights apply a pitching moment to account for the sail force.

The models are then towed through a wide range of speeds, equivalent to 3 to 13 knots full scale, heel



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The Rules of the Cup

In 1989, an international committee drafted rules that created an entirely new class of mono-hulled displacement yachts. They are longer, lighter, and faster than the previous 12-meter class that raced from 1958 to 1987. The complex new International America's Cup Class (IACC) rules cover almost 200 pages. They establish design boundaries for length, displacement, draft, beam, sail area, and hull shape.

The basic yacht dimensions are governed by a formula that balances the rated length (L) in meters, rated sail area (S) in square meters, and the displacement (DSP) in cubic meters:

$$(L + 1.25S^{1/2} - 9.80DSP^{1/3})/0.388 <= 42$$

All changes in the basic dimensions are trade-offs. If you pick up speed by increasing sail area, for example, you must pay for it by decreasing length or increasing displacement, both of which slow the boat.

There are penalties for exceeding limits in freeboard, draft (maximum 4 meters), weight (minimum 16,000 kg, maximum 25,000 kg), and beam (5.5 meters maximum). Rated lengths higher than about 22 meters become prohibitive because of a "mathematical closing function" in the rules. A similar closing function limits the rated mainsail and foresail area to about 300 square meters.

The overall effect of the rating formulas, plus other rules, has been to produce boats that look remarkably alike to the casual observer. However subtle variations in design produce significant differences in speed.

Quite different boats can satisfy the formula. A short, light boat [right] similar to the New Zealand Challenge, has a rated length (L) of 20.95m, a rated sail area (S) of 277.3m^2, and a weight (W) of 18,000kg (DSP=17.56m^3). A long, heavy boat, similar to Challenge Australia, has L=21.87m, S=311.78m^2 and W=23,000kg (DSP=22.44m^3). Computer graphic: Jim Gretzky; George Hazen Design Systems.

Dimensions of America's Cup Yachts

Yacht	Year	Boat Class/Type	Overall Length Meters	Water Line Length Meters	Sail Area m^2	Mast Height Meters	Beam Meters	Draft Meters	Weight Kg
America	1851	Schooner	31.01	27.4	523	29	6.96	3.34	120,000
Reliance	1903	Gaff Sloop	43.8	27.4	1,501	54	7.87	5.97	158,800
Ranger	1937	J Boat Sloop	41.2	26.52	701	47	6.40	4.57	150,600
Australia II†	1983	12 m Sloop	19.23	13.41	172	25	3.95	2.68	25,500
KZ1*	1988	Open Sloop	40.47	27.34	1,600	47	7.95	6.4	38,000
IACC	1992	IACC Sloop	23	17	300	32.5	5.5	4.0	20,000

† Typical dimensions of 12-meter boats. * When the challenger and defender could not agree upon rules, Michael Fay's 1988 Challenger from New Zealand was soundly beaten by Dennis Conner's 18 meter Catamaran. Fay's huge boat was the biggest to race since 1903.

angles from 0° to 30°, and yaw angles from 0° to 6°. It takes from 100 to 300 runs to define the performance of a model, depending upon the goal of the tests. Wave drag is estimated in two ways. First, wave probes on the side of the tow tank measure the energy of the radiated waves. This figure can be low if wave energy is dissipated in a breaking bow wave or spray. Second, empirical methods have been developed to compute the combined skin friction and form drag of the model. When subtracted from the total measured drag, this gives the wave drag. Tank data can then be accurately scaled up to full size.

By entering the matrix of yacht performance coefficients into the velocity prediction program (VPP) and the race modeling program (RMP), the boat can be compared with other candidate designs. The tow tank information is also used to benchmark the computational fluid dynamics (CFD) computer codes. Once the CFD computations have been calibrated with experimental data, computer optimization can be a powerful tool to refine hull and appendage shapes far more economically than by multiple model testing. Computer solutions, however, are usually verified in the tow tank before full-scale boats are built.

PHOTO: SALLY SAMINS

A 1/3.5 scale model, 6 meters long, being tested while heeled over with leeway, in the ARCTEC tow tank, Escondido, California.

Smaller (often 1/8 to 1/5.5 scale) models are used for another type of tow tank testing, called seakeeping, which is the study of the added resistance in sea waves. PACT has conducted extensive experiments at the University of Michigan in an effort to develop a computer code that would reliably predict the added resistance in waves on typical IACC hull shapes. The boats are tested moving upright into a wave train, and also heeled and yawed. Computer generated waves can give a repeatable spectrum of wave lengths and heights.

These tow tank tests are extremely time consuming since repeated encounters with the same wave train are necessary to achieve statistical validity. It takes perhaps one week to measure one model. Methods have been developed to precisely measure wave height, velocity, and force with experimental results repeatable to better than ±1%. ⚓

WIND TUNNEL TESTING

Although tow tank testing can accurately measure a boat's wave drag, it can't determine the viscous drag, since the correct scale velocity for wave drag is too low to simulate viscous friction. Therefore the appendages, rudders, keels, and ballast bulbs are usually measured in a wind tunnel where higher scale velocities are attainable.

Engineer Ed Tinoco of Boeing has tested 13 keel and ballast bulb combinations for PACT in the University of Washington wind tunnel. Wind speeds of about 160 mph were used to simulate as closely as possible a real yacht sailing in water. Yaw angles up to 8° were used. The same 1/3.5 scale appendage models as those built for the tow tank were tested in the wind tunnel. Wake surveys were taken to detect irregularities in the flow. Flow proved to be smooth and without separation, up to about 4° of yaw—typical of the maximum leeway angles in IACC yachts. Using computer systems donated to PACT by IBM, Boeing applied mathematical modeling to generate pressure and velocity distributions on the appendages.

At the huge General Motors wind tunnel in Warren, Michigan, Team Dennis Conner tested eight ballast bulb and winglet combinations. When a boat is sailing heeled over upwind, the wetted surface below the waterline is highly asymmetric. To simulate the presence of the hull and the sea surface, two mirror-image hull, keel, and rudder combinations were constructed. They were mounted back to back on the balance, simulating the presence of the water surface, and the asymmetric wetted hull. The combined drag and lift of the subsurface package was measured at various yaw and rudder angles.

Typically, keels for IACC yachts are slender, symmetric airfoils with ballast bulbs that resemble flattened torpedos with beaver tails. The purpose of the "squashed" shape is twofold: to put the weight down low and to decrease the induced drag of the keel-ballast combination when sailing upwind at a leeway angle. The keel and ballast bulbs were also tested with winglets (the winged keel), but neither Boeing nor GM is saying whether they provide an advantage.

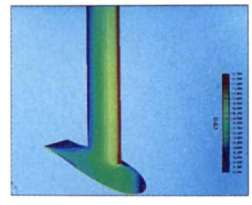
The purpose of a winged keel is to increase the effective draft when the boat is heeled over, and to help control tip vortex shedding from the keel and thus decrease the induced drag.

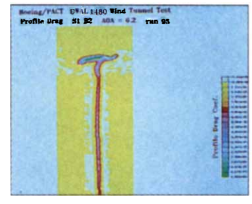
However, with the deeper draft of IACC yachts, winglets may prove to be a liability. When sailing downwind, a winged keel adds parasitic drag because of the increased wetted surface. So the lost speed must be made up on the windward legs. The span of the winglets can be adjusted to suit the expected conditions. As with every other design option, one must weigh the advantages of any solutions against the disadvantages. ⚓

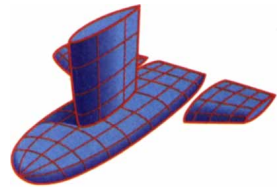
SAIL DESIGN

Today's main and head sails are primarily made from Kevlar laminated to a thin Mylar film. Kevlar sails are strong, light, air-tight and stretch much less than sails made of more conventional fabrics.

Since sails are basically airfoils, the shape is critical. The process of designing a sail that has the right flying shape starts at a computer terminal. Michael Richelsen, who has a Ph.D. in Solid Mechanics from the Technical University of Denmark, developed the modern sail design program used by North Sails Inc. North Sails has more than 50 sail lofts worldwide and makes most of the sails for the America's Cup yachts. The first step in Richelsen's design method is to specify what the flying shape of the sail should be. This shape is geometrically defined with a computer program called "Mold." The coordinates are input into a CFD numerical program called "Flow," which computes the air velocity and the pressure distribution over the sail. A third computer program, called "Membrane," uses finite element analysis and the aerodynamic loading from Flow to compute the stretch (strain distribution) of the sail using various fabric types and panel layouts. The fabric panels are oriented along the directions of principal stress in the sail. A constant strain distribution is desirable to produce a smooth sail without wrinkles.



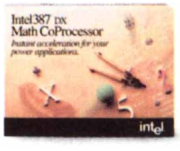




WIND TUNNEL TESTING OF KEELS AND WINGLETS

PHOTO [TOP] IS AN IACC KEEL AND BALLAST BULB IN THE UNIVERSITY OF WASHINGTON WIND TUNNEL. THE ARM BEHIND THE BALLAST BULB SURVEYS WAKE VELOCITY. THE SECOND PHOTO SHOWS THE RESULT OF A BOEING COMPUTER SOLUTION OF PRESSURE DISTRIBUTION ON THE KEEL AND BALLAST BULB AT A 6° ANGLE OF ATTACK. LIGHTER COLORS ARE HIGHER PRESSURE. THE VELOCITY IN THE WAKE BEHIND THE KEEL AND BALLAST BULB [THIRD PHOTO] IS SHOWN AT THE SAME ANGLE OF ATTACK FLOW IS FAIRLY REGULAR WITH LITTLE SEPARATION. WINGLETS [BOTTOM], INCREASE THE EFFECTIVE DRAFT WHEN THE BOAT IS HEELED OVER. HOWEVER, WHEN SAILING UPRIGHT, THEIR WETTED SURFACE AREA INCREASES THE DRAG SIGNIFICANTLY IN STRONG WINDS, THEY BECOME MORE EFFECTIVE, SINCE HEEL ANGLES ARE LARGE.

It takes lots of screaming fans



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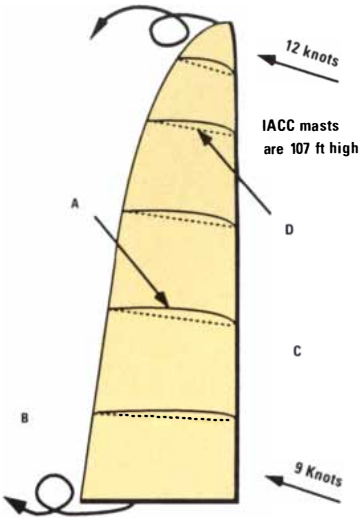


SAIL PERFORMANCE

A. THE CURVATURE OF AN IACC MAINSAIL IS CONTROLLED BY FLEXIBLE BATTENS. THE ELLIPTICAL SAIL SHAPE APPROXIMATES THAT OF AN AIRCRAFT WING. BATTEN STIFFNESS CAN BE CHANGED TO MATCH THE EXPECTED WIND SPEED.

B. INDUCED DRAG - AIR "LEAKS" FROM THE HIGH PRESSURE SIDE TO THE LOW PRESSURE SIDE, CAUSING VORTEX FLOW AT THE FOOT AND TOP. TO MINIMIZE THIS INDUCED DRAG, THE SAIL IS FLATTENED AT THE FOOT TO DECREASE THE LIFT. TOWARD THE TOP, THE SAIL IS MADE AS DEEP AS PRACTICAL TO MAXIMIZE THE LIFT WHERE THE AIR VELOCITY IS GREATEST.

C. TRUE WIND SPEED INCREASES FROM THE SEA SURFACE TO THE TOP OF THE MAST BY AS MUCH AS 60%.

D. THE CHORD LINE OF THE SAIL PROGRESSIVELY TWISTS TOWARD THE TOP TO MATCH THE CHANGING DIRECTION OF APPARENT WIND VELOCITY.

Since the shape of the sail changes under stress, the original mold shape is then adjusted by iteration until the final flying shape is correct. A computer operated laser then cuts the fabric panels and the sail is sewn and finished. Even with computer design, sails still must be tried and refined on the water. All of the America's Cup syndicates have their own sail lofts, where sails can be recut, adjusted, or repaired overnight.

Actually, most of what is known about efficient sail shapes has been gathered from race experience and from testing one sail against another on the water. Unfortunately, wind tunnels aren't of much use in testing sails. The wind speed at the top of the mast can be more than 60% greater than the speed at deck height. With the height variation in wind speed, the sail must twist progressively toward the top in order to match the apparent wind direction, and this twist cannot be reproduced in the wind tunnel.

Since velocities are greater at the top, the camber (depth and curvature) of the sail has to differ at each elevation to optimize the lift. Two other effects are unique to sailboats. As the boat heels over, sail efficiency drops because less sail area is exposed to the wind. And, as the boat pitches, the rocking of the mast disturbs the airflow over the sails which can also decrease lift efficiency. Spinnakers can blow out because of the transient aerodynamic shocks caused by a pitching boat.

By comparing numerical models and VPPs with actual sail performance, sailmakers have a good idea of what depth and curvature each part of a sail should have at a given wind speed and point of sail. Jerry Milgram used a 41% scale sailing boat at MIT to test IACC sails. An isolated mast and a sail dynamometer measure the six components of force and moments on the sails. Milgram reports that his data has led to substantial improvement in the predictive accuracy of the America^3 group's numerical sail models.

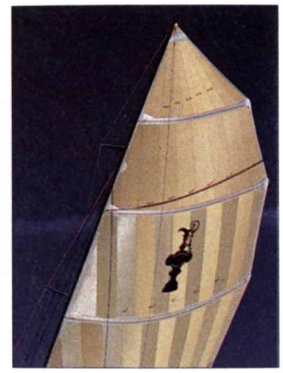
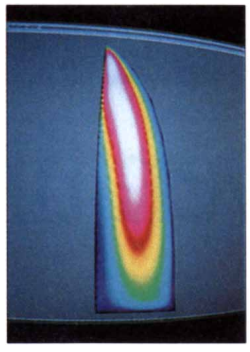


PHOTO: IL MORO DI VENEZIA

A KEVLAR MAINSAIL WITH RADIAL FABRIC PANELS THAT FOLLOW THE PRINCIPAL LINES OF STRESS. THE FABRIC WEIGHT IS HIGHEST AT THE TIPS, AND DECREASES TOWARD THE CENTER AND FROM THE OUTER EDGE [LEACH] TOWARD THE MAST.

In order to minimize induced drag resulting from leakage under the sail, the depth and curvature of the bottom of the sail normally is fairly flat, and the depth progressively increases toward the top as does the twist. The shape of the mainsail is controlled by battens of variable stiffness. The shape of the sail can be further adjusted by bending the mast, or by adjusting the tension in the rigging.

To take the guess work out of sail trimming, in 1987 scientists at the New Zealand Department of Scientific and Industrial Research (DSIR) designed a system called "Sail Spy" for the New Zealand Challenge. The system's four miniature TV cameras on top of the mast view four horizontal stripes on each sail. Using machine vision technology, the cameras detect the sail stripes as well as markers along the centerline of the deck and then digitize the information. A computer reads out the camber and twist of the sails. The crew can then test or repeat any sail shape at will. Nearly all of the America's Cup syndicates have developed their own television systems for monitoring the sails. ⚓



SAIL DESIGN

THE FIRST PHOTO [LEFT] SHOWS THE COMPUTED PRESSURE DISTRIBUTION ON AN IACC MAINSAIL, WITH WHITE BEING HIGH PRESSURE AND BLUE LOW. THE MIDDLE PHOTO IS THE STRESS DISTRIBUTION IN THE SAIL, WITH WHITE EQUALING AREAS OF HIGH STRESS. THE STRETCH [STRAIN] OF THE SAIL IS SHOWN AT RIGHT, WITH WHITE BEING AREAS OF HIGH STRAIN. IN ORDER TO MAKE A SMOOTH SAIL, FABRIC TYPE AND LAYOUT MUST BE CHOSEN TO EQUALLY DISTRIBUTE STRAIN. THE PHOTOS ARE THE RESULT OF COMPUTER SOLUTIONS BY MICHAEL RICHELSEN OF NORTH SAILS, INC.

MATHEMATICAL MODELING

Mathematical modeling plays an increasingly important role in any America's Cup campaign. Winning without the use of computers would be unthinkable. Some principal ways math-modeling is used include:

• Velocity Prediction Programs (VPPs). Using the lines of a candidate hull plus other performance data such as sail lift coefficients, these programs predict the sailing speed of a boat at a given wind velocity and heading. VPPs are the basic tool of yacht designers in optimizing candidate hull and appendage designs. These programs are coupled with:

• Race Modeling Programs (RMPs). Candidate yachts can be sailed against each other on a simulated course under various wind and sea state conditions to compare times around the course. As new data is collected from match races, new sail designs, or new appendage designs, the VPP and RMP codes are updated. These programs thus become ever more accurate and useful.

• Computational Fluid Dynamics (CFD). Computer codes calculate the pressure and velocity distributions, forces, and moments, lift, and induced drag on sails, hulls, keels, rudders, and ballast packages from input geometry information. Because these methods must solve thousands of simultaneous equations, they often require super computers. But most programs will run on computer workstations such as the IBM RISC6000 which Boeing uses for its wind tunnel studies. CFD codes have also been successfully used to compute wave making drag and the added resistance in waves.

• Computer Aided Design (CAD). Finite element programs solve for the stresses, deflections, and vibrations of the hull, mast, boom, fittings, rigging, and other structures in order to achieve minimum weight with adequate strength. CAD is also used to compute the stretch of sails.

• Experimental Design. In tow tank and wind tunnel testing, General Motors mathematicians have formulated optimization programs for Team Dennis Conner to specify how best to use a small number of experiments to gain desired information. They have also applied regression techniques to aid designers in quickly locating promising hull shapes.

• Dynamic Modeling Program. The dynamics of a yacht in tacking, rounding marks, etc. can affect race strategy. For example, a boat that turns and accelerates slowly would be reluctant to engage in tacking duels. This program can suggest proper strategy.

• On-Board Instrumentation. Information from instruments which give boat speed, direction, apparent wind speed, and heel angle, is used to compute the true wind speed and direction, and the velocity made good (the boat must choose a course that produces the fastest progress toward the mark). The target boat speed from the VPP is usually displayed for comparison. Roberto Biscontini, who developed the VPP program for the Italian syndicate's boat, combines on-board instrumentation with on-shore analysis. "Besides the real-time computer displays for the crew, we have a 'black box' on board which records the instrument readings during a race," Biscontini says. ⚓

No other sporting event, except perhaps Formula I auto racing, brings such enormous scientific and technological resources to bear in producing the equipment for the event. The America's Cup is unique in another very special way. It is a sport where some of the world's smallest nations can compete on an equal footing with the scientific skills of industrial giants such as the United States and Japan. Not only compete, but perhaps win. ⚓

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FRANK DVORAK, BRIAN MASKEW - AMI

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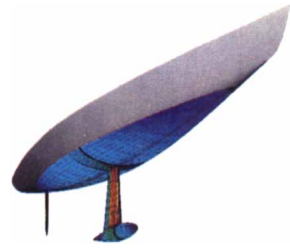

A BOEING COMPUTATIONAL FLUID DYNAMICS PROGRAM WAS USED TO COMPUTE THE PRESSURE AND VELOCITY DISTRIBUTION ON THE HULL AND APPENDAGES [ABOVE]. THE METHOD SIMULATES IDEAL FLUID FLOW BY DIVIDING THE HULL INTO A LATTICE OF SMALL PANELS AND DISTRIBUTING FLUID ELEMENTS CALLED SOURCES, SINKS, DOUBLETS AND VORTICES AMONG THE PANELS. THE COMPUTER CODE MUST SOLVE THOUSANDS OF COMPLEX SIMULTANEOUS EQUATIONS TO CALCULATE THE FORCES AND MOMENTS ON THE HULL. THE EFFECTS OF SURFACE WAVES, TURBULENCE AND FLUID SEPARATION, HOWEVER, ARE TOO COMPLEX FOR AN EXACT COMPUTER ANALYSIS, SO TOW TANK AND WIND TUNNEL DATA ARE USED TO IMPROVE THE ACCURACY OF COMPUTER MODELING.

PHOTO: SALLY SAMINS

THE FRENCH CHALLENGER, VILLE DE PARIS, ON A DOWNWIND RUN WITH SPINNAKER AND MAINSAIL.

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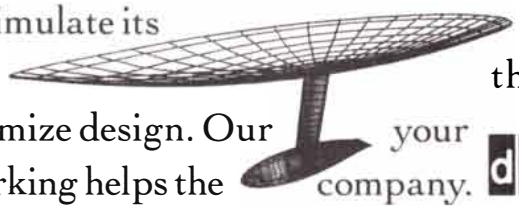

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DIGITAL. THE OPEN ADVANTAGE.

has so far favored reactor-based transmutation. The department allocated more than $100 million to the IFR and related programs this year, while giving only $2 million to Los Alamos and nothing to Brookhaven. Yet Chang, head of the Argonne program, takes pains to distance himself from transmutation. The IFR's primary purpose, he emphasizes, is to be a prototype for a future generation of commercial power reactors. Only $3 million of the IFR budget is specifically earmarked for transmutation, he says.

Transmutation is just a possible "spin-off," Chang says. He suggests some researchers have gone too far in implying that transmutation "can solve all our waste problems." "I don't blame them for trying to get attention," he says, "but they hurt the credibility of the other programs."

Indeed, transmutation involves much more than simply bombarding the radioactive waste. Before it is placed in an accelerator, the waste must undergo laborious chemical processing at various stages, primarily to separate elements requiring different treatment. Thomas H. Pigford of the University of California at Berkeley has calculated that such processing could multiply the total volume of radioactive waste—including low-level wastes—by a factor of 10.

John A. Rawlins of the Westinghouse Hanford Company in Richland, Wash., notes that all transmutation schemes require reprocessing, a technique in which plutonium and other heavy elements are separated from the other wastes for recycling (as in the IFR). In the 1970s, Rawlins points out, the U.S. abandoned reprocessing of commercial fuel and tried to discourage the practice elsewhere in order to forestall the proliferation of weapons-grade nuclear fuel.

A number of other countries still reprocess their spent fuel, and some, notably France, Japan and the former Soviet Union, are studying the feasibility of transmutation. But the U.K., which also reprocesses fuel, has pointedly rejected transmutation. At a meeting of the National Research Council in January, Charles Tanner of British Nuclear Fuels said his country had "the confident expectation that the real costs of this option will prove to be insupportable."

Those at the meeting heard an equally negative assessment from Lawrence D. Ramspott of the Lawrence Livermore National Laboratory, who recently completed a study of transmutation for the Department of Energy. Eliminating all the fuel from the current generation of nuclear reactors through transmutation could cost $84 billion, according to Ramspott; the current projected cost of a high-level repository is about a third that amount. A commitment to transmutation only makes sense, he notes, if the U.S. also commits itself to nuclear power for the long term—indeed, for centuries to come. "The bottom line was, we don't feel transmutation is justified as a waste-management option," Ramspott says.

The Department of Energy has deferred a decision on whether to commit more funds to research on transmutation by asking a panel of the National Research Council to study the issue. The panel, which is headed by Norman C. Rasmussen of the Massachusetts Institute of Technology and includes Pigford, may well deal a death blow to transmutation when it delivers its final report in 1994. One thing is clear: whatever transmutation turns radwaste into, it won't be gold. *—John Horgan*

Japan, Cold Fusion and Lyndon LaRouche

Is Japan, already perhaps the world's dominant technological power, now poised to seize control of what is potentially the most revolutionary energy technology in the history of the world? If U.S. proponents of so-called cold fusion, otherwise known as fusion-in-a-bottle, are to be believed, the answer is a resounding yes.

Cold fusion has been dismissed as "pathological science" by the vast majority of scientists since it was proposed three years ago by chemists B. Stanley Pons and Martin Fleischmann. But the undeniably attractive idea of limitless energy from batterylike cells still has its believers. To regain respectability—and, even more important, funding—proponents are raising the familiar specter of Japan. "The fact that Japanese scientists are interested in cold fusion is well known," Fleischmann says when contacted at his home near Salisbury, England. "The fact that Americans are not is also well known. The question is, what will be the consequence of that?"

On paper, the Japanese effort in cold fusion does sound impressive. It involves some 100 Japanese scientists from 40 academic and industrial institutions, according to physicist Hideo Ikegami, one of Japan's leading cold fusion proponents. Most of these workers are expected to attend the Third International Conference on Cold Fusion in Nagoya in October, which Ikegami is organizing. (The first two conferences were held in Utah and Italy.) In addition, a Japanese company is reportedly sponsoring research by Pons and Fleischmann in a laboratory near Nice, France.

But just how substantial is the Japanese commitment to cold fusion? In a memo to an American journalist in February, Ikegami declined to estimate the total financial support for cold fusion in Japan, saying, "Money is not important here." He acknowledged that cold fusion is not considered "proper" science by most Japanese scientists. Indeed, Ikegami's own employer, the National Institute for Fusion Science in Nagoya, "has never supported and will not support research into cold fusion," he said.

Like their American counterparts, Japanese cold fusion researchers periodically announce astonishing results. Akito Takahashi of Osaka University recently claimed he had generated huge amounts of excess power from an apparatus similar to the one originally used by Pons and Fleischmann—two palladium electrodes immersed in heavy water. Yet Takahashi's results remain unreproduced by other researchers and unpublished in a peer-reviewed journal.

What about the Japanese sponsorship of Pons and Fleischmann? Some American cold fusion advocates have claimed that the mysterious sponsor is Toyota, the auto manufacturer. But a spokesperson for Toyota flatly denies the company is supporting Pons and Fleischmann or any other cold fusion researchers. Fujio Nakano, a journalist who has written articles that look warmly on cold fusion, has identified the secret benefactor as Technova, Inc., which he says is a Tokyo-based think tank.

Fleischmann, when pressed, reluctantly confirms that he and Pons are indeed supported by Technova. Although he declines to reveal details about his work, he does note that "good information" on cold fusion can be found in *21st Century Science & Technology,* a journal published by followers of Lyndon H. LaRouche. LaRouche, who is now simultaneously running for president and serving a 15-year sentence for fraud, has previously claimed the existence of an international drug cartel run by the Queen of England. *—John Horgan*

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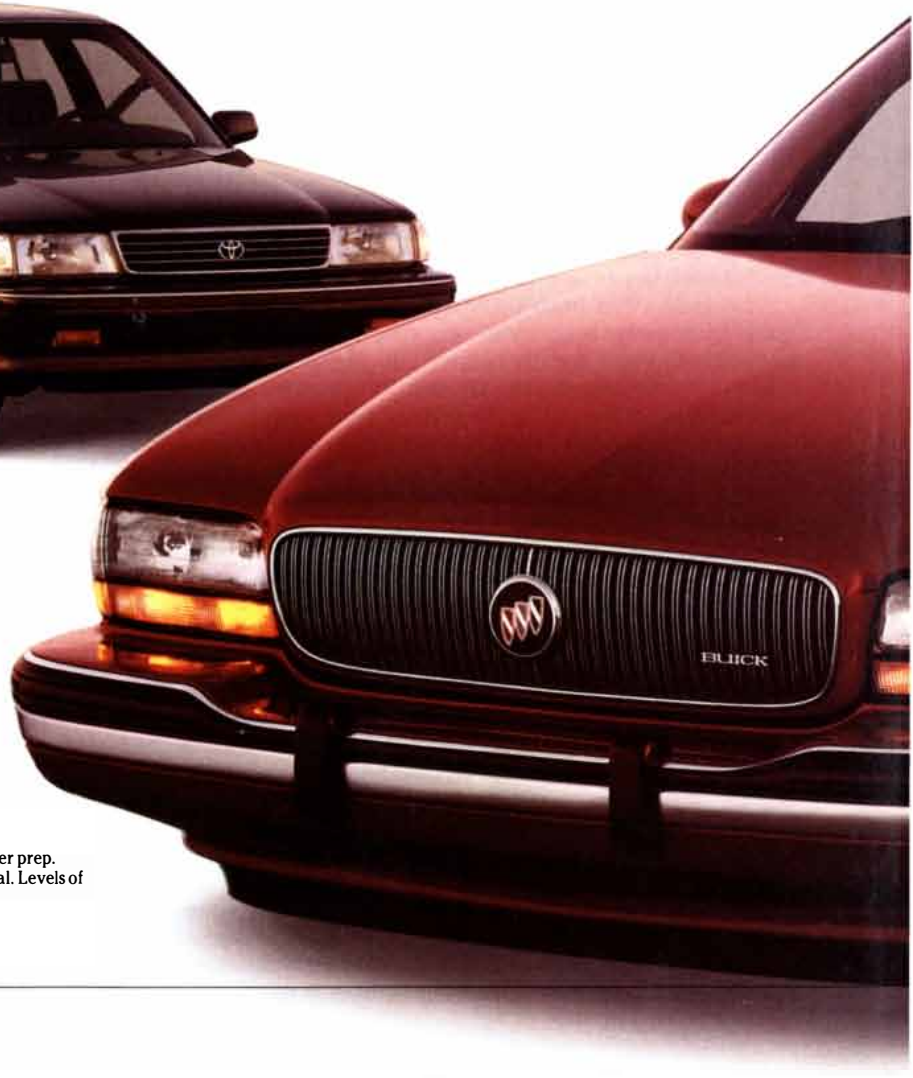

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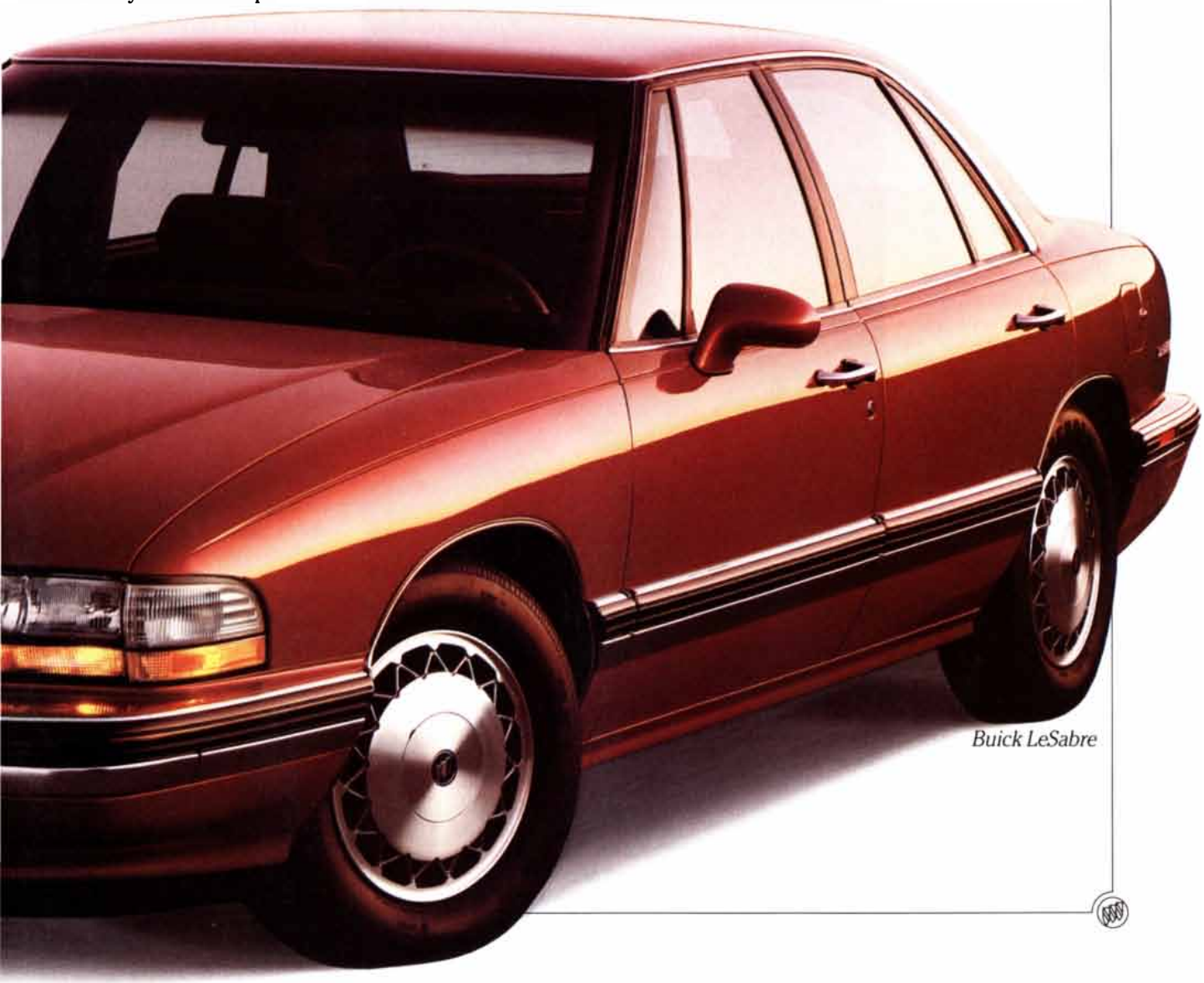


Buick LeSabre

The Builder of Bridges

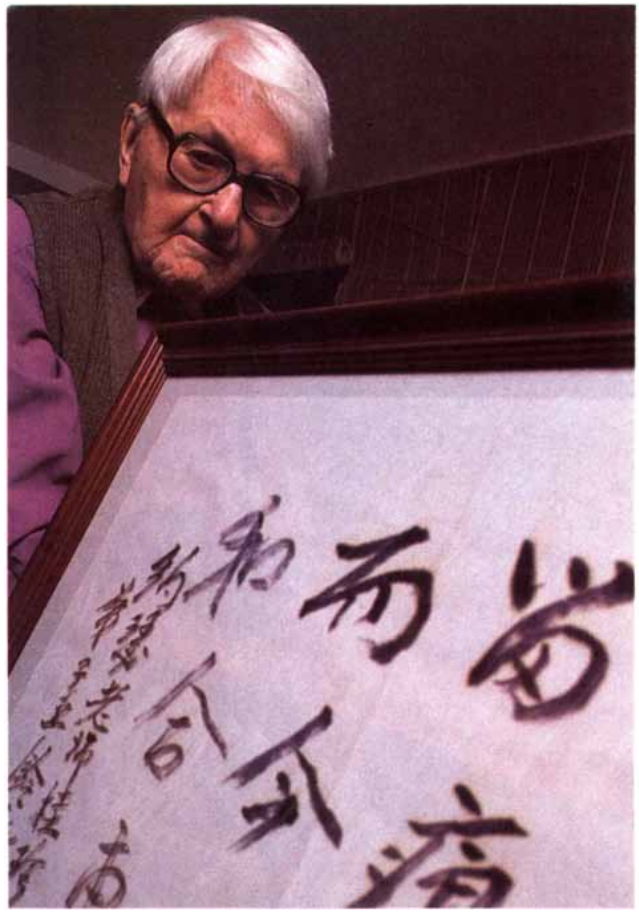
Whether it is the smallest detail of his circuitous route through China during World War II, his reaction in 1917 to news of the Russian Revolution, or the intricacies of a chemical crucial to embryonic development, Joseph Needham recalls each with clarity. A favorite limerick is no exception: "There was an old monk of Siberia / whose existence became drearier and drearier. / With a hell of a yell / he escaped from his cell / and he left with the Mother Superior," recites Needham, whose blue eyes, often downcast as he seems to peer into the past, can suddenly pin a listener with hawklike precision. "Rather nice that one."

Now 91 years of age and slowed only by arthritis, Needham devotes his time to completing his magnum opus, *Science and Civilisation in China.* The series, which won him the reputation as one of the century's greatest scholars, began as a slim work in the late 1930s. When finished, its seven volumes will fill some 25 tomes.

From the outset, Needham's pioneering research delineated the extensive scientific achievements of the Chinese at a time when few in the West, and few in China, for that matter, were aware of them. Needham has described his monumental effort as a "quasi-religious vocation, that of rendering justice at last, as well as sympathy and understanding, to a great people whose contributions to human development have been grotesquely underrated."

"Do come over and look at this," Needham urges, pointing to an illustration in one of the volumes. His long, tapering fingers trace the essential form of a steam engine, from 14th-century China. The diagram depicts a waterwheel that turns a crank and rod. The reciprocating rod moves a piston that powers the bellows for a furnace. About 400 years later James Pickard's patent on a steam engine incorporated the same mechanism, albeit in reverse: the piston turned a wheel. The design was considered purely Western until Needham published this volume in 1965.

Science and Civilisation in China is only one of Needham's achievements. The shelves of the library at the Needham Research Institute in Cambridge, England, are lined with books penned by the polymath on topics ranging from biochemistry, religion, politics and the history of science to English folk dancing, a favorite pastime. In the course of his career, Needham has embraced East, West, science, religion and socialism.



HISTORIAN Joseph Needham says Chinese science was "grotesquely underrated." Photo: David Levenson/Black Star.

The ability to unify seemingly disparate ideas began early for Needham. He was born in 1900 to feuding parents and has described his childhood as spent "ferrying between two pieces of land separated by an arm of the sea." His father, a physician, instilled in Needham a love of science as well as an Anglican religious heritage; his mother, a musician and composer, gave him what he calls a largeness of spirit.

To Needham, there is no contradiction in being devoutly religious and rigorously scientific. The work of Oxford scholar R. G. Collingwood convinced him of the five forms of human experience: religion, science, history, philosophy and aesthetics. "If you are tone deaf to one of them, you are in trouble," Needham says. "I don't think there is any necessity to reconcile them."

His ideas about socialism developed early as well. As a boy, the works of H. G. Wells and George Bernard Shaw led Needham to view science and social progress as inextricably linked. In 1917 he and a friend upset the elder Needham by saying "we thought the Russian Revolution was a very good thing because it gave everyone a chance of ruling," he recalls. His headmaster, a friend of Wells, also instilled in Needham the importance of engineering and of history.

When Needham entered Gonville and Caius (pronounced "keys") College in Cambridge in 1918, he intended to follow in his father's path—as a teenager he had assisted his father in operations. But a tutor convinced him the future lay in understanding molecules and atoms, not whole biology. So Needham, who studied with Nobel laureate Sir Frederick Gowland Hopkins, decided to investigate embryonic development.

In 1924 Needham became a fellow at the college, just after he received his doctorate. Seven years later he published an exhaustive three-volume book, *Chemical Embryology,* in which he traced the history of embryology to 1400 B.C., when Pharaoh Akhenaton described the soul in utero.

During the 1930s, Needham was one

of a group of Cambridge scientists, described in *The Visible College,* by Gary Werskey, committed to social betterment. Even so, Needham was careful not to allow his socialism to hurt his chances for scientific recognition. In 1939 he wrote a book on the Levellers, a Puritan sect of the mid-1600s that believed in religious and political equality, under the pseudonym Henry Holorenshaw. "I thought I should never get into the Royal Society if I showed an interest in things like that," Needham acknowledges. "I allowed myself the capacity of writing a preface to the book in which I said, 'My young friend Henry Holorenshaw has done a wonderful thing.'"

Needham became a fellow of the Royal Society in 1941. And in 1948 his then wife, Dorothy Moyle, became one of the first female fellows, making the Needhams the first husband and wife members—except for Queen Victoria and Prince Albert, who had not been admitted for their scientific rigor.

By 1937 the stage was set for what Needham has referred to as the great divide. That year three students arrived from China to study biochemistry. Needham was amazed to find that their minds worked much as his did scientifically. He was also fascinated that many of the ideas or instruments considered to be Western developments were in fact Chinese.

One of the group, Lu Gwei-Djen, who became his lifelong collaborator and, in 1989, his second wife for the two years before she died, was extremely knowledgeable about the history of Chinese science. Needham says her father, an apothecary, had imparted to her the sense that "whatever the Chinese have done in the past, however strange it might be to the eyes of modern science, they knew what they were about."

Needham and Lu Gwei-Djen began to sketch out a book on the history of science in China. Needham simultaneously set about learning Chinese. Although he already read or spoke Greek, Latin, French, Italian and German and could get by in such languages as Polish and Spanish, he says he had not learned anything "as strange as Chinese."

Because few British scientists spoke the language, he was asked to represent the Royal Society on a visit to China in 1942. He became scientific counselor for the British embassy in Chungking. Everywhere he traveled he met people who were interested in the history of science of their own land. "So I got to know a tremendous amount," Needham notes. "And very useful it was."

Needham also found evidence for his belief that Christians must reconsider their conviction that the entire world will eventually be ecclesiastically organized. "One of the most liberating aspects of the whole of my life was when I went to China and found that a quarter of the human race doesn't find the need of believing in a benevolent and creative god," Needham says. His alter ego Henry Holorenshaw later referred to Needham as an honorary Taoist.

Needham began shipping materials back to England and writing *Science and Civilisation in China* with his first collaborator, Wang Ling. It did not remain a modest text for very long. The book was to be organized as seven "heavenly" volumes. The original structure has been maintained, but often the volumes have become many "earthly" books: for instance, the history of chemistry will comprise 14 parts when complete.

In 1946 Needham went to Paris to direct the department of natural sciences at the United Nations Educational, Scientific and Cultural Organization. The agency was originally to be named UNECO, but Needham convinced his friend, biologist Julian Huxley, who was director of the nascent organization, to include "S" for science. Needham recalls the challenges of the job: "I built it up from naught to a staff of 600 in one year. Terrible job; awful job. I had to interview people in the bathroom."

Needham later returned to Cambridge to teach biochemistry and to work on *Science and Civilisation in China.* This "was a schizophrenic period in my life because I would be working on the structure of Chinese ships, for example, and have to go off and give a lecture on the sterol metabolism of mollusks," he says wryly.

During this time, Needham also weathered a period of intense criticism. In 1952 he participated in a commission that evaluated whether the U.S. had employed biological warfare during the Korean War. Needham and his colleagues determined that the U.S. had done so; they documented, for example, the use of insects as carriers of plague and anthrax. The report was made more inflammatory by the inclusion of testimony of prisoners of war.

As a result, Needham was ostracized by the British press and by many academics and says he was barred from entering the U.S. for many years. Despite the derisive and bitter reactions evident even today among his peers when the report is mentioned, Needham says he was glad of his involvement. And he denies that the testimony of the POWs strengthened his conclusion.

Needham and indeed others, including a few scholars and journalists who have researched the matter, believe his observations were correct. Many of the techniques he described resembled those used by Unit 731, a Japanese group stationed in occupied Manchuria during World War II. The infamous group used insects as vectors for the plague and other diseases (in addition to carrying out vivisections and other atrocities). In 1981 *The Bulletin of the Atomic Scientists* reported that members of Unit 731 were not prosecuted by the U.S. after the war in exchange for the data on biological warfare.

Into this climate of criticism the first volume of *Science and Civilisation in China* appeared. At that time, the history of science was a relatively new subject, and the West viewed China as a backward civilization. Needham and his collaborators, however, demonstrated that the collar harness, the seismograph, the magnetic compass, cast iron and even chemical warfare were Chinese in origin. They also traced the movement of these innovations to the West.

Although the significance of the work has not been questioned, aspects of it have met with criticism. Some detractors believe Needham emphasizes only positive aspects of the culture. Others have decried his "Marxist" tendency to put science in a socioeconomic context. Needham's unfailing (until Tiananmen Square) support of the Chinese government has also made some characterize him as politically naive or mistaken.

But others offer a different interpretation. "Joseph has backed China rather than whoever happens to be running it," comments Kenneth Robinson, senior research fellow at the Needham Research Institute, which was established in 1986. Defenders argue that Needham's unique synthesis of socialism, religion and science permitted him to make observations others were unable to.

Today Needham lives and works at his institute with a very small, partly volunteer staff—the institute is struggling under modest funding—to answer the nagging question of why modern science arose in 17th-century Europe, despite the vast scientific foundation in place in the East. Needham explains that the bureaucratic nature of Chinese feudalism, in part, inhibited the growth of modern science. But another aspect of the conclusion does not please him. "I think the answer is going to be that modern science arose with capitalism," he says. "And I don't like that, because I have been a socialist all of my life."

Of course, the conclusion poses no paradox for Needham—he remains a socialist. As one of his colleagues said recently: "Dr. Joseph Needham / dances with philosophic freedom. / You'd better watch your toes if / you dance with Joseph." —*Marguerite Holloway*

SCIENTIFIC AMERICAN

Understanding the AIDS Pandemic

Mathematical models help to reveal how the AIDS virus infects individuals and communities. They sometimes produce results that upset simple intuition

by Roy M. Anderson and Robert M. May

Despite 10 years of intensive research and consistent efforts to develop therapy, the spread of the virus that causes AIDS continues unabated throughout much of the world. While the world waits for the promise of medical and clinical intervention to materialize, efforts to understand the epidemic and cope with it through behavioral change are receiving help from new tools: mathematical models that seek to comprehend the overall transmission process at the population level.

In sub-Saharan Africa, and increasingly in India and parts of Southeast Asia, the rates at which the human immunodeficiency virus (HIV) is spreading reveal an alarming picture: levels of infection are extremely high in such groups as female prostitutes and their male clients as well as among intravenous drug users. Infection rates are also rising steadily in the general population.

Some countries in the developed world show encouraging evidence of a decreasing rate of growth of the epidemic in male homosexuals, brought about in part by changes in behavior. The spread continues, however, among intravenous drug users, and there is the worrying trend of a slow, steady rise in heterosexual populations. At present, the spread among heterosexuals in North America and Western Europe is typically restricted to poor ethnic groups in cities. Many observers believe this trend simply reflects the early stages of a more widely disseminated epidemic.

Optimism concerning the speedy development of vaccines has waned. The practical and ethical problems that surround both the testing of potential products in human populations and the need for large numbers of primates in laboratory experimentation have tempered initial hopes. In the absence of vaccines, the only way to restrict the spread of infection lies in education. The public must understand how the virus is transmitted and what changes in sexual behavior can reduce the risk of infection.

Mathematical models can serve as powerful tools in promoting such an understanding. In epidemiology, as elsewhere in the sciences, mathematics offers a method for thinking about complicated issues in a precise way. In particular, such models in epidemiology can help identify what needs to be measured. They allow us to interpret observed patterns. Even more important, they help us untangle the complex relations between the biology of infection in individuals and the transmission of infection in communities.

Mathematical models chart a slow but continuous development of the AIDS epidemic over many decades. Because they reveal a pattern where the numbers of cases of HIV infection (and thence of AIDS) increase faster as time goes on, in compound-interest fashion, the models have an important role to play in convincing governments and international aid agencies of the wisdom of acting now, not later.

The AIDS virus almost certainly evolved in Africa. The homologies of human strains with viruses discovered in wild primates in sub-Saharan regions strongly suggest this origin. In the worst-afflicted urban cen-

ROY M. ANDERSON and ROBERT M. MAY collaborate in the U.K. on the study of infectious diseases. Anderson is professor of biology and head of the department of biology at Imperial College, London. As a student at the same institution, he was an enthusiastic rugby player; May says that "Anderson's scientific career has been characterized by the same wing-three-quarter's quick grasp of the essentials in complex situations." May has been Royal Society Research Professor at the University of Oxford and Imperial College since 1989. Trained as a theoretical physicist at Sydney University, he later held a personal chair in physics there before moving to Princeton University in the early 1970s as Class of 1877 Professor of Zoology. Since the late 1970s Anderson and May have shared an interest in how infectious diseases contribute to regulating the numerical abundance or geographic distribution of animals and in the transmission and control of infections in human populations. Much of this work is drawn together in their recent book, *Infectious Diseases of Humans: Dynamics and Control.*

ters in Africa, 20 to 30 percent of pregnant women are infected with HIV. This level of infection has sometimes been attributed to socioeconomic conditions.

It is more likely that this high rate of infection is a consequence of the length of time over which the virus has been spreading in these areas: the epidemic is simply further advanced. Analyses from molecular sequencing indicate that the human virus could have been slowly spreading in parts of Africa for 100 to 200 years, possibly even longer. It could be that in these much earlier times, the complex beginnings of the epidemic (as localized flickerings in rural areas) could not be detected against a high background noise of infection and disease. Or it may be that ancestral forms of HIV in humans did not lead to AIDS.

The epidemic developed quickly in the early 1980s among intravenous drug users and male homosexuals in the U.S. and Western Europe. This rapid advance undoubtedly resulted from the introduction of the virus into communities having behavior patterns ideally suited to viral spread: drug injection and frequent intercourse with many different sexual partners.

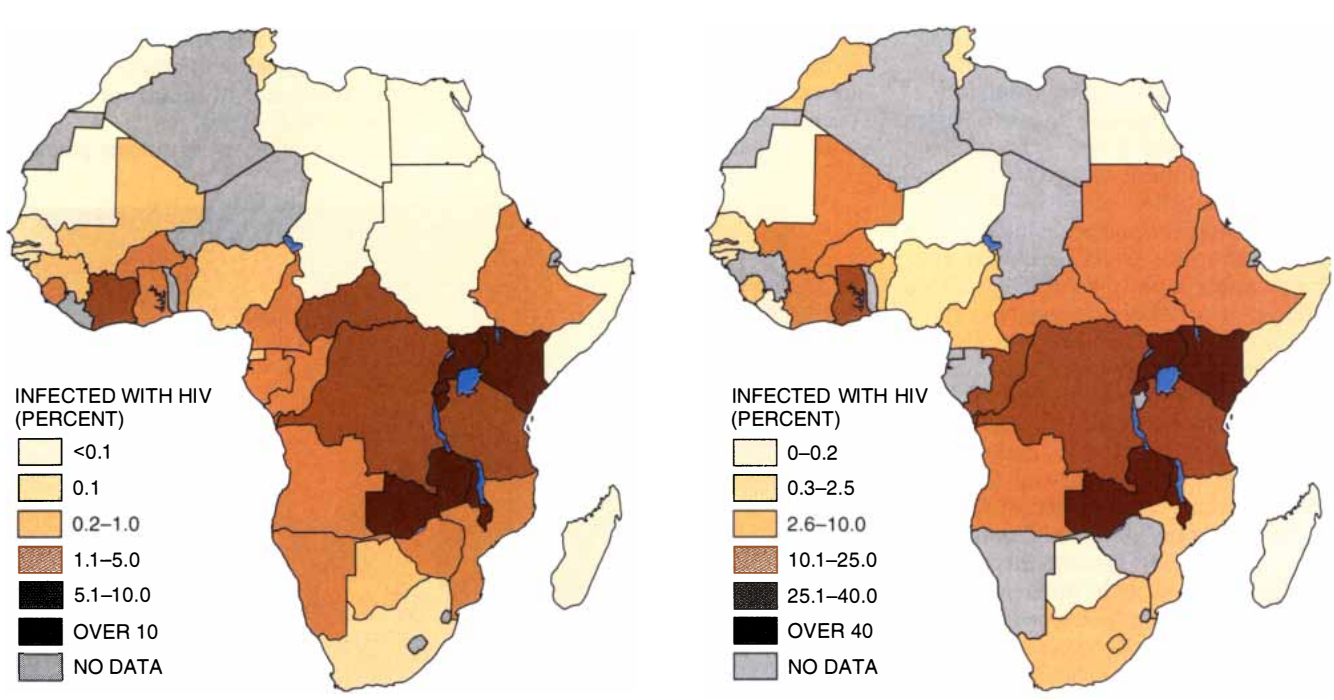
In sub-Saharan Africa the situation is harder to interpret, but the rapid recent growth of the disease probably reflects the normal development of an epidemic. Assuming exponential growth, with a doubling time of, say, three years, it would take 30 years for the prevalence of HIV infection to change from a thousandth of a percent to a detectable level of 1 percent, but only three years to change from 10 to 20 percent. The doubling time could well have been slower in earlier years. Various social and economic factors were also likely to have contributed to accelerating the advance (and shortening the doubling time): population movements caused by conflict, for example, and the relocation of men to jobs far from home, which spurred frequent contact with female prostitutes because of separation from wives and girlfriends.

Whatever the causes of the variation in the time of spread in different locations, it is gradually becoming accepted that in addition to afflicting minority groups, HIV also poses a serious threat to most sexually active adults and to infants born to infected mothers. The AIDS cases recorded over the first "visible" decade of the epidemic (the 1980s) are but a small fraction of what will be recorded in the 1990s.

The balance of reported cases will shift rapidly from a majority in the Western world, largely the U.S., to a majority in the developing world. Given the long incubation period of AIDS, averaging about 10 years in adults, the currently reported incidence of AIDS (formally reported as 350,000 cases but estimated to exceed one million) probably reflects only about 10 percent of the actual number of people infected. Moreover, even in this early stage of the global pandemic, recent data suggest that AIDS is already the leading cause of mortality in adults and a major determinant of infant mortality in some cities in Africa.

The potential severity of the pandem-

OFFER OF CONDOMS is made by a boy in Kinoni, Uganda. The condoms are distributed free by the government as part of a program to control the spread of AIDS. The program is aimed in particular at men who come alone to the cities seeking work and so are likely to have frequent sexual encounters with many partners.



EXTENT OF HIV INFECTION among heterosexuals in African countries varies widely. Although the geographic pattern of prevalence is strikingly similar for the general population and the high-risk groups, the levels of infection are much higher for the latter. Data, from the U.S. Bureau of the Census, cover 1985–1990; current levels of infection are undoubtedly higher.

ic is made even worse by the enormous plasticity of the HIV genome. Great genetic diversity is found in viral isolates obtained either sequentially from the same patient or from different patients. The diversity is so large that viral isolates must be considered as populations of closely related genomes, commonly referred to as quasispecies. History has shown that it is extremely difficult to develop protective vaccines against organisms that can mutate quickly and present constantly changing antigens to the immune system.

In the past the increase in viral diversity during the incubation period has been interpreted as a consequence of the slow destruction of the immune system. As the immune system is broken down, more types of virus survive in the body. But is the diverse array of antigens really the consequence of the destruction of the immune system, or is it the cause? Recent work based on simple models seems to support the causal assumption.

During the incubation period, high levels of virus in the blood are observed for a short but variable period (weeks to months) following infection. Soon after this initial peak in virus level, antibodies are detectable in the blood. It is subsequently difficult to isolate the virus, however, during the long and variable asymptomatic period between first infection and the occurrence of AIDS. The incubation period is characterized by low-level viral replication and a constant or slowly decreasing number of a type of white blood cell called $CD4^+$ cells, which play a major part in the immune system's defense against HIV. Some patients have minor upsurges in virus level for short periods during the course of this incubation. As symptoms of disease develop, the ease of virus isolation increases, and in AIDS patients the virus level is typically high. Ten years from the time of infection, about 50 percent of male homosexuals have acquired the disease; after a diagnosis is established, life expectancy is roughly one to two years in the absence of treatment with drugs such as zidovudine (AZT).

An example of such trends for two homosexual men in Amsterdam is shown in the illustration on page 66. In both patients the antigenic diversity was initially low but slowly increased during the asymptomatic period. One of the patients acquired AIDS, and in his case it can be seen that the viral diversity peaked before the onset of AIDS and declined thereafter. Such a decrease might at first appear counterintuitive, but it is exactly what would be predicted from the theory. Over the long incubation period the number of different strains of HIV increases. Yet all are controlled by the immune system. Therefore, as the number of strains increases, members of each are present in about the same number. This increasing diversity thus shows up in relatively small samples of serum or cells. But in the AIDS phase, as viral abundance increases and the immune system collapses, those HIV strains with high replication rates dominate and tend to be the only ones found in the samples.

A mathematical model of the process yields patterns of temporal change in viral level and diversity that match the observed trends quite well. The model predicts that viral diversity has a critical threshold below which the immune system can suppress viral abundance and above which it is unable to regulate viral growth. In other words, the model suggests that the development of serious immunodeficiency in HIV-infected patients is a consequence of the ability of the virus continually to produce variants and to kill $CD4^+$ cells. Antigenic diversity is the cause, not the consequence, of immunodeficiency.

The model can also be used to explore the impact of zidovudine drug treatment. The therapy appears to impede the rate of progression of AIDS. Different timings of treatment over the long incubation period of AIDS indicate that early, as opposed to late, treatment can significantly prolong the period before which serious immunodeficiency develops.

Mathematical models are also elucidating the dynamics of how HIV is transmitted within and between various communities. The potential for spread depends on the magnitude of the reproductive rate of the infection. This rate, denoted as R_0, defines the average number of secondary cases of infection generated by one primary case in a population where almost everyone is susceptible to infection—as in the early stages of the epidemic. If R_0 is greater than one, each infection has more than one "offspring," and the result is a chain reaction, or epidemic. If R_0 is less than one, the infection cannot sustain itself. The larger the value of R_0, the shorter the time it takes for the number of cases to double.

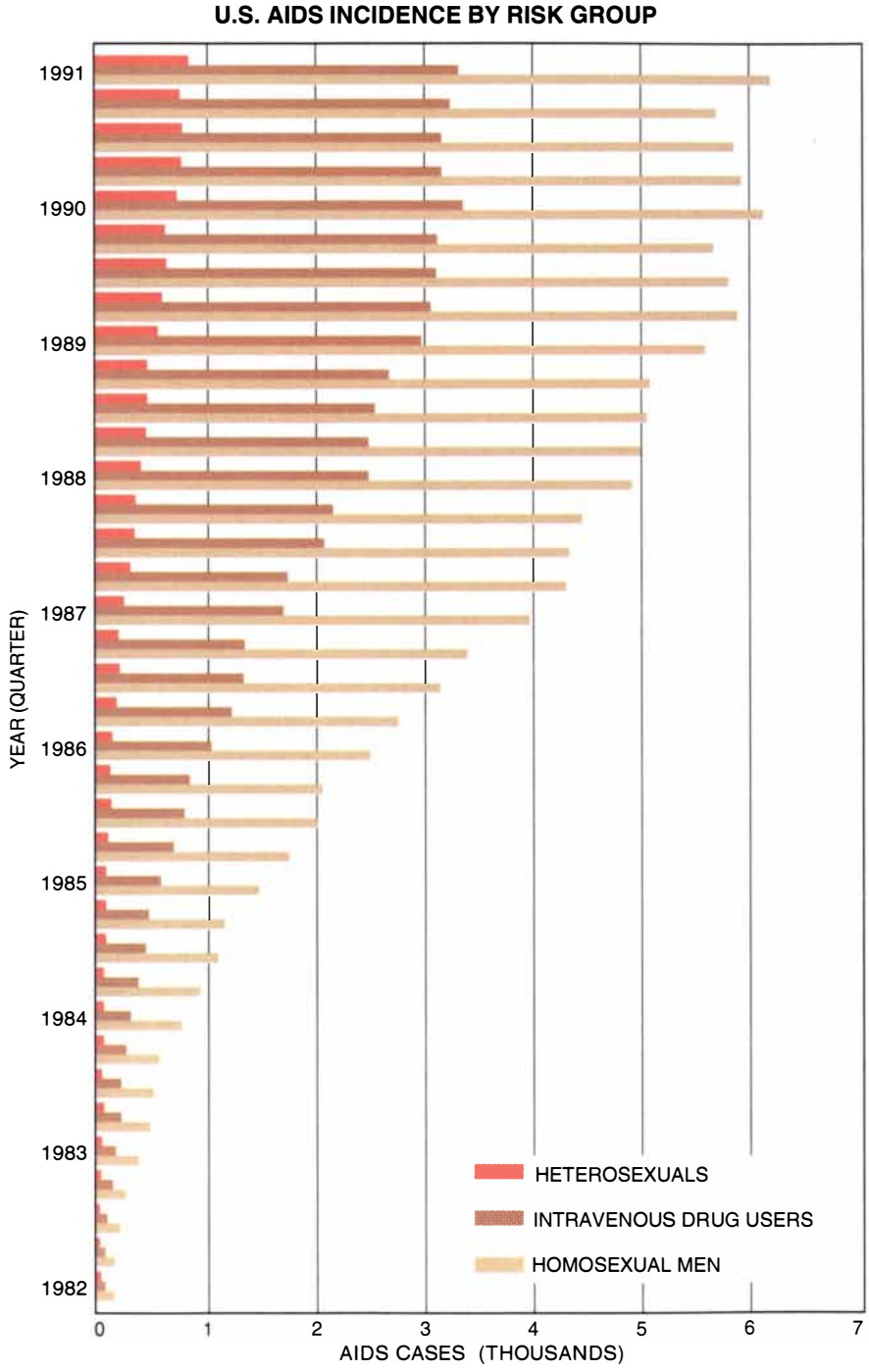
For HIV, R_0 is essentially a product of three factors: the average probability that an infected person will infect a partner over the duration of the partnership, the average number of partners acquired per unit of time and the average duration of infectiousness. Although this simple definition hides many complications, it serves to focus attention on what must be measured to understand the rate of spread of infection.

Two complications associated with defining R_0 are that its value differs significantly from one risk group to another and that the value can change over time in response to behavioral changes. Variability in sexual activity within a given population is of particular importance in determining the spread of infection: What kind of sexual activity takes place, and how often? How often are partners changed? What is the network of sexual contacts? Unfortunately, these are questions about which we know very little, partly because of the sensitivities of governments and individuals to the study of what is a private area of human behavior.

The limited data available on the rates of sexual-partner change and frequency of sexual intercourse reveal great heterogeneity within populations. Within the variability, one can distinguish patterns. These patterns appear to be fairly consistent both across different communities (heterosexual and homosexual, for instance) and across different cultural settings (developed and undeveloped countries, for instance).

The notion of variability in sexual behavior can be incorporated into the definition of R_0 by replacing the average number of partners acquired per unit of time by an expression that takes account of both the average and the variance. A high variance will increase the value of R_0. Logically enough, those individuals who change partners frequently are more likely both to acquire and to transmit infection. Survey work shows that such individuals make up a small fraction of a total population. Fewer than 20 to 30 percent of the individuals surveyed form 70 percent of the reported sexual partnerships. Paradoxically, then, a high variance enhances the overall transmission success of HIV (in terms of R_0) and hence increases the likelihood that an epidemic will occur. But it also implies that the infection will be restricted, to some extent, to the small fraction of individuals who are extremely active sexually.

The degree to which infection will be constrained within a small core of highly sexually active people depends on who mixes with whom: the network of sexual contacts among those who are very active sexually and those who are not. To define such a network, one must ask questions not only about numbers of sexual partners but also



NUMBERS OF CASES OF AIDS IN THE U.S. differ according to risk group. For these three groups, the data, which are courtesy of the HIV/AIDS Division of the Center for Infectious Diseases, were taken through June 1991.

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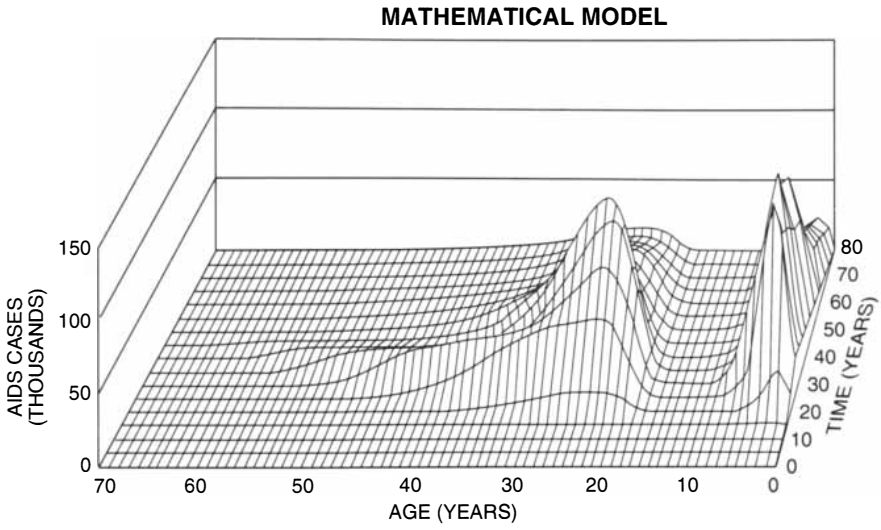
about who those partners were. This information is necessary to determine how often they, in turn, change partners. The understandable reluctance of participants to identify their sexual partners makes such studies very difficult.

In the absence of data, we have no choice but to turn again to mathematical models to assess how important it is to acquire such information. Models can reveal the degree to which assortative mixing (like with like) influences the epidemic. In this case, it is no longer sufficient to define a single reproductive rate of the infection, R_0. We must assign a matrix, or set, of reproductive rates to characterize the transmission of infection within and among various groups. Depending on the pattern of mixing among groups, some elements of the reproductive rate matrix could be greater than one (the infection spreads in that group), and others could be less than one (the infection dies out). Simply put, a few groups could maintain the infection in the total population, whereas in their absence, it would die out. The observation indicates that education should be targeted at individuals who contribute the most to the reproductive success of the infection.

The projected epidemic in the scenario with random mixing is far worse than in the assortative case. The infection spreads more rapidly at first in the assortative scenario. The small core of highly sexually active individuals is infected, creating a minor epidemic. But the development is limited in the larger group of less sexually active individuals. The major point to note is that highly assortative mixing can generate a multipeaked epidemic as the infection spreads from the higher- to the lower-risk groups.

Similar principles apply if we consider divisions on a larger scale. In any one country the epidemic is likely to develop as a series of waves moving from high- to low-risk groups through contact between groups. One such chain of contact consists of male homosexuals, bisexual men and heterosexual women. Another chain links heterosexual intravenous drug users and heterosexual nonintravenous drug users. A third consists of female prostitutes, their male clients and the female partners of the clients. Whether the overall epidemic will manifest itself as a series of distinct peaks or whether it will appear as a smooth single peak depends both on the size of each risk group and, more significantly, on the degree of contact among various groups.

In many Western countries the peak in cases of HIV infection in male homosexuals appears to have been reached.



DEMOGRAPHIC EFFECTS OF AIDS, as shown in a mathematical model and as seen in Uganda, are compared. The impact predicted by an age-structured mathematical model of HIV transmission shares basic similarities with the observed age and sex

We are now seeing a second epidemic, not yet at its peak, in intravenous drug users. A third wave, in heterosexuals, is just beginning, but its overall magnitude is uncertain at present. In developing countries, particularly in sub-Saharan Africa, the early peak in female prostitutes is being overtaken by much more widely disseminated infection in the general heterosexual population. In Southeast Asia, a similar pattern is emerging, although in Thailand the first wave was seen in intravenous drug users as well as in female prostitutes. In both Africa and Asia, HIV infection is sufficiently extensive in the general population to create concern over the demographic and economic consequences in the coming decades.

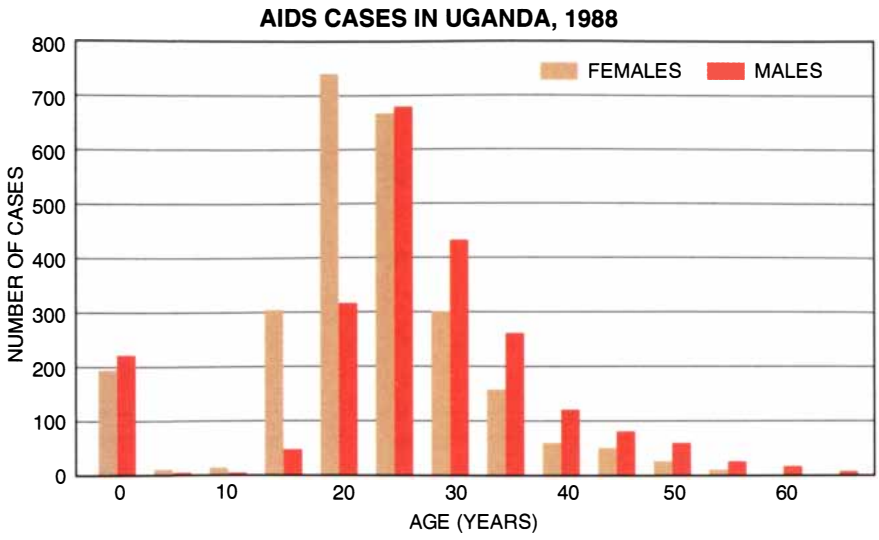
To assess the demographic impact of AIDS in the worst-afflicted regions of the world, we must develop models that combine descriptions of HIV spread and of population growth. The first analyses in 1988 suggested that AIDS is capable of turning positive growth rates into negative rates over time scales of a few to many decades. Even the annual growth rates of 3 percent or more in sub-Saharan Africa could be converted to negative rates. Much controversy surrounded these early predictions, mainly because of the uncertainties in assigning parameters and the failure to account adequately for differences in sexual activity between and within communities.

More recently researchers have accumulated data to help in estimating the most important epidemiological parameters, but considerable uncertainty still surrounds many of these efforts. Studies in developed countries appear to show that the average incubation period of AIDS in cases transmitted from infected mother to unborn infant is one to two years. Roughly 13 to 30 percent of infants born to infected mothers in developed countries appear to acquire the infection; the number is closer to 40 percent in Africa.

The greatest uncertainty in assessing the rate of transmission centers on the prevailing patterns of sexual behavior within and between communities. The World Health Organization has initiated wide-scale surveys on sexual behavior in Africa, and data are beginning to accumulate. At present, our meager understanding of the processes that dictate sexual behavior in different societies is for the most part anecdotal in character.

Under these circumstances, mathematical models can once again offer guidance, this time in identifying the linkages between sexual activity and the observed pattern of HIV spread. In the past few years, models have been developed that address various aspects of these issues, although it must be emphasized that theoretical developments have greatly outstripped the available data. The major role of such models is to provide qualitative guidelines concerning the interpretation of observed patterns. The model should also provide a framework within which to assess the potential impact of different interventions. Understanding is best developed by the gradual inclusion of complexity, in a manner akin to that adopted by the experimental scientist, who changes one factor at a time, while holding the other factors constant.

As an illustration of what these mod-



distribution of AIDS cases in Uganda in 1988. In particular, both the results from the model and the actual data show two peaks of AIDS incidence, one in infants and young children and one in sexually active teenagers and adults.

els can show us, we consider two examples of the effect of variability in sexual contact on the potential effect of AIDS in Africa. Our first example deals with the influence of contact patterns between different age classes of the two sexes. In particular, we focus on the tendency of African men to form sexual partnerships with women who are five to 10 years younger than themselves. Other factors being equal, models that take into account the observed age bias suggest a significantly enhanced demographic impact as compared with predictions based on restricted contact within the same age class. The increased impact is a consequence of the concentration of infection in young women who are just entering childbearing age. The models also suggest that the ratio of HIV infection in men and women will change over the course of the epidemic. This shifting ratio may help explain why widely different figures have been reported in Africa, ranging from a male to female ratio of close to 1:1 to 1:2.

Our second example concerns the patterns of mixing between men and women with high and low rates of sexual-partner change. The simplest of models—based on the stratification of the population by sex and classes of sexual activity—illustrates well the significance of sexual-contact networks.

When high-activity men (such as migrant male laborers in urban centers) have greatest contact with high-activity women (such as female prostitutes) but also have some contact with low-activity women (wives or girlfriends), a multiple epidemic may occur. First comes a rapidly developing epidemic in the small proportion of high-activity men and women. A more slowly developing, but much larger, epidemic follows the initial outbreak. The second epidemic involves the low-activity men and women who constitute the majority of the population. The epidemic in the high-activity classes serves to seed the slower-growing epidemic, and the peaks in the two classes may be separated by a decade or more.

The scenario predicted by this simple model may reflect what is actually occurring in cities such as Nairobi. There, levels of infection are high in female prostitutes (60 to 80 percent), moderate to high in their male clients (20 to 40 percent) and low in pregnant women in the general population (5 to 6 percent). The model suggests that the low levels in the general population will rise over the coming decade. This increase will herald a second and much larger epidemic, similar to what has already happened in the cities of Malawi, Tanzania and Uganda.

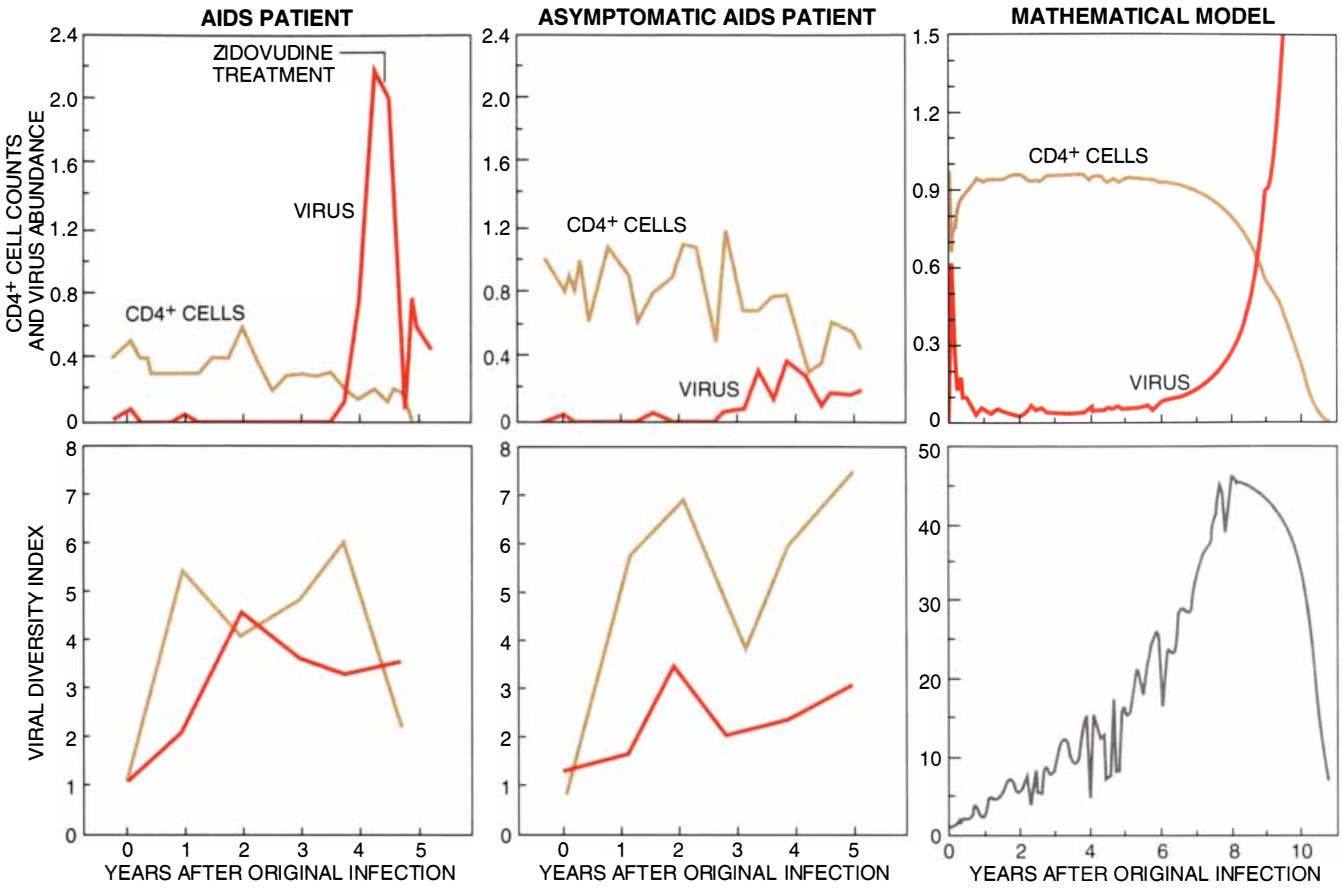
Available facts indicate that in the absence of major changes in behavior or the development of better drugs, AIDS is likely to cause serious demographic changes in some African countries over the coming decades. It also appears increasingly likely that the pattern will be repeated in parts of India and Southeast Asia.

What can be done to reduce the spread of infection? Models that assess the influence of behavioral changes on the rate of advance show the importance of the timing of these changes. The effects of timing are not necessarily intuitively obvious, given the nonlinear character of the epidemic. Changes introduced early in the course of the epidemic have a disproportionately greater effect than similar changes introduced later. As a consequence, significant resources should be directed toward inducing behavioral changes to try to prevent a widely disseminated lethal epidemic some 10 to 20 years from now.

Targeting education and condom distribution at high-risk groups will always be beneficial in the early stages of the epidemic, when infection in the general population is limited. Such a policy would clearly be beneficial in countries, such as Nigeria, where the levels of HIV infection in high-risk groups such as female prostitutes and their male clients are low to moderate and the levels are very low in pregnant women. If mixing patterns are highly assortative, an approach aimed at high-risk groups is particularly worthwhile. It may even turn out that the rates of sexual-partner change in the general heterosexual population are insufficient to maintain the transmission of HIV. If infection has taken hold to a significant degree within lower-risk groups, however, as is the case in Malawi, Tanzania and Uganda, education and condom distribution must be aimed more widely. Indeed, in these circumstances models suggest that much is to be gained by focusing efforts on young teenagers before they become sexually active.

The subtle interplay among rates of sexual-partner change, patterns of mixing between sexual-activity classes and the need to balance supply with demand for sexual partners can trigger perverse outcomes. Reducing rates of sexual-partner change in the general population offers an interesting example. Suppose a community has liberal attitudes regarding the formation of sexual liaisons. Most men and women will have a number of different sexual partners every year, with the result that the men have limited contact with female prostitutes. If education reduces partner-change rates among women, which concomitantly means that men have more frequent contact with prostitutes, the result may be an acceleration in the rate of spread of the virus in the general population in the short term. In the long term, however, the overall size of the epidemic would be reduced. The example illustrates the need to assess the influence of education not only on rates of sexual-partner change but also on the pattern of sexual mixing within a given community.

More generally, a growing body of evidence points to the importance of other sexually transmitted diseases (STDs).



COURSE OF AIDS INFECTION for two homosexual men in Amsterdam (*left and center columns*) is mimicked quite well by the results of a simple mathematical model (*right column*). The top row charts the abundance of both the virus and the white blood cell CD4+. The bottom row shows that the genetic diversity of the virus generally increases over time. The red and tan curves at the bottom left and center refer to two indices employed to measure the viral diversity.

These diseases seem to enhance the likelihood of HIV transmission, presumably through the genital lesions that STDs can cause. This evidence shows the need to control the spread of STDs in developing countries, particularly in Africa. Simple models of concomitant STD and HIV transmission lend support to such an effort. Another advantage of improving control of STDs is that the programs facilitate counseling and condom distribution to a high-risk segment of the population.

Developed countries have another option for minimizing the effects of AIDS: the use of zidovudine and other drugs that appear to slow the progression of the disease. A randomized trial in the U.S. tested two dosage levels of zidovudine (500 or 1,500 milligrams a day) and a placebo on asymptomatic patients. The trial was halted prematurely because patients being given zidovudine showed a considerable reduction in rates of progression of AIDS and advanced AIDS-related complex (ARC).

Zidovudine treatment may, under certain circumstances, have a negative side. Although the treatment is life-prolonging and therefore good for the individual, there are situations where it can be detrimental for the community. Depending on the extent to which the treatment reduces infectiousness, which is currently uncertain, it could be that lengthening the incubation or symptomatic periods in treated individuals can increase the incidence of HIV within the community. In extreme circumstances, the outcome could be an increase in the AIDS-related death rate in the community. Given that AIDS is a lethal disease and that zidovudine appears to slow its progression, it would certainly be unethical to refuse treatment to individuals. Nevertheless, mathematical models confirm the possibility that what is beneficial for the individual is not necessarily so for the community.

Clearly, there is a need for virological research of a quantitative nature to measure the impact of drug treatment on infectiousness and for reduced infectiousness to be part of the protocol of drug development. Moreover, these considerations highlight the desirability of linking treatment with counseling to promote safe sex practices among treated individuals.

In the absence of effective drugs and vaccines, changes in sexual behavior provide the only weapon against AIDS. Mathematical models, with their sometimes surprisingly counterintuitive revelations, can channel those changes into the most advantageous paths.

FURTHER READING

CURRENT AND FUTURE DIMENSIONS OF THE HIV/AIDS PANDEMIC IN WOMEN AND CHILDREN. James Chin in *Lancet,* Vol. 336, No. 8709, pages 221–224; July 28, 1990.

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THE SPREAD OF HIV-1 IN AFRICA: SEXUAL CONTACT PATTERNS AND PREDICTED DEMOGRAPHIC IMPACT OF AIDS. R. M. Anderson, R. M. May, M. C. Boily, G. P. Garnett and J. T. Rowley in *Nature,* Vol. 352, No. 6336, pages 581–589; August 15, 1991.

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THE POWER IS ON

Biological Roles of Nitric Oxide

This previously elusive and obscure chemical is proving to be of vital physiological significance. Nitric oxide may be the first of a novel class of neurotransmitters

by Solomon H. Snyder and David S. Bredt

Small, simple and highly toxic, nitric oxide seems an unlikely biological jack-of-all-trades. Indeed, most of the body's functions are regulated by extraordinarily large and complex proteins and compounds. The tools of modern molecular biology have revealed such elaborate chemicals as the hormone testosterone and the immune system protein gamma interferon.

Such chemical complexity seems almost ostentatious when compared with seemingly plain and unassuming nitric oxide. Nitric oxide, or NO, is a gas under atmospheric conditions. It is not to be confused with nitrous oxide, or N_2O, the laughing gas used as an anesthetic. Nitric oxide is notoriously noxious because of its free-radical structure: it possesses an extra electron, making it highly chemically reactive. And although it has long been known that bacteria contain nitric oxide, no one anticipated that such a reactive agent would have a crucial function in mammals.

Five years ago this belief was dispelled when a series of discoveries from many different avenues of research came together, revealing the major biological roles of nitric oxide. Studies have shown that the chemical is perhaps one of the most important messenger molecules. It enables white blood cells to kill tumor cells and bacteria, and it allows neurotransmitters to dilate blood vessels.

Nitric oxide simultaneously serves as a messenger for neurons, much like a neurotransmitter, in the brain and other parts of the body. In fact, nitric oxide may prove to be the first in a series of neurotransmitters unlike any of those previously elucidated. Understanding the molecular mechanisms of this potent compound, its distribution and its relation to other important bodily agents has led to clues that may be illuminating for memory research and for the treatment of certain neurodegenerative disorders.

Early studies of nitric oxide suggested the compound was anything but beneficial. Nitric oxide is extremely labile, that is, short-lived. It exists for about six to 10 seconds and then is converted by oxygen and water into nitrates and nitrites. Although humans excrete nitrates, scientists used to think these compounds derived solely from dietary sources. Therefore, in 1956, when P. N. Magee and J. M. Barnes of the Medical Research Council Laboratories in Surrey, England, reported that the body converts nitrates from cured foods to carcinogenic nitrosamines, people rushed to change their eating habits. Bacon and other cured foods high in nitrates were shunned.

In 1981 Steven R. Tannenbaum and his associates at the Massachusetts Institute of Technology noted that humans and rats fed low-nitrate diets still excreted substantial amounts of nitrates. Obviously, diet was not the sole source. Where did the compounds originate? Tannenbaum found a valuable clue in one of his subjects: a man who excreted very high levels of urinary nitrates while he had infectious diarrhea. Inflammatory processes associated with the diarrhea were apparently responsible for nitrate formation. Tannenbaum noted that injections of bacterial endotoxin, which causes an inflammatory response to bacteria, stimulated nitrate excretion in rats.

The precise source of nitrate formation and its relation to inflammatory responses were ultimately pinned down by Michael A. Marletta of the University of Michigan and his student Dennis J. Stuehr and by John B. Hibbs, Jr., of the University of Utah. Marletta had been a student of Tannenbaum's at M.I.T., and he remained intrigued about the part the immune system played in the endotoxin-induced nitrate formation. Marletta found that mice with a certain genetically determined macrophage deficiency excreted few nitrates. He thereby established an association between the presence of macrophages and the presence of nitrates.

Marletta probed further. He isolated cultures of the missing macrophages. He then introduced endotoxin into the culture along with gamma interferon, an immune modulator protein that activates other immune cells and that is formed by *T* lymphocytes. After this infusion the macrophages were suddenly able to produce nitrates.

By selectively testing different aspects of the cultures, Marletta also discovered macrophages could not produce nitrates when the amino acid arginine—normally present in the incubation medium—was absent. That finding enabled him to prove that a specific enzyme in the macrophages converts arginine into an intermediate chemical. The chemical turned out to be nitric oxide, which is quickly transformed into nitrites and nitrates.

Meanwhile Hibbs, working independently, was evaluating the ability of

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STAINED NEURONS become rust colored if they contain nitric oxide synthase (NOS), the enzyme that converts arginine to nitric oxide. Grayish blue-stained neurons do not contain NOS.

macrophages to kill tumor cells and bacteria. He cultured tumor cells with macrophages and noted that the tumor-killing ability of the macrophages disappeared when arginine was removed from the medium. Hibbs also proved arginine was converted not only into nitrates but also into the amino acid citrulline. In this way, he provided evidence that a specific enzyme produced nitric oxide from arginine.

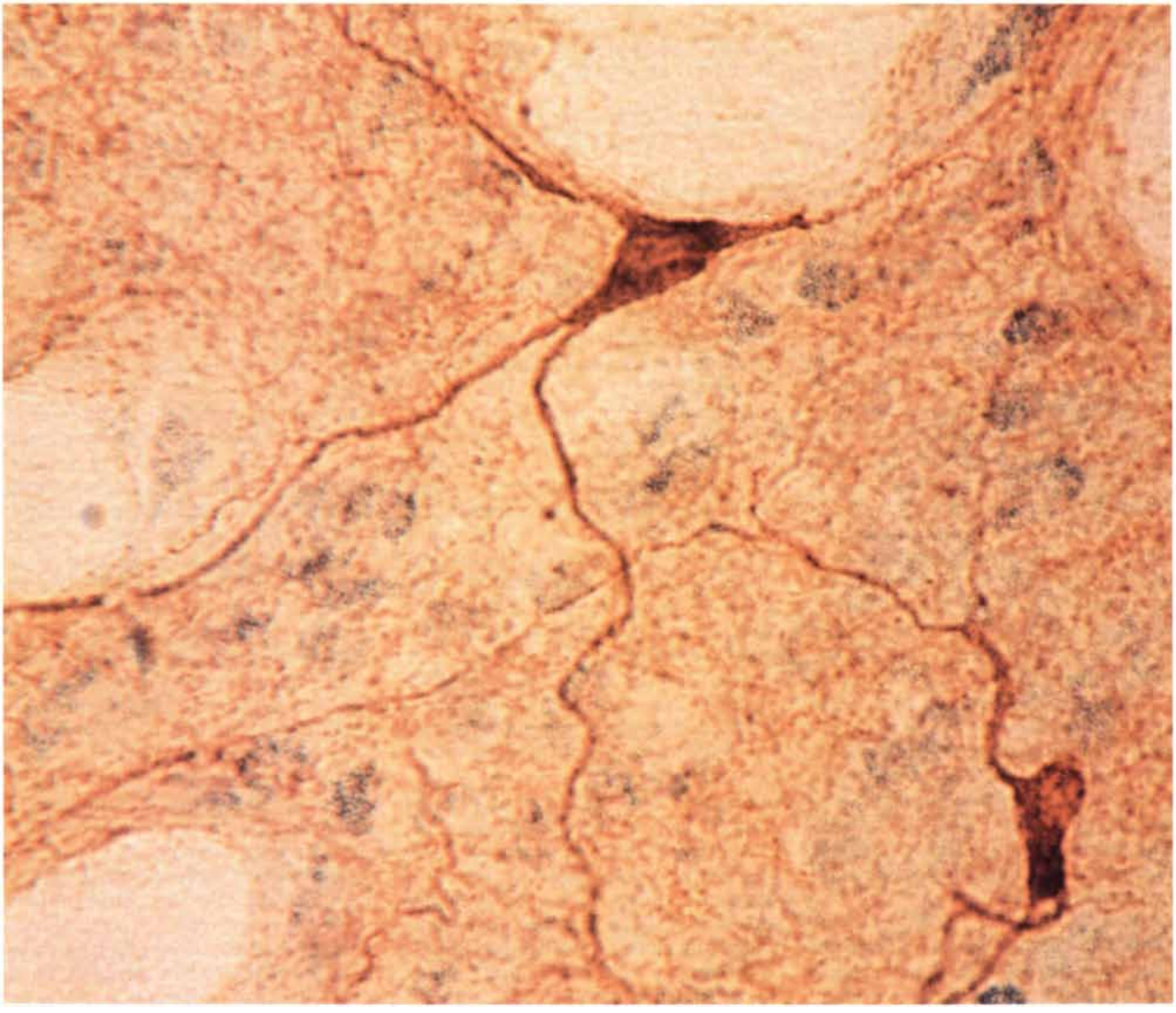
Hibbs went on to demonstrate that nitric oxide gas was as toxic to the tumor cells as were the activated macrophages. And he identified the first inhibitor of the enzyme synthesizing nitric oxide. Hibbs did this by showing that a derivative of arginine—specifically a methyl derivative—blocked both the formation of nitrates and the macrophage's tumor-destroying prowess. Without an enzyme producing nitric oxide from arginine, no macrophage defense could be mounted.

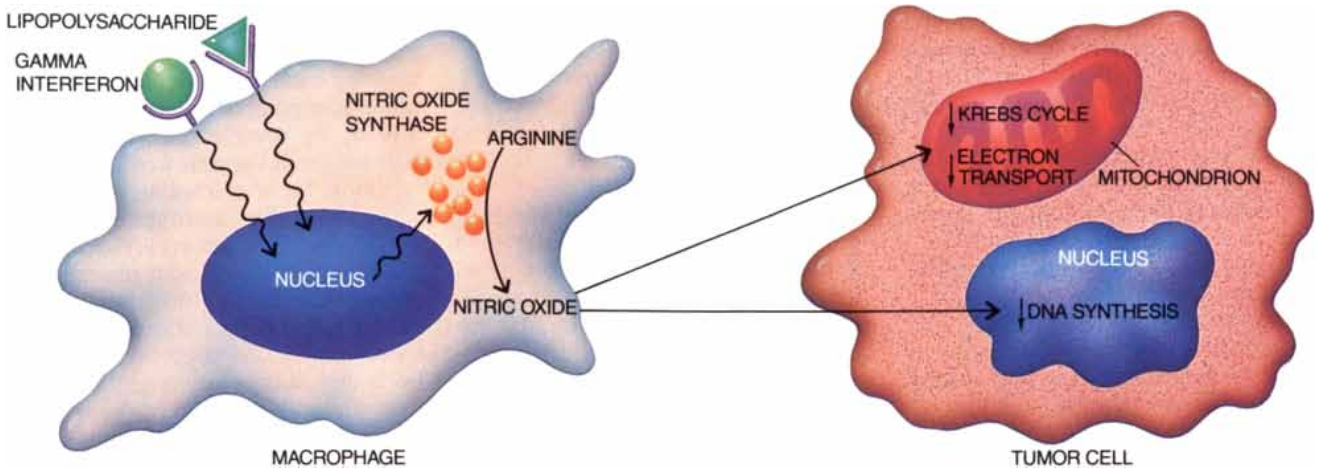
This is where research stood several years ago. When macrophages are activated by endotoxins or *T* cells, they respond by converting arginine into nitric oxide. The toxic, free-radical nitric oxide, in turn, allows macrophages to kill bacteria, fungi and tumor cells.

In a completely unrelated series of investigations, researchers identified nitric oxide as a messenger molecule. There are two parts to this aspect of the nitric oxide story. The first entails the mechanisms by which neurotransmitters dilate blood vessels; the second concerns the drugs that relieve the symptoms of angina, a form of heart disease in which the coronary arteries of the heart constrict. Both lines of research coincided recently to reveal more about the intricacies of nitric oxide's functions.

Blood vessels are dilated by neurotransmitters that cause the muscle layer of the vessels to relax, such as acetylcholine. Counterbalancing this effect are other neurotransmitters that contract the muscle and constrict blood vessels, such as norepinephrine. Because norepinephrine receptors occur directly on muscle cells, most scientists assumed the cells would also bear receptors for acetylcholine.

In 1980 this assumption proved wrong. That year, Robert F. Furchgott, a prominent cardiovascular pharmacologist working at the Downstate Medical Center in Brooklyn, noticed that the relaxation of blood vessels brought about by acetylcholine no longer occurred when the endothelial layer was stripped from the vessels. Endothelium is the thin layer of cells on the interior surface of blood vessels, immediately adjacent to the muscle layer. In a series of experiments, Furchgott demonstrated that acetylcholine acts on receptors located on the endothelial cells. This action provokes the release of a small molecule that diffuses to the adjacent muscle layer and relaxes it.





IMMUNE SYSTEM STIMULI gamma interferon and lipopolysaccharide transmit signals to a macrophage nucleus. The signals cause production of nitric oxide synthase, the enzyme that converts arginine to nitric oxide (NO). NO destroys tumor cells by inhibiting the energy-producing Krebs cycle and electron transport activities as well as DNA synthesis.

The mysterious molecule, or endothelium-derived relaxing factor (EDRF), as it was soon called, was nearly impossible to identify. Numerous investigators, including Furchgott and Louis J. Ignarro of the University of California at Los Angeles, tried unsuccessfully to isolate the labile compound. Despite their inability to identify EDRF, the researchers made a significant discovery. They proved EDRF stimulates the formation of cyclic guanosine monophosphate (GMP), a so-called second messenger for neurotransmitters and hormones. Cyclic GMP is related to the better-known second-messenger molecule, cyclic adenosine monophosphate (AMP).

Meanwhile another vein of research was being pursued, one that would come to bear on the work of Furchgott and Ignarro. Investigators, such as Ferid Murad of Abbott Laboratories, were seeking to understand the intricacies of nitroglycerin's effectiveness as a treatment for heart attack. This potent drug alleviates the symptoms of cardiac arrest by dilating coronary arteries and the veins that supply blood to the heart. Nitroglycerin, the active chemical in dynamite, was invented by Alfred Nobel, who endowed the Nobel Prize. Its therapeutic effects were well known in the late 1800s. Nobel, who suffered from angina, wrote to a friend about them: "It sounds like the irony of fate that I should be ordered by my doctor to take nitroglycerin internally." The therapeutic success of the drug resulted in numerous derivatives (the organic nitrates), which remain the mainstays of anginal treatment.

Although Nobel had discovered the compound nearly a century before, not until the late 1970s was any insight into the molecular mechanisms of nitroglycerin available. Murad, then at Stanford University, found that nitroglycerin and the organic nitrates are themselves inactive, although they elicit blood vessel relaxation once they are metabolically converted to nitric oxide. Moreover, nitric oxide relaxes muscle by stimulating the formation of cyclic GMP, just as EDRF does. The two lines of research, EDRF and nitroglycerin, seemed to have converged.

By 1986 both Furchgott and Ignarro had predicted that nitric oxide or some closely related derivative might account for EDRF's activity. Finally, in 1987, proof that EDRF is identical to nitric oxide was provided. Salvador Moncada and his associates at the Wellcome Research Laboratories in Beckenham, England, stimulated the release of EDRF from endothelial cells and monitored its relaxing effect on smooth muscle. At the same time, they chemically measured the amount of nitric oxide released from the endothelium. The endothelium released enough nitric oxide to account fully for the relaxation of adjacent muscle cells; therefore, nitric oxide is EDRF. Ignarro's group soon obtained similar results. In addition to relaxing blood vessels, nitric oxide inhibits blood clotting by preventing the aggregation of platelets. It has also been found to be the normal regulator of penile erection.

Today nitric oxide's role in the vascular system has been shown to be even more extensive. Although other substances, such as angiotensin and norepinephrine, were assumed to be the major determinants of blood pressure, nitric oxide apparently is the principal regulator of blood pressure. Several investigators have administered inhibitors of the enzyme that makes nitric oxide—nitric oxide synthase—to both animals and humans. Such treatment provokes a rapid increase in blood pressure, an increase more notable than the alterations produced by drugs influencing norepinephrine or angiotensin. Changes in the regulation of nitric oxide could be associated with hypertension or other blood pressure abnormalities.

The pace of discovery about nitric oxide verges on dizzying. Knowledge about its importance to the immune and vascular systems is itself relatively recent, but there is even fresher news: nitric oxide's function in the brain. The first hint that nitric oxide was involved in the nervous system came only in 1982. Takeo Deguchi of the Tokyo Metropolitan Institute for Neurosciences noticed that cyclic GMP formation in the brain requires arginine. Of course, at that time, no one knew that nitric oxide was a messenger molecule or that it was formed from arginine. In 1989 Moncada, at Wellcome, reasoned that arginine's role in cyclic GMP formation in the brain must relate to nitric oxide formation. In fact, he found nitric oxide–forming activity in brain tissue preparations.

Simultaneously, another body of evidence was accumulating. John Garthwaite of the University of Liverpool observed the formation of a short-lived substance that had the properties of nitric oxide when he stimulated brain tissue by administering the amino acid glutamate. Glutamate, an excitatory neurotransmitter, accounts for synaptic transmission at more sites in the brain than does any other neurotransmitter. Its effects are mediated by several subtypes of receptors. The one best characterized is the NMDA receptor, short for *N*-methyl-D-aspartate, a synthetic

amino acid that acts selectively at this subtype of glutamate receptor. At NMDA receptors, glutamate opens calcium ion channels, gatekeepers of neuronal transmission, thereby sending a strong excitatory impulse.

When released in large amounts, however, glutamate can cause damage by opening these channels. For example, the death of neurons during most strokes results perhaps from a cascade of glutamate acting on cells already deprived of oxygen. The added stress of having to fire more rapidly because of the glutamate stimulation exhausts and then kills the cells [see "Stroke Therapy," by Justin A. Zivin and Dennis W. Choi; SCIENTIFIC AMERICAN, July 1991]. Neuronal damage in animals in which strokes have been induced can for the most part be prevented by drugs that block NMDA receptors. The private sector has been quick to respond. NMDA antagonists are being developed by several companies as potential treatments for stroke.

Garthwaite's observation that stimulating NMDA receptors releases nitric oxide implicated the agent as a glutamate mediator. So in early 1989 we decided to investigate a possible role of nitric oxide in synaptic function. Because nitric oxide was known to act through cyclic GMP in blood vessels, we looked for a part of the brain in which glutamate had been shown to influence cyclic GMP. Fortunately, in the 1970s James Ferrendelli of Washington University had added glutamate to slices from the cerebellum and observed a rapid, pronounced increase in cyclic GMP.

Using similar cerebellar brain preparations, we developed a technique to measure the activity of the nitric oxide–forming enzyme, nitric oxide synthase. Because arginine produces nitric oxide and citrulline in equal proportions, we monitored the conversion of radioactive arginine to citrulline. Whatever the amount of citrulline we measured, it would therefore indicate that the same amount of nitric oxide had been produced. By this method we found that nitric oxide synthase activity tripled when we added NMDA or glutamate to the slices. We were struck by the extreme rapidity of this effect: it took place in a matter of seconds. This discovery was somewhat perplexing because increasing the activity of an enzyme usually requires a long time.

In the same brain slices, we confirmed that NMDA provoked large increases in cyclic GMP levels. We decided to examine whether there was a causal link between the formation of nitric oxide and of cyclic GMP. This question was easily addressed by adding inhibitors of nitric oxide synthase—specifically the methyl arginine derivative mentioned above—to the slices. Methyl arginine blocked the formation of cyclic GMP at the same concentrations as it inhibited nitric oxide synthase. Because both processes were inhibited by the same amount of methyl arginine, it seemed clear the two were related. Garthwaite and Moncada also observed this blockade of cyclic GMP formation.

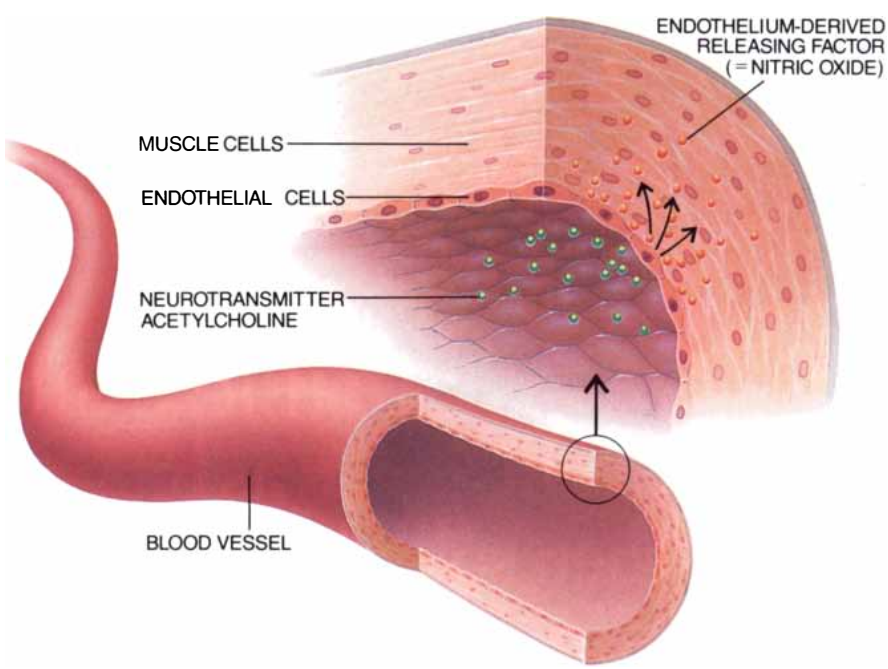
Our next step was to explore where nitric oxide worked in the brain. Normally, neuroscientists glean such functions of an important molecule by finding its specific neuronal locations, which are, in turn, associated with particular biological pathways and functions. But trying to locate a short-lived molecule such as nitric oxide seemed hopeless. Instead we attempted to localize nitric oxide synthase.

One of the most efficient means of localizing proteins is provided by immunohistochemistry. An antibody to the molecule that is to be traced is applied to tissue samples. It binds with the molecule, or antigen, in question. Various techniques, including staining, are then used to mark where the antibody is bound to its antigen.

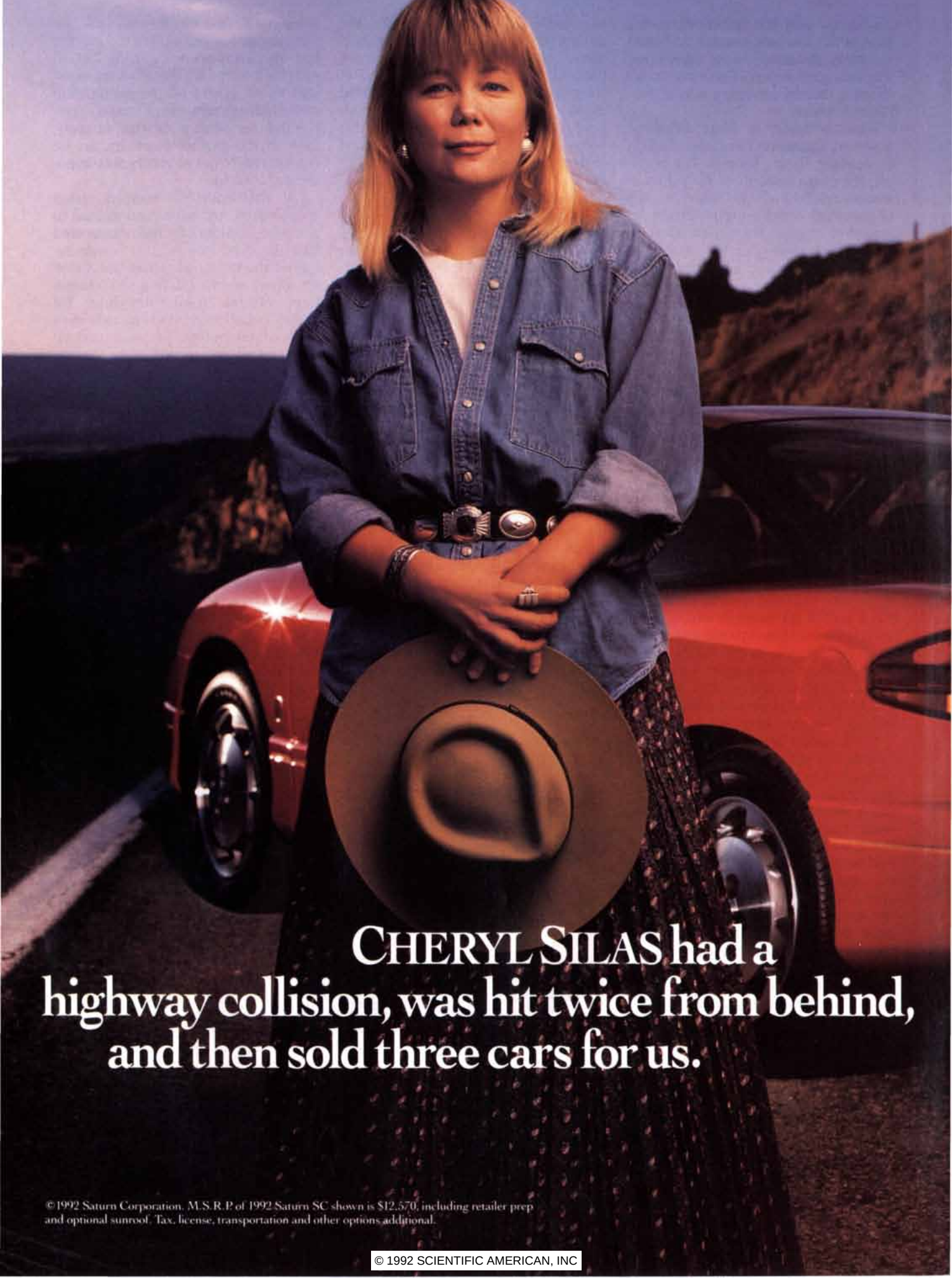
Before we could proceed with our immunohistochemical experiments, however, we had to obtain antibodies to nitric oxide synthase. And before we could do that, we had to isolate the enzyme itself. This was no easy task. We tried numerous purification techniques, but with each one we quickly lost all enzyme activity. We therefore reasoned that some aspect of the purification procedure was removing a crucial chemical that served as a cofactor, or assistant, in the enzyme's activity. So we considered trying to purify this hypothetical cofactor.

But that approach seemed rather complicated, and we turned instead to guesswork. Moncada had discovered that the synthesis of nitric oxide required the presence of calcium. Calcium often acts by binding to a ubiquitous cofactor called calmodulin. We added a small amount of calmodulin to some of our enzyme preparations and immediately saw a profound enhancement of enzyme activity. Fortuitously, calmodulin was the missing crucial cofactor for nitric oxide synthase.

Recognition of the association between nitric oxide, calcium and calmodulin enabled us to proceed with the purification of our enzyme. More important, it explained why NMDA receptors set in motion nitric oxide synthesis so quickly after being triggered by glutamate. As is well known, glutamate causes synaptic transmission at NMDA receptors by opening the ion channels that promote the movement of calcium ions from the exterior to the interior of neurons. Therefore, glutamate causes calcium to move into cells; the calcium ions then bind to calmodulin and acti-



BLOOD VESSELS DILATE when a neurotransmitter, such as acetylcholine, binds to endothelial cells on the vessel's inner walls. These cells release endothelium-derived releasing factor (EDRF), which travels to adjacent muscle cells and causes them to relax. In 1987 EDRF was found to be identical to nitric oxide.



A policeman at the accident, Officer Jimmie Boylan, thought, "She's lucky to be alive." Cheryl had just stepped out of her totalled Saturn coupe. Upon impact, her shoulder harness and lap belt held her tight as the spaceframe of her car absorbed most of the collision. He watched as Cheryl's sport coupe and the other cars were towed away.

The following week, Cheryl made the return trip to Saturn of Albuquerque and ordered another SC, just like her first. And then we started noticing some rather unconventional "referrals."

A few days later, Officer Boylan came into the showroom and ordered a grey sedan for himself. Then a buddy of his, also a policeman, did the same. And shortly thereafter, Cheryl's brother, more than a little happy that he still had a sister, and needing a new car himself, bought yet another Saturn in Illinois.

But the topper came when a very nice young woman walked into the showroom to test drive a sedan. She said she just wanted to know a little more about what our cars were like. Not that she was going to buy one right away, or anything. She'd just never seen a Saturn up close until she'd rear-ended one out on the highway several weeks earlier.

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vate nitric oxide synthase. This entire process takes place in milliseconds.

Once we purified the nitric oxide synthase protein, we and Paul M. Hwang, a doctoral student in our laboratory, developed antibodies against it. We then tracked down its presence in the brain and the rest of the body. Our most dramatic observation was that nitric oxide synthase occurs almost entirely in neurons. Neurons make up only 15 percent of brain cells; the other 85 percent are glial cells that provide metabolic and other support for neurons. Yet no enzyme was detected in glia.

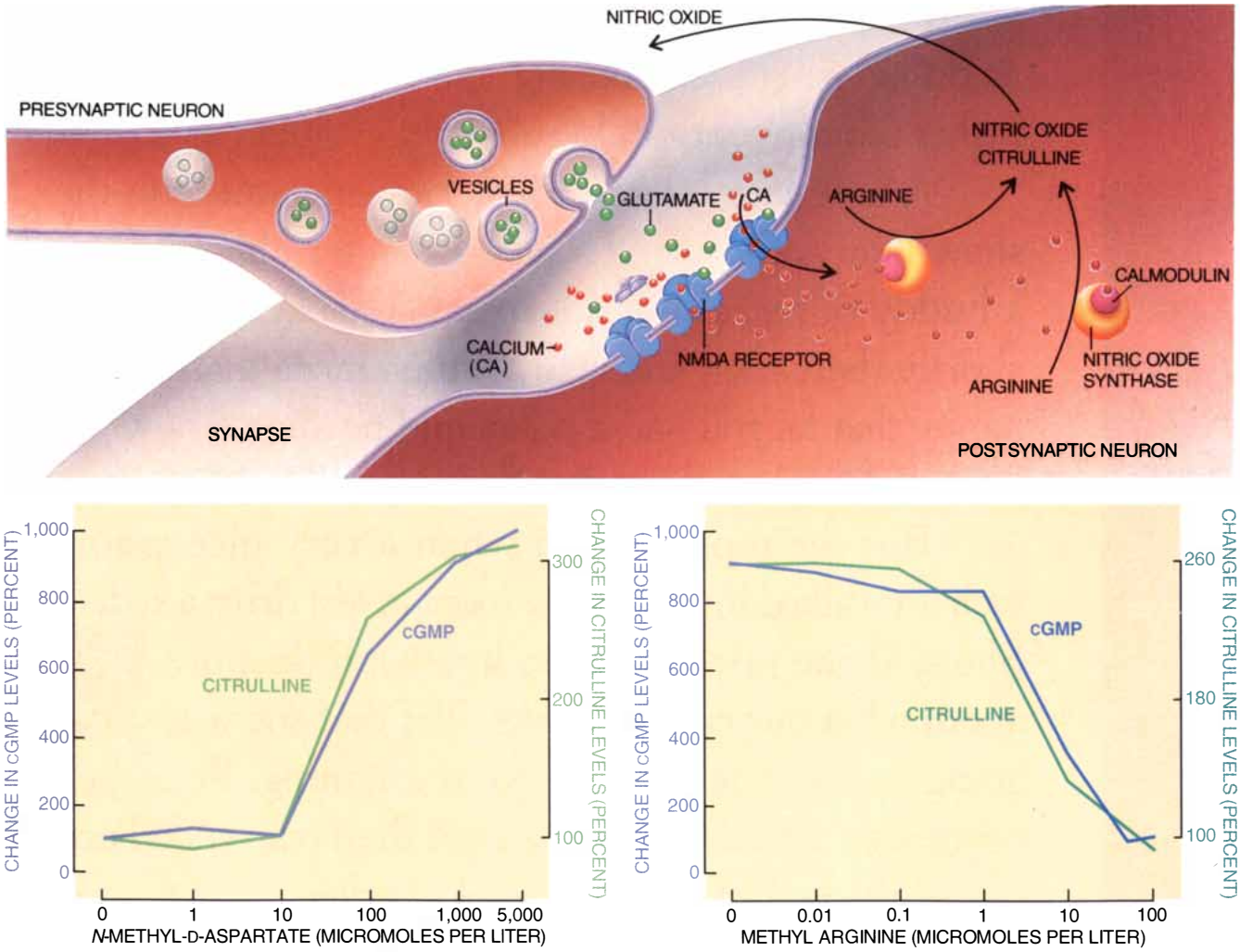
Interestingly, nitric oxide synthase was present only in discrete populations of neurons. In the pituitary gland, for instance, the enzyme exists in neurons whose cell bodies lie in the hypothalamus, whence they extend into the posterior lobe of the pituitary gland. These particular neurons synthesize and release the hormones vasopressin and oxytocin. In the adrenal gland, nitric oxide synthase is highly concentrated in a network of neurons that stimulate adrenal cells to release epinephrine, or adrenaline. In the intestine the enzyme resides in a collection of neurons referred to as the myenteric plexus. These nerve cells regulate peristalsis. In the cerebral cortex, however, the enzyme occurs in only about 2 percent of the neurons. Outside the brain, nitric oxide synthase is found in the endothelial layer of blood vessels.

The localizations we observed are extraordinary in that nitric oxide synthase is present predominantly in neurons. The functions of nitric oxide in nerve cells must therefore be comparable in importance to its functions in macrophages and blood vessels, perhaps even more so.

Although we successfully traced nitric oxide throughout the brain, our findings did not immediately suggest any clear function for the compound. The localizations seemed rather mysterious because they did not match the placement of any known neurotransmitter. But a breakthrough was soon made when we noticed that the peculiar localization of nitric oxide synthase in the cerebral cortex resembles another peculiar pattern of neurons, those stained by a certain dye.

This stain was developed by the British histochemist Anthony Pearse of the University of London in the mid-1960s. When Pearse stained brain slices with a dye called nitro blue tetrazolium, he observed that certain neurons turned bright blue when he added an enzyme cofactor called reduced nicotinamide adenine dinucleotide phosphate (NADPH). These neurons, called diaphorase neurons, made up about 2 percent of the cerebral cortex. NADPH donates electrons for oxidative enzymes, and so diaphorase was presumed to mediate a form of oxidation.

Few researchers, however, were ini-



NEURONAL NITRIC OXIDE is released when glutamate binds with the NMDA receptor (*top*). Binding causes calcium ions to enter the neuron; the ions bind to calmodulin, which activates NOS. NOS converts arginine to citrulline and NO. As shown below, levels of second-messenger cyclic GMP and citrulline increase when the receptor is activated (*left*). When the receptor is blocked by methyl arginine (*right*), levels of these compounds decrease, marking a decrease in NO.

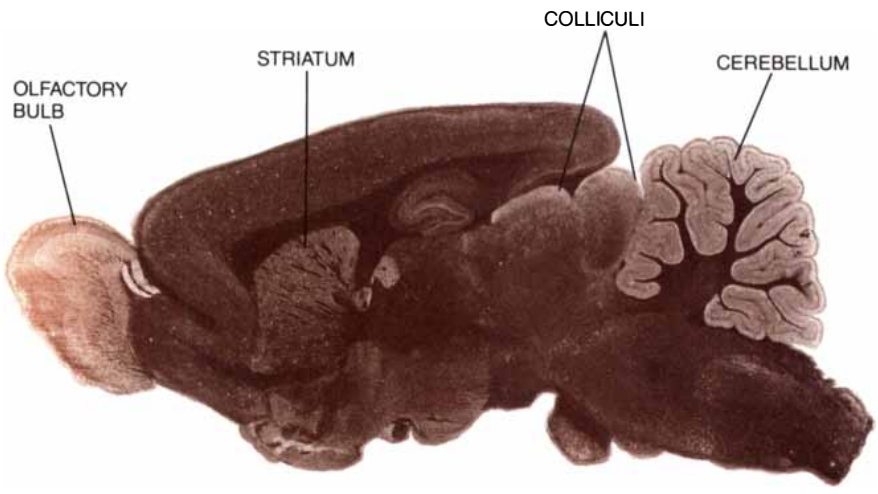
tially interested in this stain. In the mid-1980s M. Flint Beal and Joseph B. Martin of the Massachusetts General Hospital observed that neurons stained by this dye were selectively resistant to the neurodegenerative loss associated with several diseases. In Huntington's disease up to 95 percent of neurons in an area called the caudate nucleus degenerate, but virtually no diaphorase neurons are lost. In vascular strokes and in some brain regions involved in Alzheimer's disease, diaphorase neurons are similarly resistant. Neurotoxic destruction of neurons in culture by NMDA, a model for stroke, can kill 90 percent of neurons, whereas diaphorase neurons are completely preserved.

Researchers have been mystified as to why diaphorase neurons survive these neurotoxic insults. Insights into this puzzle would have therapeutic implications for major neurological conditions, including stroke, Alzheimer's disease and Huntington's disease.

The newly discerned overlap between diaphorase neurons and cerebral neurons containing nitric oxide synthase was inspiring. Because the potential relation of nitric oxide to NADPH was important, we set to work immediately, joined by Hwang, Ted M. Dawson, a neurologist working in our laboratory, and Majid Fotuhi, a graduate student. Soon we were able to show that precisely the same neurons stain for nitric oxide synthase and diaphorase, both in the brain and in the peripheral tissues. We also explained why nitric oxide synthase activity accounts for diaphorase staining: the dye accepts electrons that normally are used to oxidize arginine to nitric oxide, creating a blue color.

Our finding, while exciting, seemed illogical. Clearly, something about nitric oxide synthesis makes neurons resist neurotoxic damage. Yet at the same time, nitric oxide was the result of glutamate activity, and glutamate is responsible for neurotoxicity. Knowing the molecular mechanism responsible for such resistance could resolve the paradox and lead to insights about why neurons lacking nitric oxide synthase die so readily during neurotoxicity.

A way out of this dilemma would be to propose that the neurons making nitric oxide release it and that the nitric oxide, because of its toxicity, kills adjacent neurons. We already knew that after stimulation by moderate levels of glutamate, nitric oxide provokes the formation of cyclic GMP in adjacent nerve cells. But perhaps in the presence of high levels of glutamate, nitric oxide–producing neurons behave like macrophages—that is, they release lethal amounts of nitric oxide. If this theory is correct, then one might expect inhibitors of nitric oxide synthase to prevent neurotoxicity.



NITRIC OXIDE SYNTHASE in this rat brain can be seen as the light-colored regions of the olfactory bulb, striatum (the region most affected in Huntington's disease), colliculi (where visual and auditory information is processed) and cerebellum.

To examine that question directly, Valina L. Dawson and Edythe D. London of the Addiction Research Center in Baltimore, together with Dawson and us, examined the neurotoxicity of NMDA in cultures of cerebral cortical neurons. In this model, developed by Dennis W. Choi, then at Stanford, NMDA is added to cultures made from brain cells of fetal rats. One day after being exposed to NMDA for only five minutes, up to 90 percent of the neurons are dead. This model reflects the neurotoxicity that occurs in vascular strokes.

In these cultures we observed that nitroarginine, a particularly potent and selective inhibitor of nitric oxide synthase, completely prevents the neurotoxicity elicited by NMDA. Removing arginine from the incubation mixture similarly protects the cells. Moreover, hemoglobin, which binds with and thereby inactivates nitric oxide, also inhibits the toxic effects.

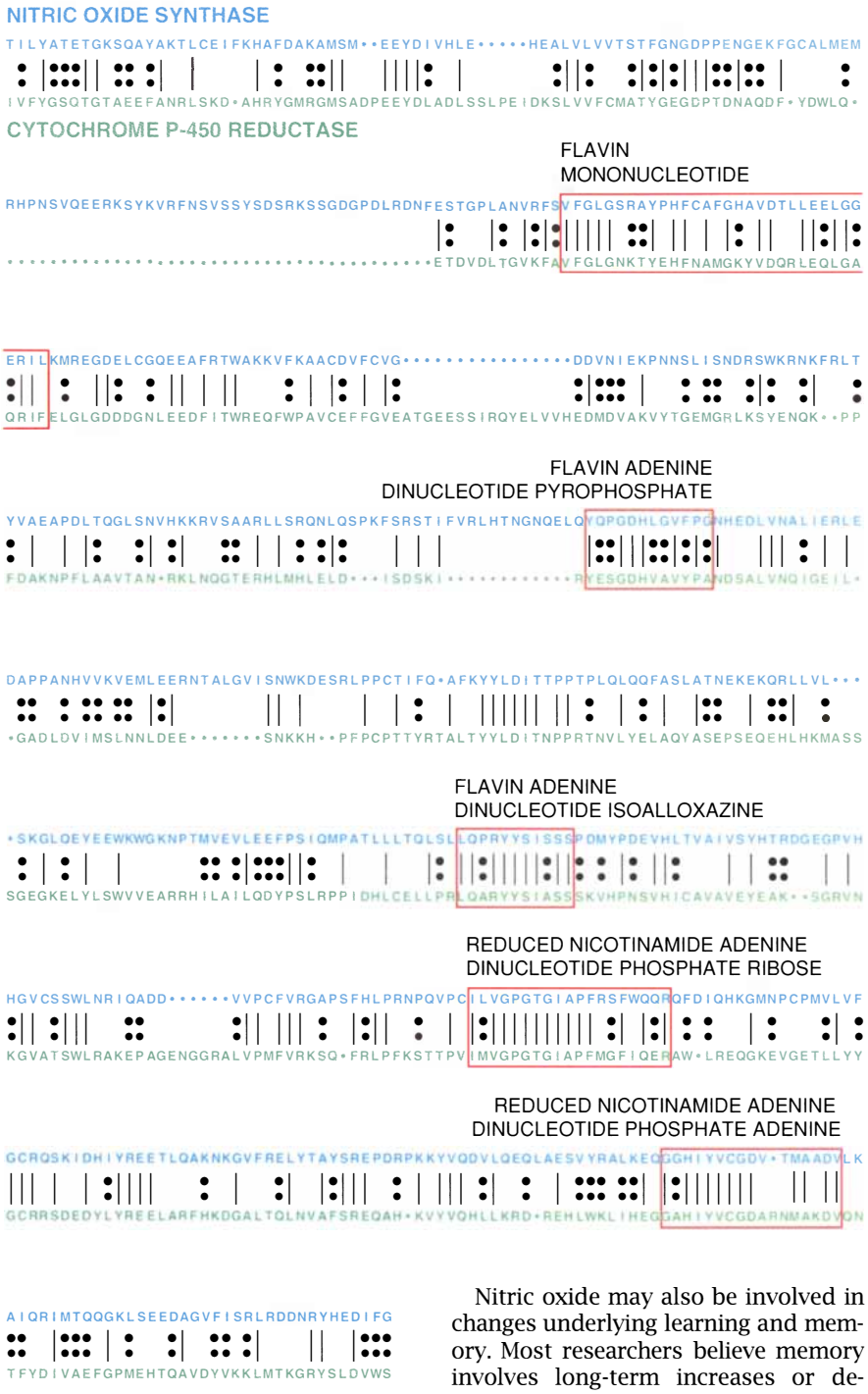
Thus, nitric oxide is clearly responsible for the neurotoxicity produced by glutamate acting at NMDA receptors in the cultures. Because NMDA antagonists can block the glutamate-induced damage associated with vascular strokes, nitric oxide may also modulate neuronal destruction caused by stroke.

Bernard Scatton and his colleagues at Synthelabo in Paris very recently injected small doses of nitroarginine into mice immediately after initiating a stroke. Nitroarginine reduced stroke damage by 73 percent; in a parallel experiment, however, a potent NMDA antagonist produced only 55 percent protection. These findings suggest that inhibitors of nitric oxide synthase may have therapeutic benefit in stroke and neurological damage associated with excess glutamate release.

The precise function of nitric oxide in neurons remains to be elucidated, and although we have made some progress, this mystery continues to unfold. Several lines of evidence indicate that nitric oxide acts very much like well-known neurotransmitters. In the intestines, for instance, the muscle relaxation involved in peristalsis is mediated by the myenteric plexus of nerves. But the neurotransmitter responsible for this relaxation had been elusive. Our demonstration that nitric oxide synthase is concentrated in these neurons suggested nitric oxide might be the missing messenger. Several laboratories have subsequently shown that the normal relaxation of muscle produced by electrically stimulating myenteric plexus neurons can be blocked by inhibitors of nitric oxide synthase. Moreover, direct addition of nitric oxide to the intestines mimics the effects of nerve stimulation.

If nitric oxide is a neurotransmitter, it is a most atypical one. Neurotransmitters are usually stable chemicals stored in synaptic vesicles in nerve terminals. They are released by a process in which the synaptic vesicle fuses with the neuronal membrane. On release, neurotransmitters interact with receptor proteins on the outside surface of the membranes of adjacent neurons.

In contrast, nitric oxide is not stored in vesicles. Together with Marcello Costa of Flinders University in Australia, we used electron microscopy to visualize nitric oxide synthase in myenteric plexus neurons. There the enzyme is located in the cytoplasm, not in synap-



AMINO ACID SEQUENCES deduced from segments of NOS and cytochrome P-450 reductase DNA suggest a common activity. Both have binding sites for cofactors (*red*), compounds assisting enzymes. Lines between amino acids indicate they are the same; two dots indicate they are very similar.

tic vesicles. Thus, nitric oxide is probably synthesized on demand in a neuron. Its release apparently involves simple diffusion from the nerve ending. Instead of acting at a membrane receptor protein, nitric oxide diffuses into an adjacent neuron. Its receptor target is iron in the active center of the enzyme that forms cyclic GMP. By binding to iron, nitric oxide initiates a three-dimensional change in the shape of the enzyme, which increases its activity and, consequently, the production of cyclic GMP. Because of this unique mode of action, nitric oxide represents a completely novel class of neuronal messenger.

Nitric oxide may also be involved in changes underlying learning and memory. Most researchers believe memory involves long-term increases or decreases in transmission across certain synapses after the repetitive stimulation of neurons [see "The Meaning of Dreams," by Jonathan Winson; SCIENTIFIC AMERICAN, November 1990]. Accordingly, in memory models such as long-term potentiation (LTP) and long-term depression, scientists repetitively stimulate particular neurons; they then detect persistent increases or decreases in synaptic transmission.

Researchers have recently examined the role of nitric oxide synthase in these long-term processes. Eric R. Kandel and his associates at Columbia University, Daniel Madison and his colleagues at Stanford and Georg Böhme and co-workers at Rhône-Poulenc Rorer in France independently studied the effects of nitric oxide synthase inhibitors. They determined the effects of the inhibitors on LTP in the hippocampus, a brain region known to be involved in memory. The researchers all found that the inhibitors blocked LTP. In addition, Katsuei Shibuki and Daisuke Okada of the Laboratory for Neural Networks in Japan showed such inhibition in the cerebellum.

We wondered whether nitric oxide might be only the first in a family of novel neuronal messengers. Some insights into this possibility have come from our molecular cloning of nitric oxide synthase. We performed the cloning with Hwang, Charles E. Glatt and Charles Lowenstein in our laboratory and in collaboration with Randall R. Reed of the Hopkins's Howard Hughes Medical Institute.

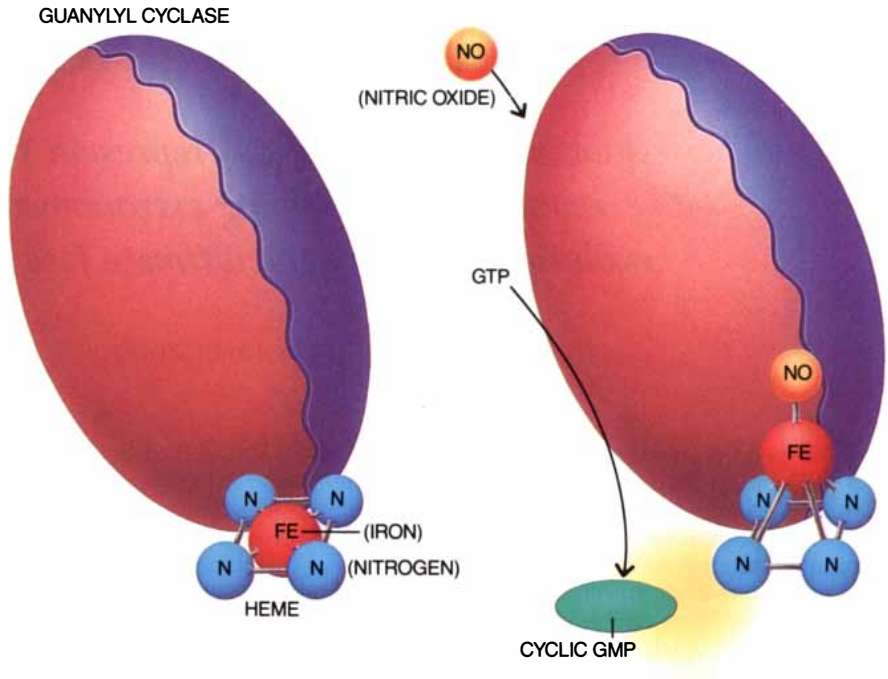
Once the amino acid sequence was established, we compared it with all known proteins. We found similarities to only one other known mammalian enzyme: cytochrome P-450 reductase. This finding was puzzling because cytochrome P-450 reductase had never been associated with the brain or with a neurotransmitter function.

Instead this enzyme serves as an electron donor for the P-450 enzymes in the liver. The P-450 enzymes metabolize a wide variety of drugs and, in some organisms, are set in motion by such environmental contaminants as dioxins and certain aromatic hydrocarbons. The electron-donating functions of cytochrome P-450 reductase are mediated by three cofactors that transfer electrons. Consequently, the enzyme's amino acid sequence has recognition sites for each of these three cofactors: NADPH, flavin adenine dinucleotide and flavin mononucleotide.

It is striking that nitric oxide synthase possesses recognition sites for the same three cofactors. Furthermore, the sites are located in the same places as they are in cytochrome P-450 reductase. There is also considerable similarity in the overall amino acid sequences of the two enzymes.

Nitric oxide synthase, however, has several other binding sites that are absent from cytochrome P-450 reductase.

It has a site for calmodulin and for phosphorylation. (Phosphorylation involves the addition of phosphate groups to proteins by a family of enzymes referred to as protein kinases.) The work of Paul Greengard of the Rockefeller University as well as many other researchers has established that protein phosphorylation relays information from second messengers, such as cyclic AMP, to various proteins inside cells. Phosphorylation is one of the major signaling mechanisms inside cells. We had noted earlier that nitric oxide synthase can be phosphorylated by a cyclic AMP–dependent protein kinase, a calcium-calmodulin–dependent protein kinase and an enzyme called protein kinase C. These kinases are important phosphorylating enzymes that regulate cellular responsiveness to hormones, neurotransmitters and growth factors.



NITRIC OXIDE RECEPTOR is iron in the enzyme guanylyl cyclase (*left*), which makes the second messenger, cyclic GMP. Nitric oxide binding (*right*) causes the iron-containing heme group to undergo a three-dimensional change that increases the production of cyclic GMP from GTP, a chemical with diverse functions.

Because nitric oxide synthase has so many sites for regulation, it is clearly influenced by more factors than are most other enzymes. This responsiveness makes sense when we consider the crucial role nitric oxide plays in providing subtle modulation for a number of processes. This function seems to contrast with the more mundane part performed by cytochrome P-450 reductase, despite the many similarities between their sequences.

What might these two enzymes have in common? Besides regulating drug-metabolizing enzymes, cytochrome P-450 reductase has one other function. It donates electrons to the enzyme heme oxygenase, which breaks down heme, the iron-containing oxygen-carrying constituent of red blood cells. The best-characterized form of heme oxygenase, called number one, is concentrated in the spleen, where red blood cells are normally degraded. But another, less understood form of the enzyme, number two, occurs at high levels in the brain. Because the presence of heme oxygenase number two overlaps so consistently with the presence of cytochrome P-450 reductase, it seems likely that donating electrons to number two is a major function of cytochrome P-450 reductase.

A close examination of this electron-donating process revealed what may well prove to be the second of the new class of neuronal messengers. During this process, heme oxygenase liberates carbon monoxide. Most of us know of carbon monoxide as a toxic gas from car exhaust. It binds to the hemoglobin and impairs its oxygen-transport activity. Carbon monoxide, however, is a normal body compound. By binding to the heme of guanylyl cyclase, the enzyme that produces the second messenger, cyclic GMP, it stimulates the formation of cyclic GMP, just as nitric oxide does.

Ajay Verma, a doctoral student in our laboratory, suggested that carbon monoxide was an excellent candidate to serve as a neuronal messenger. Together with David Hirsch, an undergraduate student, he rapidly amassed evidence favoring this notion. Verma and Hirsch showed that messenger RNA for heme oxygenase number two is situated in populations of neurons that closely resemble the distribution of both cytochrome P-450 reductase and guanylyl cyclase.

These findings are consistent with the possibility that carbon monoxide is the main regulator of cyclic GMP in the brain. When Verma and Hirsch treated cultures of brain neurons with an inhibitor of heme oxygenase, levels of cyclic GMP plummeted, but inhibitors of nitric oxide synthase had no effect. Thus, apparently carbon monoxide normally maintains levels of cyclic GMP in a number of brain regions. The similar structure of nitric oxide synthase and cytochrome P-450 reductase would seem to reflect their parallel roles in the synthesis of the two sister messengers: carbon monoxide and nitric oxide. Although the two compounds are found in different regions of the brain and appear to be involved in different pathways, their modes of action are very similar.

Whether or not carbon monoxide is another member of a new group of neurotransmitters, nitric oxide clearly is an extraordinary, novel and important messenger molecule. Small, short-lived and having strange ways, it appears to rival the major neurotransmitters in significance.

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Planetary Nebulae

These fluorescent clouds of gas represent the last gasp of dying, sunlike stars. They are helping astronomers understand stellar evolution and even the ultimate fate of the universe

by Noam Soker

Like people, stars grow old and die. The most massive ones live short spans and terminate in brilliant supernova explosions. The much more common, intermediate-mass stars like the sun expire more gracefully. As they exhaust their thermonuclear fuel, they swell and, in a final spasm, shed their outer bulk, creating an expanding spherical cloud of gas. The small, hot remnant of the central star heats the gas, causing it to glow. For a few thousand years, the dying star is surrounded by an eerily beautiful, gleaming cloud known as a planetary nebula.

Planetary nebulae display a spectacular array of shapes, sizes and structures. This diversity holds fascinating clues about the nature of stellar evolution and about the myriad ways in which stars interact with their environments. For example, some of the heavy elements (such as carbon, nitrogen and oxygen) that form in a star's core migrate into its outer layers. The abundances of these elements in a planetary nebula can reveal how material mixes through the various parts of a star's interior. The expanding nebula merges with the interstellar medium—the gas filling the space between stars—and enriches it with these heavy elements. This is the primary process by which matter returns from stars to interstellar space.

In recent years, astronomers have also begun using planetary nebulae, which are bright and relatively easy to identify, to improve measurements of the distances to remote galaxies. Such calculations help cosmologists determine the age and ultimate fate of the universe.

NOAM SOKER has extensively studied the structure and evolution of planetary nebulae. His research interests also include interactions between binary stars and hot gas in clusters of galaxies. Born and raised on a kibbutz, Soker completed his Ph.D. in physics at the Technion–Israel Institute of Technology in 1986. He then moved to the University of Virginia. Since 1989 Soker has been working at the Harvard-Smithsonian Center for Astrophysics. This fall he will become a senior lecturer of physics at the University of Haifa. Soker is a U.S. National Chess Master.

Planetary nebulae cannot be seen with the unaided eye. Indeed, the study of these objects did not begin in earnest until long after the invention of the telescope. Observations of planetary nebulae have been hampered by the fact that these objects have very low surface brightnesses and so tend to fade into the background of the sky. The light of the Helix Nebula (NGC 7293), for example, spreads out over an area as large as the full moon.

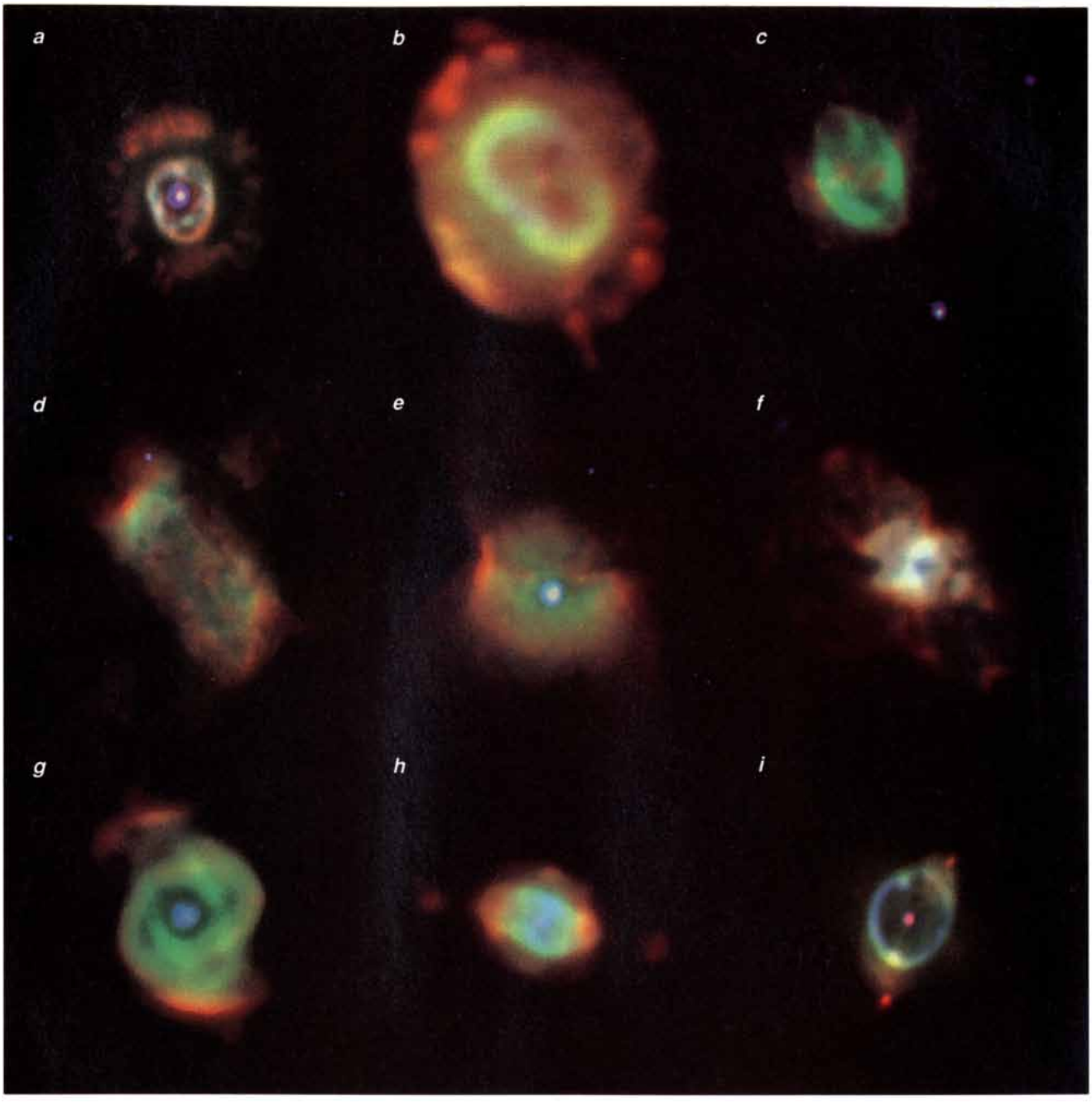
In the 1780s the great English astronomer William Herschel began a detailed investigation and cataloguing of nebulae, fuzzy patches of light that did not look like stars. In a paper published in 1785, he coined the term "planetary nebula" to describe a class of objects whose round shapes suggested ghostly versions of the images of the planets. (Herschel's list later was extended into the New General Catalogue; planetary nebulae are now commonly referred to by their NGC number.) Herschel wrongly guessed that planetary nebulae represent young objects that had not yet condensed into stars.

Since Herschel's time the number of catalogued planetary nebulae has grown from a handful to more than 1,600 in our galaxy alone (the total number may be 20 times higher). More important, astronomers have learned much about the true nature of planetary nebulae by means of spectroscopy, wherein an object's radiation is spread out and examined by wavelength or color. Every element radiates and absorbs radiation at certain characteristic wavelengths, or spectral lines. These wavelengths grow shorter if the radiating object is moving toward the viewer and longer if it is moving away. This seemingly simple effect, known as the Doppler shift, has yielded a wealth of information about the structure and dynamics of planetary nebulae.

Early in the 20th century, astronomers discovered that the spectral lines of planetary nebulae have a distinctive double-peaked shape, which indicates that the objects are expanding. Radiation from the approaching side of the nebula is shifted to a slightly shorter wavelength, whereas that from the receding side is shifted to a somewhat longer wavelength. Clearly, these objects are not clouds collapsing into new stars but rather material ejected from old ones. In 1956 the Soviet astrophysicist Iosif S. Shklovsky established the modern view that nebulae develop out of the discarded outer layers of aged, red giant stars and so represent not the beginning but the end of the stellar life cycle.

Numerous observations have shown that planetary nebulae expand at velocities ranging from five to 100 kilometers per second; the average rate of expansion is about 20 kilometers per second. In some cases, these figures can be checked by visually examining the growth of the nebula. By estimating the size of the nebula and the rate at which its expansion slows, one can calculate its age. The inferred ages, which run from a few thousand to 30,000 years, have helped constrain models of the evolution of planetary nebulae and their central stars.

Researchers examining Doppler-shifted lines have also discovered that high-speed streams of gas, known as fast winds, blow from the central stars in many planetary nebulae. Stellar winds produce a distinctive spectral pattern because atoms can absorb radiation at the same wavelength at which they emit it. Atoms lying along the line of sight to the star absorb part of its light before it reaches the earth, causing a dark (absorption) line in the star's spectrum. These atoms lie in the part of the wind moving toward the earth. The line is therefore shifted to a shorter wavelength. Other atoms, which are not sil-



PLANETARY NEBULA forms when an aged solar-mass star expands and casts off its outer layers. Radiation from a hot stellar remnant illuminates the surrounding gas. Nearly round nebulae, such as NGC 2392 (*a*), are the exception. Elliptical shapes, exemplified by NGC 7662 (*b*) and 7354 (*c*), are more common. NGC 650-1 (*d*), 2346 (*e*) and 2440 (*f*) show complex butterfly shapes; NGC 6543 (*g*) defies classification. Bright knots surround some nebulae—for example, NGC 7009 (*h*) and 3242 (*i*). In these images, emission from ionized oxygen is shown as green, nitrogen as red and helium as blue. The dominant light-emitting element in each region depends on local temperature, density and amount of radiation received.

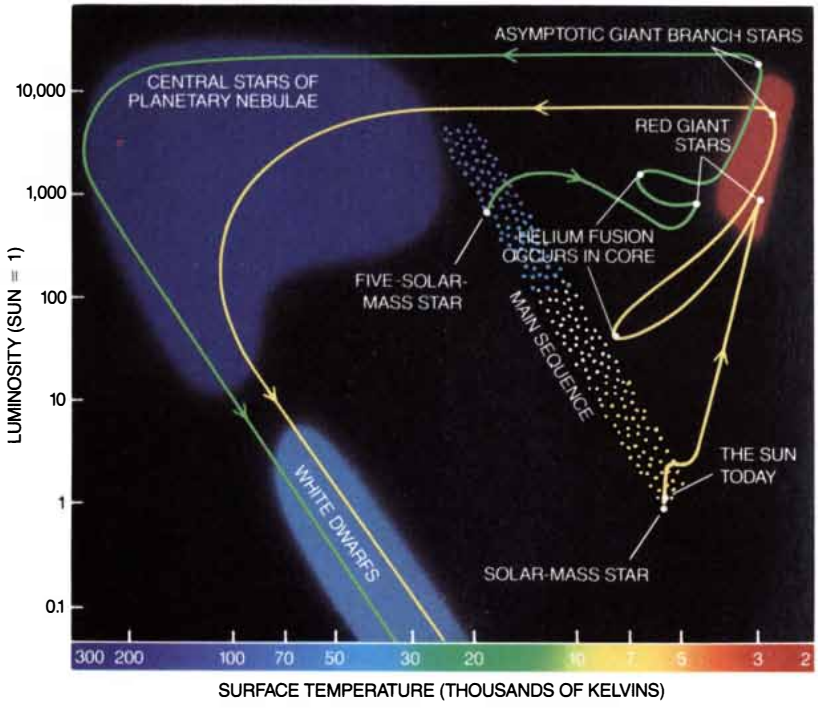
houetted against the central star, are seen emitting rather than absorbing radiation. The emitting atoms are moving in all directions and so show no net Doppler shift.

As a result, the star's spectrum contains an emission line as well as an absorption line whose wavelength is slightly shorter. The wavelength at which the absorption line appears indicates the velocity of the outflow. Observers have measured fast winds moving at up to 4,000 kilometers per second. The intensities of the absorption and emission lines can be used to infer the density of the wind and hence the rate of mass loss from the star, but this method remains highly uncertain.

Spectroscopic observations have also revealed the composition of planetary nebulae. Every atom produces a distinctive pattern of spectral lines that can be observed and matched with those seen in the laboratory. But the appearance of planetary nebulae initially proved mysterious. The British astronomer William Huggins found in 1866 that many nebulae radiate quite strongly at three particular lines, two of which did not correspond to any known line. He attributed these lines to a hypothetical new element, logically called nebulium. In 1927 Ira S. Bowen of the California In-

The Life Cycle of Sunlike Stars

Stellar evolution is plotted on this diagram of luminosity versus surface temperature. The lines follow the evolutionary tracks of two stars, one having the mass of the sun, the other five times as massive. Evolving stars spend about 90 percent of their lives in a stable band, called the main sequence. Massive stars evolve faster then do lighter ones. When their central hydrogen fuel is depleted, the two stars expand and cool, moving off the main sequence and becoming red giants. Then helium begins to fuse, and the stars briefly shrink. After all the helium is consumed in the core, the stars expand to become asymptotic giant branch stars. Such stars grow unstable and completely shed their outer layers within 100,000 years. As the remnant cores shrink and become hotter, their radiation causes the surrounding gas to glow, creating planetary nebulae. Their fuel exhausted, the stars begin to cool. After 10,000 to 30,000 years they can no longer illuminate the expanding nebulae. The now naked stars spend the rest of their days as extremely dense remnants known as white dwarfs.



stitute of Technology realized that the mysterious spectral lines were actually emitted by oxygen ions, atoms that had been stripped of some of their electrons. He identified the radiating ion as doubly ionized oxygen (atoms missing two electrons), which is extremely unstable on the earth but can persist for a long time in the near-vacuum of space.

The wavelength of emission lines uniquely identifies both the element and the number of missing electrons, known as the state of ionization. Nearly all the radiation from planetary nebulae is emitted by ions, either as they are excited by collisions or by other radiation from the hot star or as they recapture free electrons. Lawrence H. Aller of the University of California at Los Angeles, James B. Kaler of the University of Illinois and many others have examined emission lines to determine atomic abundances in planetary nebulae, using both optical telescopes and the *International Ultraviolet Explorer* satellite, which has been operating since 1978.

Planetary nebulae contain about 70 percent hydrogen and 28 percent helium by weight. Of the remaining 2 percent, the most common elements are carbon, nitrogen and oxygen. Other heavy elements, including neon, sulfur, sodium, argon and chlorine, are present in even lower concentrations.

Many of these elements are thought to be synthesized in thermonuclear reactions that take place in the centers of stars. Their presence in a nebula suggests they were somehow carried outward from the stellar core. Planetary nebulae show no sign of violent processes, so the material must have traveled by means of convection, the transport of material and energy by turbulence in the star. The relative abundance of heavy elements in planetary nebulae, for instance, implies that material was dredged from the helium-rich core and ferried into the star's outer layers. A dense wind emanating from the star then carried off these outer layers. Analysis of the composition of planetary nebulae reveals some of the processes that occurred in the progenitor star, especially the efficiency and depth of the star's internal convection.

The intensities of various spectral lines even reveal the temperatures and densities in planetary nebulae. Astronomers find that the temperature typically averages around 10,000 kelvins. The density varies from several atoms per cubic centimeter at the center and outermost periphery to as many as 100,000 atoms per cubic centimeter in the bright, compressed limb regions. Such densities are thousands of times higher than the overall density of the material between the stars. (Nevertheless, planetary nebulae are remarkably empty by terrestrial standards; a cubic centimeter of air at sea level contains about 10^{19} atoms.) Younger and hence smaller nebulae tend to have relatively high densities.

The many discoveries about the physics of planetary nebulae have helped theorists refine their ideas about stellar evolution. During the past two decades, elaborate computer simulations of stellar models have been developed by Bohdan Paczynski, now at Princeton University, and later by Icko Iben, Jr., of the University of Illinois, as well as by Detlief Schünberner of the University of Kiel in Germany and many others. These simulations have enabled astronomers to piece together the following story of the evolutionary stages leading up to the formation of planetary nebulae.

A star spends roughly 90 percent of its life steadily producing energy in its core through nuclear fusion. Hydrogen nuclei fuse with one another to form helium nuclei, releasing energy in the process. During this stable stage, the star is called a main-sequence object; fortunately for life on the earth, the sun is such a star. How long a star remains on the main sequence strongly depends on its mass. Heavy stars shine much brighter and consume their hydrogen fuel far faster than do light ones. A star of one solar mass lasts about 10 billion

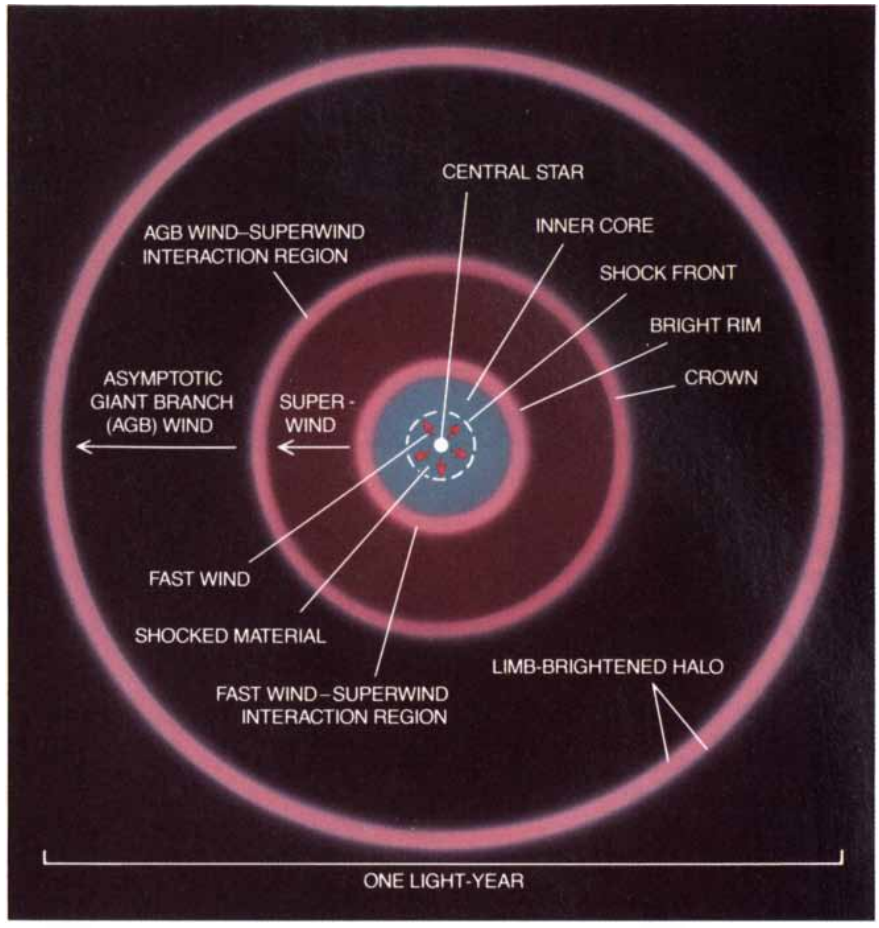
years as a main-sequence object. Stars five times as massive as the sun, in contrast, spend only 60 million years on the main sequence.

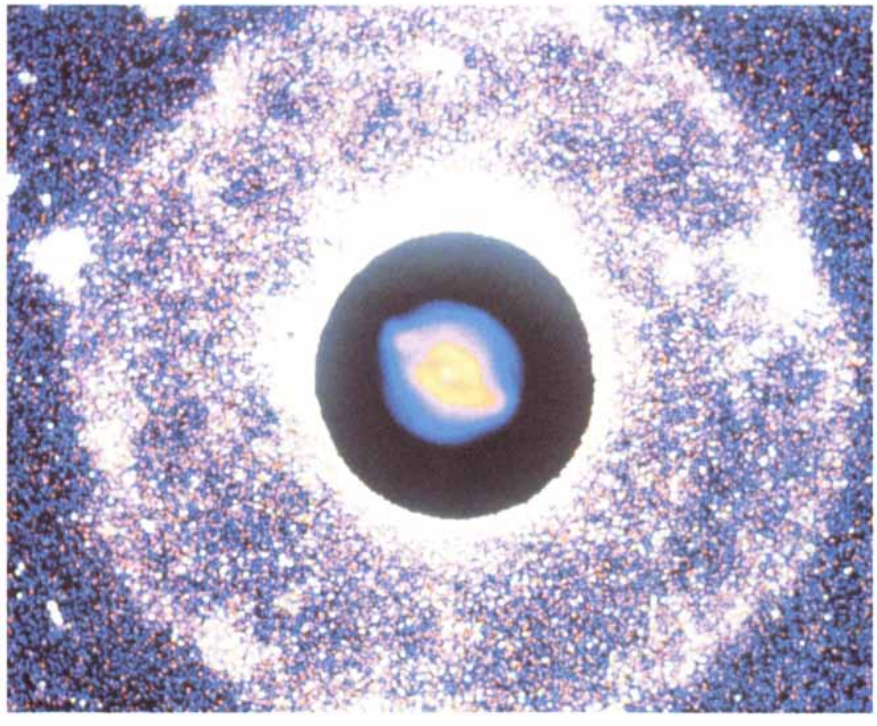
As a star ages, helium collects in its center. When all the hydrogen there is consumed, the helium core contracts under its own gravity and grows hotter. Fusion moves outward to a shell surrounding the core, where hydrogen-rich material is still present. During that phase, the star expands to several tens of times the diameter of the sun (about 1.4 million kilometers). Its surface, now far removed from the central energy source, cools and glows only red hot; its total luminosity, however, increases more than 100-fold. At this evolutionary stage the star is known as a red giant.

Hydrogen fusion in the shell continues to deposit helium ash onto the core, which becomes ever hotter and more massive. When the core temperature reaches about 100 million kelvins, helium nuclei there start to fuse together, forming carbon and oxygen nuclei. Meanwhile the outer parts of the star shrink, causing its surface to become hotter and bluer. Eventually the helium at the center is depleted. As the central energy source dwindles, gravitational forces again predominate. Consequently, the core contracts and grows hotter and denser. Helium fusion then migrates to another shell. The structure of the star's interior resembles an onion: an outer, hydrogen-fusion layer and an inner, helium-fusion layer surround an inert core of carbon and oxygen.

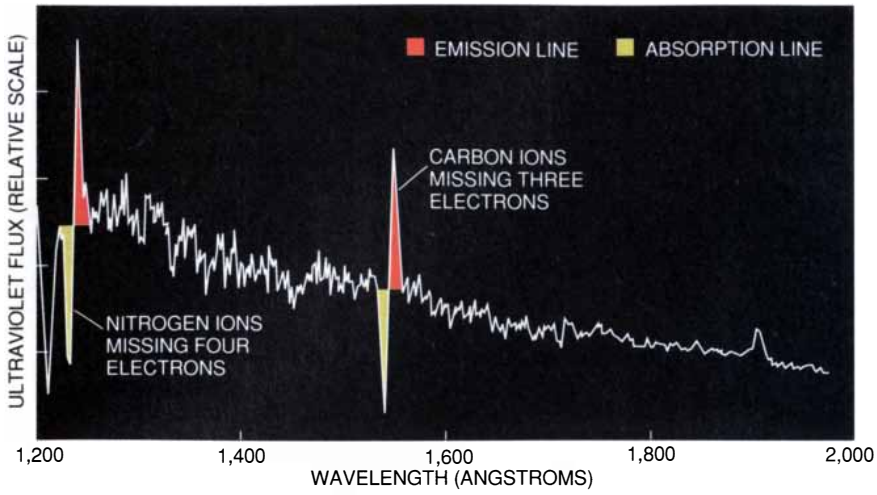
After the formation of the helium shell, the star swells to several hundred times the sun's diameter, at which point it is called an asymptotic giant branch star. Outside the dense core extends a huge but tenuous gaseous envelope, the distended outer part of the star. Because of the tremendous expansion, its surface temperature drops to about 3,000 kelvins, compared with 6,000 kelvins for the surface of the sun.

Because the next stage of stellar evolution proceeds extremely rapidly, the exact sequence of events is not yet well understood. An asymptotic giant branch star generates an intense wind that carries off its outer envelope. The existence of such winds is well documented, but the precise mechanism driving them is still somewhat of a mystery. The high rate of mass loss probably has to do with the fact that asymptotic giant branch stars oscillate significantly in radius, temperature and luminosity. Because of their substantial fluctuations in brightness, such stars are often called Mira variables, named after the bright pulsating star Mira, whose behavior is typical of the class.





PLANETARY NEBULA SCHEMATIC (*top*) shows an inner region of gas disturbed by a fast wind from the central star. A bright rim forms where the fast wind collides with the denser but more sluggish superwind. At greater distances, the superwind interacts with material shed earlier in the star's evolution, creating a crown. The earlier, AGB wind, which has had more time to travel away from the star, may compress outlying interstellar matter, giving rise to a limb-brightened halo. An image of NGC 6826 (*bottom*) displays many of these features. The sensitivity of the outer parts of the image has been greatly increased to reveal faint details.



ULTRAVIOLET SPECTRUM of the planetary nebula NGC 6826 records radiation emitted by ions (*peaks*) in the fast wind and absorbed by those ions (*dips*) moving toward the earth, seen silhouetted against the central star. The wavelength and intensity of the observed spectral features indicate that the wind moves at 2,000 kilometers per second and carries off about one ten-millionth of a solar mass per year.

Stars shed some material even while on the main sequence. But a star like the sun loses mass at a rate of only about one ten-trillionth of a solar mass a year into the solar wind, which moves outward at a rate of roughly 600 kilometers per second. When the star becomes an asymptotic giant branch object, the rate of mass loss picks up to about one millionth of a solar mass a year.

In their later stages, such stars generate an even more intense flow, called the superwind, which carries away as much as one ten-thousandth of a solar mass a year. Most of the remains of the star's outer envelope are siphoned off via the superwind. Asymptotic giant branch stars are so large that their outer layers are only weakly held by the gravity of the dense core. Gas need not move terribly fast to escape from the star. As a result, the superwind moves outward at a modest 10 to 20 kilometers per second.

Around 1980 several theorists, including Amos Harpaz and Attay Kovetz of Tel-Aviv University outlined a detailed, quantitative model of how giant stars transform themselves into planetary nebulae. Once the star has rid itself of most of its outer envelope, the superwind subsides. All that is left of the original star is a hot, naked core. This stellar remnant shrinks and becomes hotter, powered by fusion of what little hydrogen remains. Despite all the changes, the star's brightness remains constant at several thousand times the luminosity of the sun. Remarkably, the remnant star has about 0.6 times the mass of the sun, almost independent of the object's initial, main-sequence mass.

The cloud of gas around the star cools as it expands. When the temperature drops below about 1,000 kelvins, dust grains composed of carbon, oxygen, silicon and other heavy elements begin to coalesce. Each grain is one thousandth to one ten-thousandth of a millimeter across. The dust obscures the star by absorbing most of the visible radiation and reemitting it as less energetic, longer-wavelength infrared radiation. Although invisible in optical telescopes, such protoplanetary nebulae have been observed by infrared detectors on the ground and, in 1983, by the *Infrared Astronomical Satellite* in earth orbit.

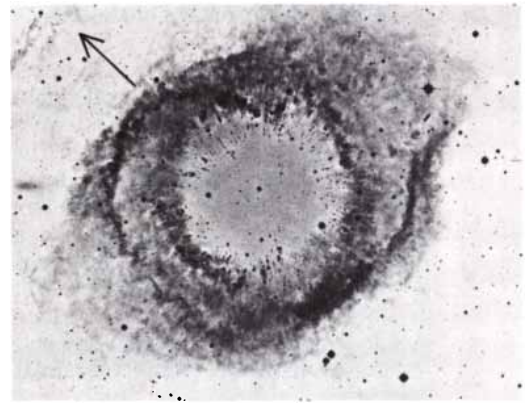
Several hundred to several thousand years after the end of the superwind, the surface of the contracting central star has heated to a temperature of 25,000 kelvins. By then the radiation from the star is so energetic that it strips electrons from the atoms in the nebula. That is why nearly all the observed gas in planetary nebulae is ionized. As ions collide with or combine with freed electrons, they emit bright spectral lines, primarily at optical and ultraviolet wavelengths.

Energetic radiation from the star is absorbed first by the inner regions of the nebula. As the central star continues to heat up and as the nebula expands (becoming less dense), ever larger regions of the nebula become ionized. Simultaneously, the dust thins out, and the visible luminosity of the nebula rapidly increases. When the gas cloud grows bright enough to be observed by optical telescopes on the earth, the object is classified as a planetary nebula. At its peak, a few thousand years after the ejection of the planetary nebula, the star attains a temperature of about 200,000 kelvins and a luminosity similar to its brightness when it was a giant star (several thousand times the luminosity of the sun).

The gradual penetration of ionizing radiation through the nebula explains the observed positive correlation between the size of a planetary nebula and its total ionized mass. The lightest planetary nebulae have a mass of about 0.01 solar mass and a radius of about 0.05 light-year; the most massive ones contain about one solar mass and extend several light-years across. The wavelength and intensity of radiation emitted by different elements depend on conditions (such as temperature, density and energy of ionizing radiation) that vary substantially across the nebula.

Some matter continues to stream out of the central star even after the asymptotic giant branch stage. The star now loses mass at a low rate (one ten-billionth to one ten-millionth of a solar mass a year), but this thin stream of material moves at an extremely high velocity, some 1,000 to 4,000 kilometers per second. This is the fast wind seen in spectral studies of some planetary nebulae. Its swiftness reflects the fact that the star is now much smaller and denser. Material must move roughly 100 times faster than the superwind to escape the star's surface gravity.

Although the total mass it transports is negligible, the fast wind plays a significant dynamic role in the development of planetary nebulae. The importance of the fast wind was first proposed by Sun Kwok of the University of Calgary, C. R. Purton of Dominion Radio Astrophysical Observatory and M. Pim FitzGerald of the University of Waterloo. The fast wind forms a shock wave surrounded by a hot, tenuous gas bubble in the central region of the nebula. The pressure of the bubble accelerates



STAR PLATES reveal the intricate structure of the Helix Nebula. The mottled, elliptical inner region (*left*) reflects ir-

the slower-moving, outlying superwind material. A thin shell of especially dense gas, which appears as a bright rim, arises where the two flows of gas meet.

In some cases, the outward front of the superwind compresses material from the regular wind that was emitted by the star earlier in its asymptotic giant phase. This process can give rise to a bright shell, called a crown. The regular wind may likewise interact with tenuous interstellar material, producing a faint, limb-brightened halo.

After several thousand years the star becomes very compact, and the fast wind ceases. Once the star exhausts the remaining hydrogen near the surface, nuclear fusion ends, and the star begins to cool and dim. Continued expansion also causes the surface brightness of the nebula to decrease. Eventually the planetary nebula disappears entirely, at which point the compact, naked central star is called a white dwarf. The duration of the fast wind and the time required to exhaust the hydrogen fuel strongly depend on the initial mass of the central star: massive ones shine brighter and evolve faster than do light ones. Roughly 10,000 to 30,000 years after it makes its first appearance, the planetary nebula fades to invisibility.

Not every star passes through a planetary nebula phase. Those less than 0.8 times the mass of the sun are insufficiently massive to form a nebula. Stars of more than eight solar masses are also ruled out because they end their life in violent supernova explosions. Astronomers have therefore concluded that only stars weighing between 0.8 and eight times the mass of the sun can evolve to form planetary nebulae.

This view is supported by the way that planetary nebulae are distributed throughout the galaxy. Most of the known nebulae are concentrated in the planar disk of the Milky Way. Disk stars are generally relatively young objects. The preponderance of planetary nebulae in the disk indicates that they have mostly evolved from young, short-lived stars more massive than the sun. On the other hand, five nebulae have been observed in the outer reaches of the galactic halo, a tenuous, spherical population of stars surrounding the disk. Halo stars are on average 10 billion years old, suggesting that planetary nebulae in the halo must have evolved from stars as light as or somewhat lighter than the sun.

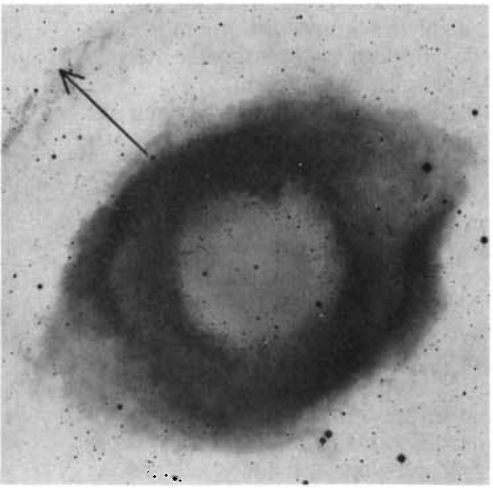
The structure of a planetary nebula is highly sensitive to the environment in which it forms and develops. In the absence of any outside influence, stars might be expected to blow perfect gaseous bubbles. But less than one tenth of the catalogued planetary nebulae are spherical. Most have a distinct axis of symmetry, indicating that additional forces are at work.

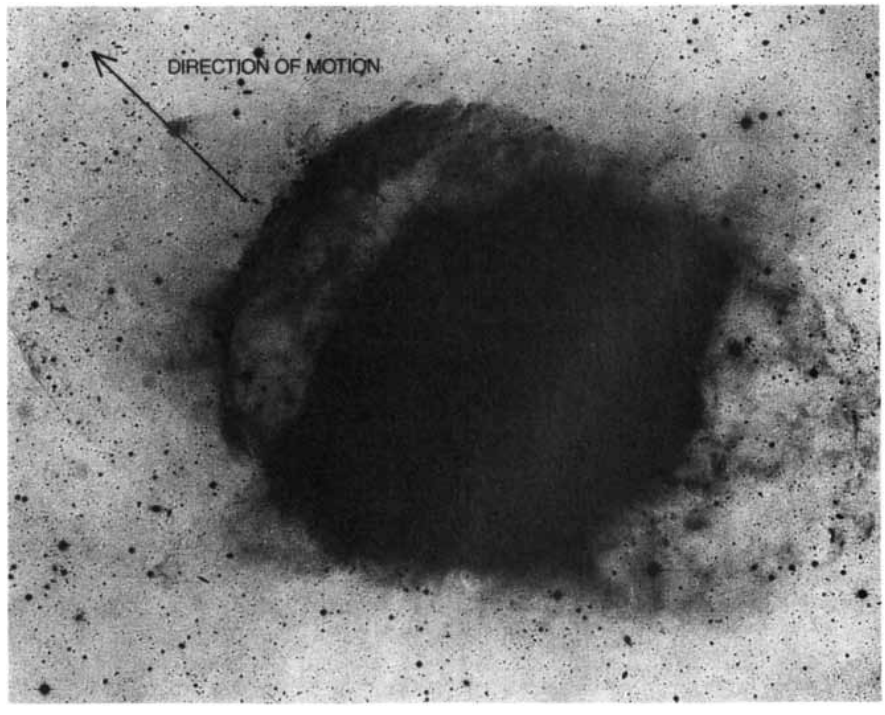
Planetary nebulae are classified as elliptical if they have moderate asymmetry, as is the case for NGC 3242 (the Ghost of Jupiter); they are considered butterfly if they show severe asymmetry, as do NGC 650-1 (the Little Dumbbell) and NGC 2346. Many nebulae also contain two bright knots along the poles on opposite sides of the star, as illustrated by NGC 7009 (the Saturn Nebula). These various kinds of nebulae all are axisymmetric; in other words, their two halves are mirror images of each other around the symmetry axis.

Most models hold that the axisymmetric shapes result from disproportionately high loss of mass in the equatorial plane of the star during its superwind phase. Bruce Balick of the University of Washington pointed out that observational data, which show that gas concentrates in the stars' equatorial planes, tend to support these models.

Mark R. Morris of the University of California at Los Angeles has proposed that aspherical planetary nebulae develop around binary star systems. He maintains that during its asymptotic giant branch phase the progenitor star grows so large that its outer envelope spills onto its companion. Gas from the envelope forms a swirling disk around the companion; two jets of matter squirt out perpendicular to the disk (the physics behind this process remains murky, but polar jets are commonly found emanating from stars surrounded by disks of matter). Tidal effects from the companion star cause the superwind to concentrate in the plane of its orbit. Material ejected in the polar jets produces bright knots of gas in the perpendicular direction.

In collaboration with Mario Livio of the Technion–Israel Institute of Technology, I have developed a model that





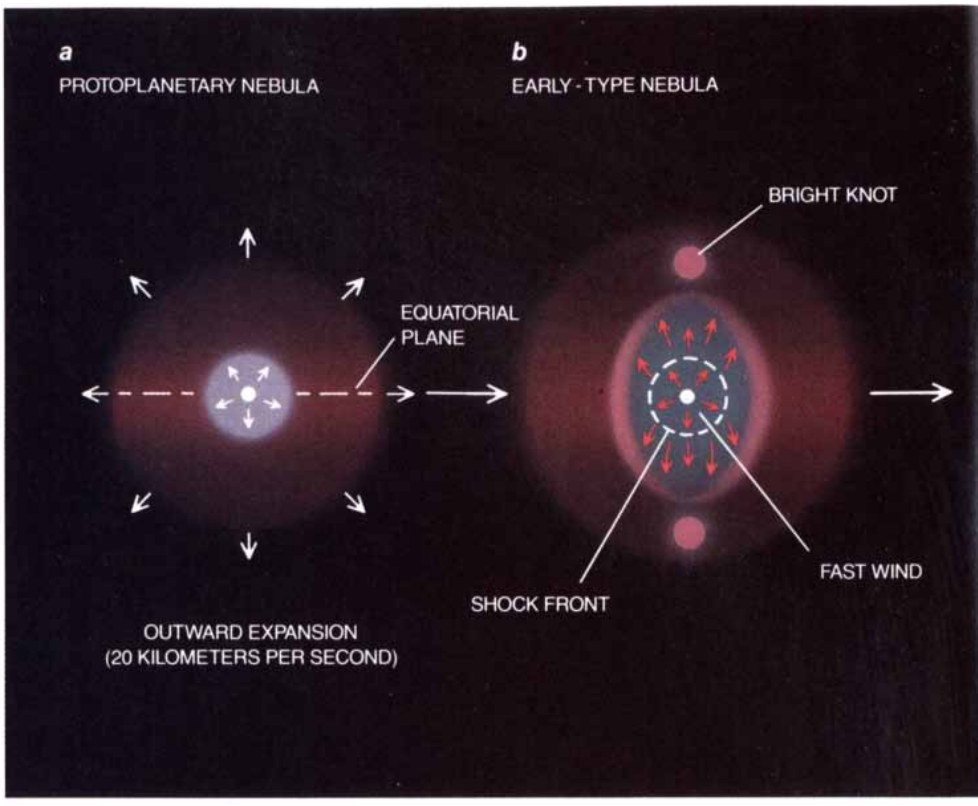
regular flow of matter from the central star. The star's motion through the interstellar medium compressed an outlying arc of gas, as seen at the upper left in a longer exposure (*center*). The most sensitive view of the nebula (*right*) overexposes the central regions but draws out a faint conical formation ahead of the nebula and ripples of low-density gas trailing behind.

accounts for the origin of more gently elliptical planetary nebulae. Our model is similar to the one developed by Morris except that the companion star orbits closer, inside the envelope of the progenitor star. Tidal forces and gravitational drag cause the companion star to spiral inward. In compensation, the gas in the companion's orbital plane migrates more quickly outward, with the effect that the superwind is particularly strong in the plane of the orbit.

In this case, the nebula expands into an elliptical rather than spherical shape. Astronomers have found that a number of elliptical and butterfly planetary nebulae do in fact have binary systems in their centers whose orbital periods are only hours to days. The brevity indicates a tight-knit pair of stars orbiting less than a few million kilometers apart.

A planetary nebula's shape may also be influenced by its motion through the interstellar medium. The interstellar medium is extremely rarefied: its density is about one atom per cubic centimeter in the galactic plane and drops off sharply above and below the plane. As a star and its attendant nebula orbit through the Milky Way, the interstellar medium blows by at velocities ranging from 40 to 150 kilometers per second. The part of the nebula facing the flow is decelerated and compressed in the direction of motion. The compressed face grows relatively dense and so glows brighter than its immediate surroundings.

Complicated features may appear where nebular material meets the interstellar medium. In the case of the Helix Nebula, very tenuous gas seems to have been stirred and compressed some distance ahead in the nebula's direction of motion. At present, only about 10 planetary nebulae have been observed that show clear signs of interacting with the interstellar medium. If this sample can be substantially enlarged, astronomers will have a useful tool for probing the density and other physical properties of the interstellar medium.



EVOLUTIONARY SCHEMATIC explains the myriad shapes of planetary nebulae. Outflow from the star often concentrates in the equatorial direction (*a*), probably because of gravitational effects from a stellar companion. As a result, the nebula

Despite the many advances in the study of planetary nebulae, some of their fundamental physical attributes, such as mass and size, remain uncertain because of the difficulty in determining their distances. Fortunately, quite a few nebulae are part of well-understood stellar systems. Two have been observed in globular clusters—dense spherical clusters of as many as one million stars—whose distances have accurately been determined. Several hundred nebulae appear to reside near the galactic center. They can all be assumed to lie at about the same distance from the earth as the center itself, about 25,000 light-years.

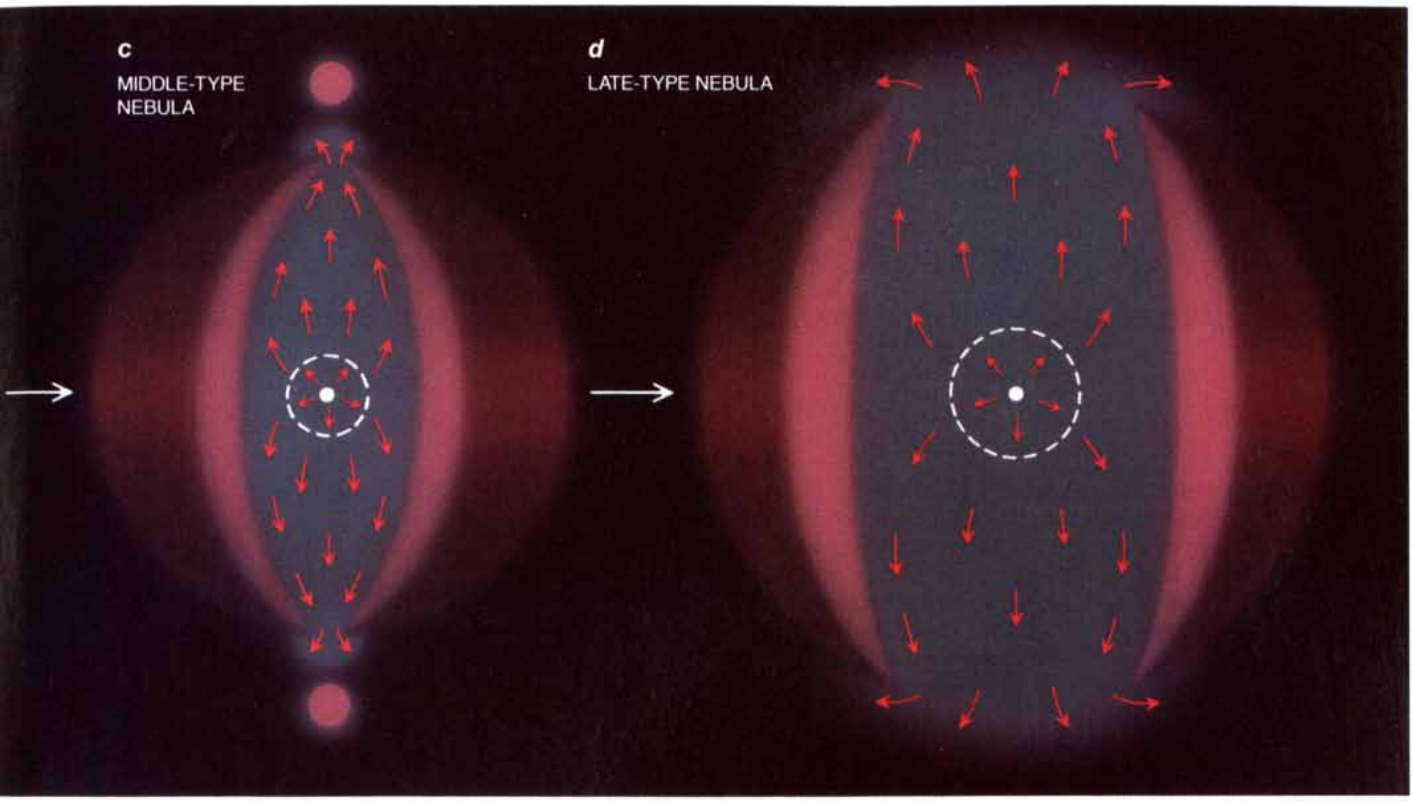
Stars in other galaxies are all about equally far from the earth. Hence, estimates of the distances to planetary nebulae in nearby galaxies are reasonably accurate. Some 60 planetary nebulae have been found in the Small Magellanic Cloud (one of the Milky Way's satellite galaxies, about 190,000 light-years away), 130 in the Large Magellanic Cloud (160,000 light-years) and a few hundred in the Andromeda galaxy (two million light-years).

For most planetary nebulae, the existing techniques for distance measurement are accurate to no better than plus or minus 50 percent. One technique, pioneered by Julie H. Lutz of Washington State University, depends on the dimming of light by interstellar dust, a phenomenon called extinction. Extinction increases at progressively shorter wavelengths in the optical and ultraviolet bands. By contrasting the observed intensity of two emission lines at different wavelengths with the theoretically expected ratio, Lutz deduced the total amount of dimming. After estimating the extinction per unit distance in the direction of the nebula (from measurements of the light of stars in the same part of the sky), she could then calculate its distance.

Several methods for finding distances rely on the average properties of a large number of planetary nebulae. For example, if it is assumed that they all contain the same amount of ionized gas, the distance to a remote nebula can be extrapolated from the distance to a much more proximate one. To find the distances to planetary nebulae, scientists compare the angular size and strength of the emission from hydrogen ions of an unknown nebula with those of a known one. This method will be highly inaccurate for any individual nebula but can yield reasonable average distances for a large group.

Distance determinations based on samples of planetary nebulae have potentially important applications for cosmology. Researchers dearly want to obtain reliable measurements of the distances to remote galaxies in order to determine the expansion rate of the universe, known as the Hubble constant. Finding the real value of the Hubble constant will enable scientists to deduce the size and age of the universe. That information in turn will help answer questions about how the universe began and when and how it will end. At present, the Hubble constant is known only to within a factor of two.

Astronomers measure distances to nearby galaxies by studying a class of



assumes an elliptical or butterfly form. The star may also expel gas in the polar direction, giving rise to bright knots (*b*). The fast wind (*red arrows*) from the star creates a compressed, bright shell where it meets the superwind. Because of the lower density at the poles, the fast wind breaks there first (*c*) and expands into the interstellar medium (*d*).

stars called Cepheid variables. Planetary nebulae are bright and fairly easily identified in galaxies whose stars all appear smeared together. Moreover, nebulae radiate strongly at a few specific wavelengths, which makes it easy to separate their emission from that of the rest of the galaxy. Robin Ciardullo of Pennsylvania State University, George Jacoby of Kitt Peak National Observatory and Holland Ford of the Space Telescope Science Institute, along with several collaborators, have therefore set out to use planetary nebulae as celestial yardsticks.

The researchers work from the supposition that similar types of galaxies should contain similar populations of planetary nebulae. Specifically, if the nebulae are divided into several luminosity classes, the proportion of the population in each class should remain about the same from galaxy to galaxy. Because the goal is to find the distance to remote galaxies, astronomers have focused their attention on the brightest planetary nebulae and have observed them specifically at the doubly ionized oxygen line (5,007 angstroms), where they are easily identified.

Ciardullo and his colleagues have found that even in galaxies whose structure and stellar compositions differ slightly, the brightest planetary nebulae do indeed have about the same luminosity at 5,007 angstroms. They concluded that this subgroup can be used as a standard candle—that is, a source whose absolute brightness is known and does not depend on the location.

From the expected luminosity of the brightest nebulae, one can deduce the distance to any galaxy in which planetary nebulae can be positively identified. Stuart R. Pottasch of the Kapteyn Astronomical Institute in the Netherlands has demonstrated that this method yields accurate distances to the galactic center, which have been measured by other, better-established techniques.

Ciardullo's group has estimated the distance to the Virgo galaxy and calculated a value for the Hubble constant that lies on the high end of the range of previous estimates. Their finding implies that the universe is smaller and younger (in the vicinity of 10 billion years old) than most cosmologists think. These numbers are tentative and somewhat controversial. Observations of planetary nebulae in additional galaxies and further cross-checking with other distance yardsticks will help refine the technique of using planetary nebulae as standard candles.

Many other aspects of planetary nebulae cry out for further clarification. The extraordinarily rapid transformation of asymptotic giant branch stars into nebulae is poorly understood. The nature of the superwind and fast wind and how the two interact remain puzzling. As researchers refine their studies of planetary nebulae, they will uncover new information about space environments ranging from the interiors of old, sunlike stars to the tenuous material that floods the entire Milky Way. They will also obtain an ever improving understanding of the brief, final moment of glory that awaits our sun five billion years hence.

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Blind Spots

Investigating how the visual system compensates for gaps in perception is helping researchers to elucidate how the brain processes images

by Vilayanur S. Ramachandran

As he dissected a human eye, the 17th-century French scientist Edme Mariotte noticed the optic disk—the area of the retina where the optic nerve attaches to the eyeball. He realized that, unlike other parts of the retina, the optic disk is not sensitive to light. Applying his knowledge of optics and the anatomy of the eye, he deduced that every eye should be blind in a small portion of its visual field.

The reader can easily confirm Mariotte's conclusion by examining the illustration below of a disk on a colored background. Close your right eye and hold the page about a foot away from your face. Concentrate on the square as you slowly move the illustration toward your eye. At some critical distance, the disk should fall within your blind spot and disappear completely. In fact, you should perceive the disk as covered by the color of the surrounding background. This visual process is known as filling in.

Recently psychologists have begun to appreciate that filling in is a manifestation of a more general perceptual mechanism called surface interpolation. When a person looks at a table, for instance, it seems likely the visual system extracts information about its edges and creates a mental representation that resembles a cartoon sketch of the table. The visual system might then apply surface interpolation to fill in the color and texture of the table. Such a process would allow the visual system to avoid the computational burden of creating a detailed representation of surface colors and textures.

To understand how the brain interpolates visual information, my colleagues and I at the University of California at San Diego have conducted many experiments that test percep-

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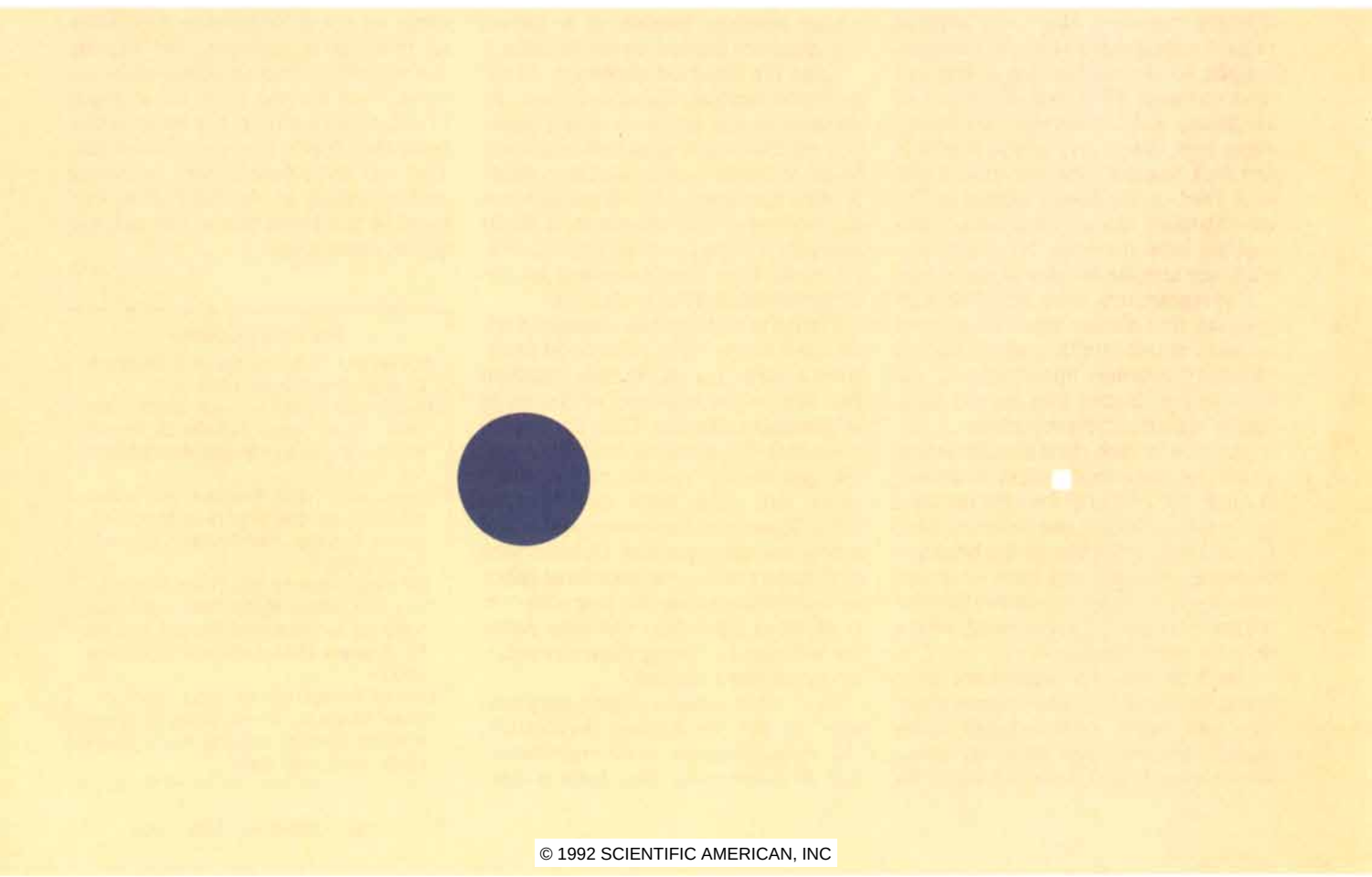


tion in the blind spot. The illustrations in this article offer the reader a chance to try a few of these experiments. To enrich our analysis, we have also investigated two types of "artificial" blind spots. First, we developed a harmless technique for inducing temporary blind spots. Second, we examined several individuals who suffer from scotomas—regions of blindness caused by damage to a small portion of the brain. The work has enabled us to discover many characteristics of the filling-in process, and we have begun to understand how filling in relates to other visual processes, such as edge detection and motion perception.

Psychologists have known for some time that if a person glances at an object, a perceptual representation of the object forms in the visual areas of the brain. In contrast, the brain uses another strategy to keep track of objects outside the visual field, such as those behind the head. For such objects, the brain creates what might be loosely called a conceptual representation, something similar to a logical inference. The distinction is not merely semantic. Perceptual and conceptual representations are probably generated in separate regions of the brain and may be processed in very different ways.

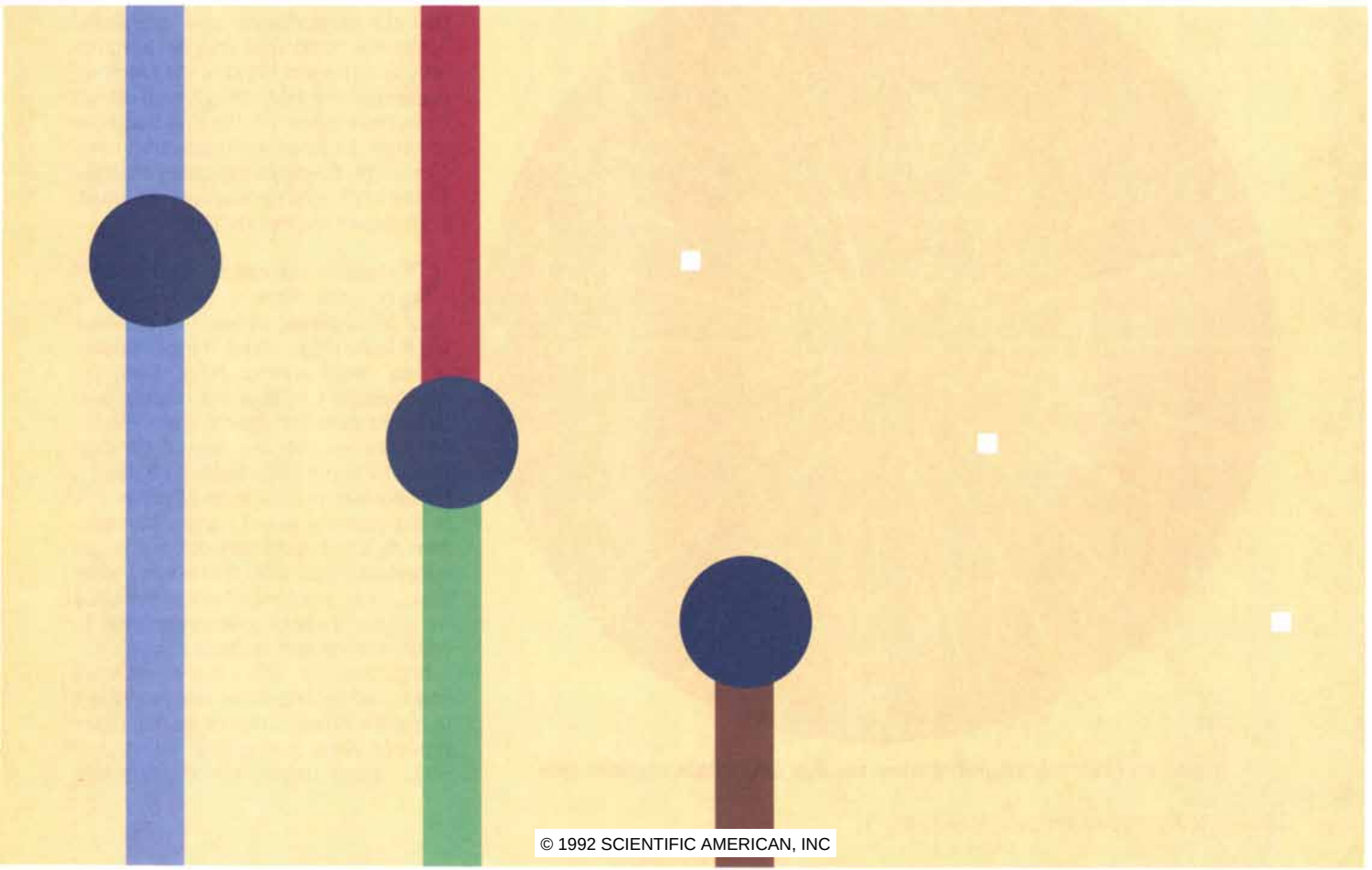
How rich is the perceptual representation in the region corresponding to the blind spot? To answer this question, we asked volunteers to examine a series of simple images. We began with an image in which a line is interrupted by a disk [*see illustration below*]. When a volunteer aimed his blind spot so that it covered the disk, the line appeared continuous in both form and color. Similar observations were made when we displayed a vertical segment that was red on top, green on the bottom and covered by a disk where the segments meet. Subjects reported that when the disk falls in the blind spot, the line appears continuous even though, paradoxically, they could not actually see the border between the green and red segments. The paradox arises presumably because part of the visual system is signaling that the line is continuous while another part is unable to discern a border between the red and green colors.

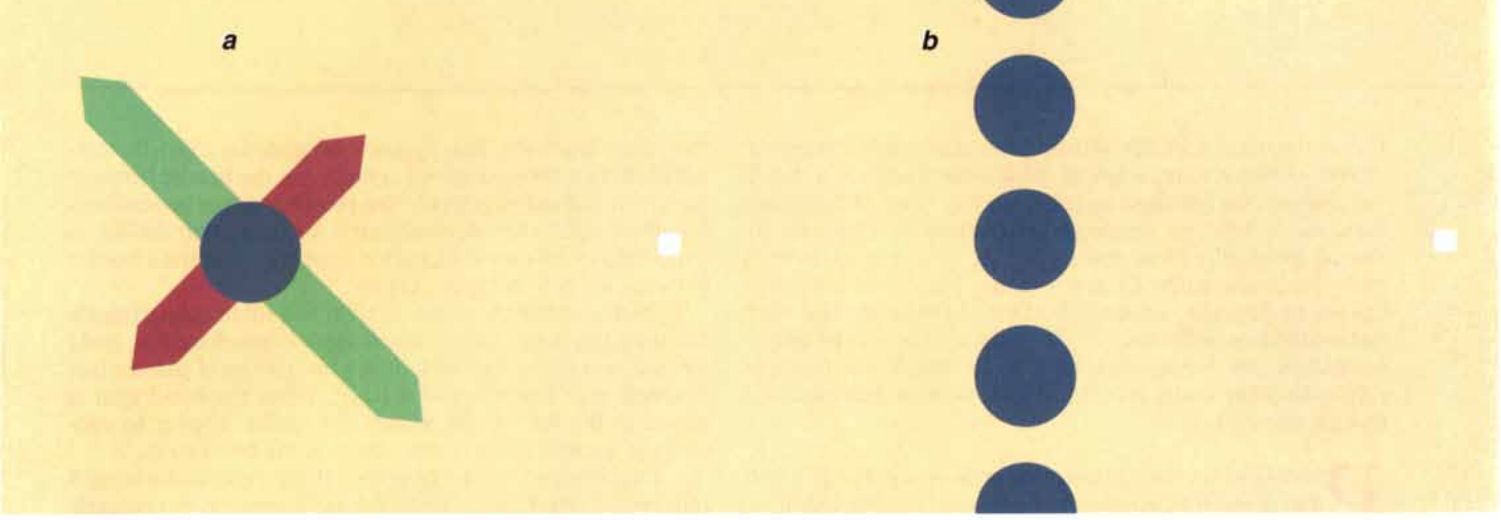
To test whether the visual system will fill in more complicated patterns, my wife, Diane Rogers-Ramachandran, and I devised several figures, including a bicycle wheel pattern [*see illustration at bottom of next page*]. When the blind spot is aimed at the hub of the wheel, the spokes appear to converge at a single point in the center of the blind spot.

A similar effect can be observed if the center of a large X falls on the blind spot. The X appears complete. But remarkably, if one of the segments that make up the X is longer than the other, only the longer segment appears complete [*see illustration at top of next page*]. This result suggests that the filling-in process can be influenced by visual stimuli quite distant from the blind spot.

We were also able to show that filling in is not "cognitive," that is, it is not based on expectations of what things ought to

DISK (*opposite page*) will disappear if it is positioned within your blind spot. Shut your right eye, and hold the page about a foot away from your face. Focus your gaze on the square and at the same time slowly move the illustration toward your eye. At some point, the disk will disappear and will be filled in with the background color. If the disks below fall within your blind spot, they, too, will be filled in. The leftmost line will appear complete. The middle line will also appear continuous, but the color of the line in the filled-in region should not be discernible. In the rightmost figure, the line segment will not protrude into the blind spot.



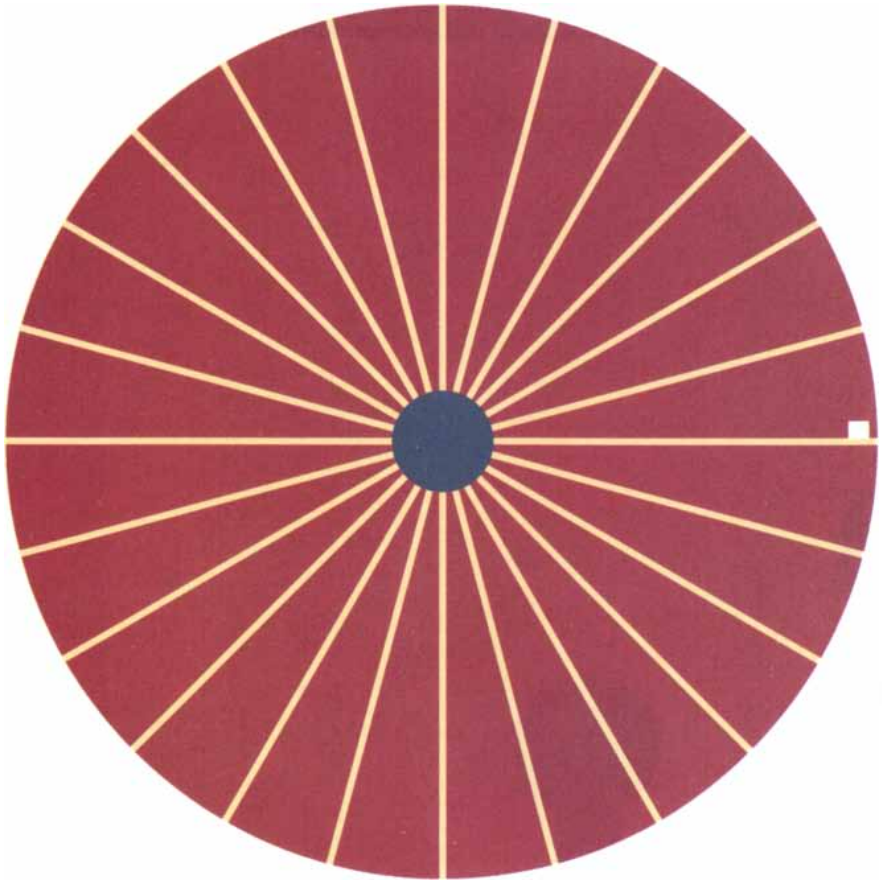


FILLING-IN PROCESS associated with the blind spot is a sophisticated visual function. If the blind spot falls on the center of a cross (*a*), only the longer segment appears complete. For a pattern of dots (*b*), the dot positioned within the blind spot simply disappears into the background. In illustration *c* the vertical and horizontal segments are misaligned, but when the disk is positioned within the blind spot, the vertical line looks continuous and straight, and the horizontal line looks staggered. This effect was first noticed by Jerome Lettvin and his colleagues at Rutgers University. Motion also influences perceptions that are associated with the blind spot. If you flip back and forth between illustration *d* and the one at the top of page 91, the line will appear to move diagonally. But if you aim your blind spot at the gap and then flip be-

look like. For example, we generated an image that consisted of a vertical column of large spots, one of which was positioned inside the blind spot [*see illustration above*]. All subjects saw the spot vanish; they did not "hallucinate" the missing spot in order to preserve the pattern.

One of the most interesting insights came when we experimented with illusory contours. The visual system produces these contours when the eye records certain sets of incomplete shapes or broken lines. For example, we generated an image consisting of several horizontal lines on a colored background [*see illustration on next page*]. Each line had a small gap about a third of the way from one end. The visual system does not interpret the image simply as several broken lines; instead it produces two illusory contours defining a vertical strip.

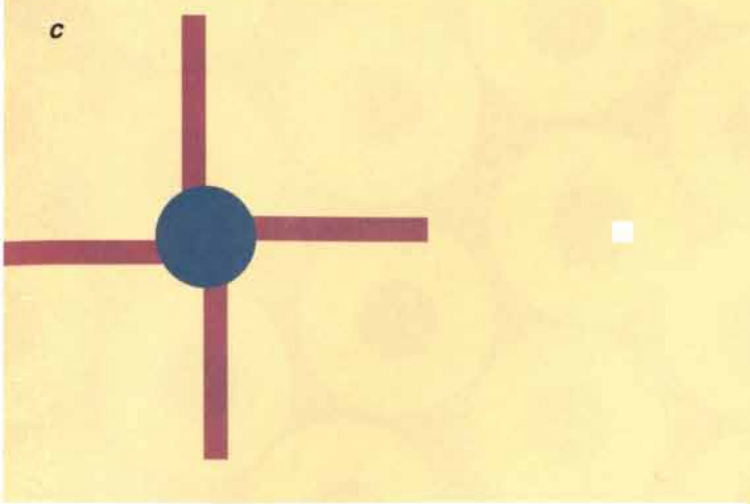
When we asked volunteers to position their blind spot on a break in one of the horizontal lines, most reported that the vertical strip was completed across the blind spot, and the horizontal line remained broken. Yet when we presented the same image with all but three lines removed, the line that runs through the blind spot appeared complete. The filling-in process therefore seems to depend on whether the illusory contours are well defined.

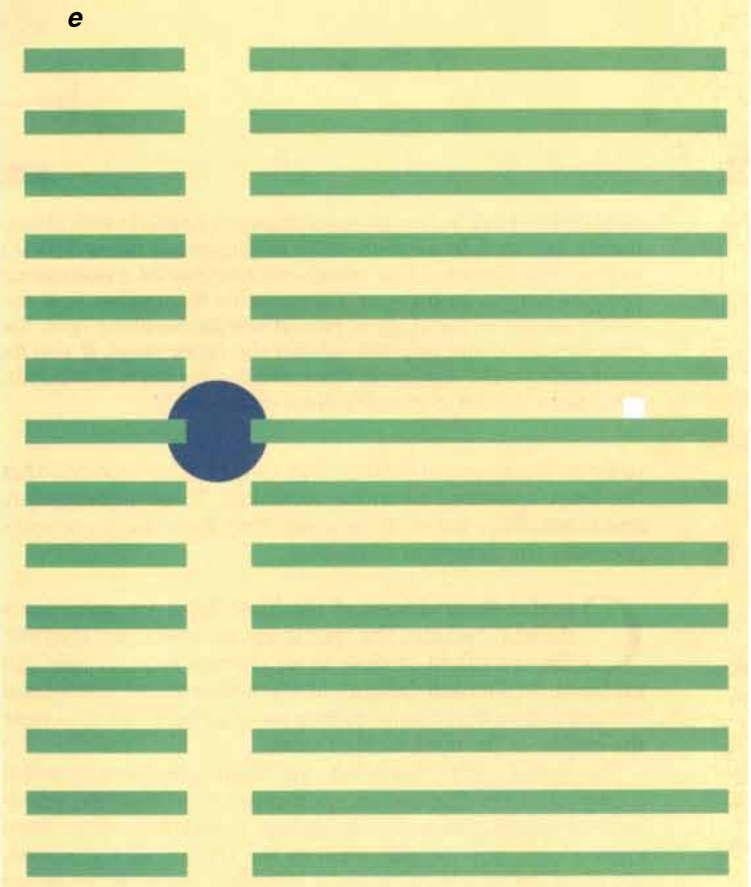


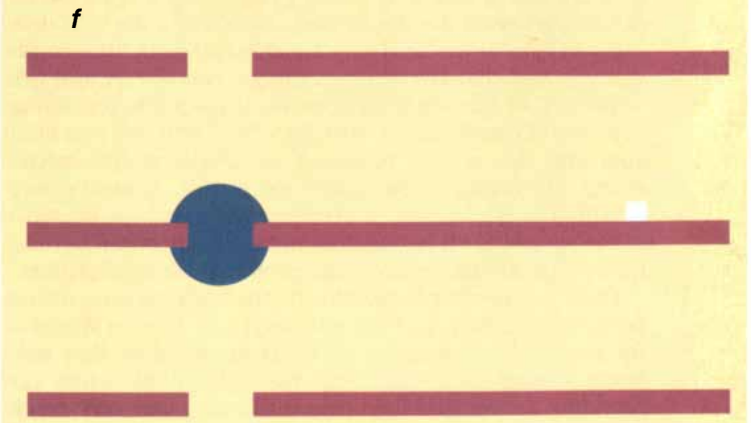
WHEEL PATTERN is completed when the disk falls within the blind spot.

Scientists can deduce the basics of how the filling-in process works by applying decades of accumulated knowledge about the physiology of the visual system. First of all, the light-sensitive cells of the retina translate light intensity and color into electrical impulses that are relayed through the optic nerve to the brain. Specifically, the impulses reach a sheet of nerve cells in the primary visual cortex. The neurons in this region sort out the visual information and relay it to several other areas. Each area seems to be specialized for a type of visual processing, such as color, motion and perhaps shape.

Beginning in 1987, my co-workers and I tried to determine whether filling in occurs before, after or during other types of visual processing. We started with a rather simple type of processing







tween the pages, the line will only move vertically. In illustration *e*, the subjective contours give the illusion of a vertical strip between several horizontal lines. The vertical strip appears continuous when the disk is positioned within the blind spot. If the vertical strip is not well defined (*f*), the horizontal line that falls within the blind spot will be filled in rather than the vertical strip.

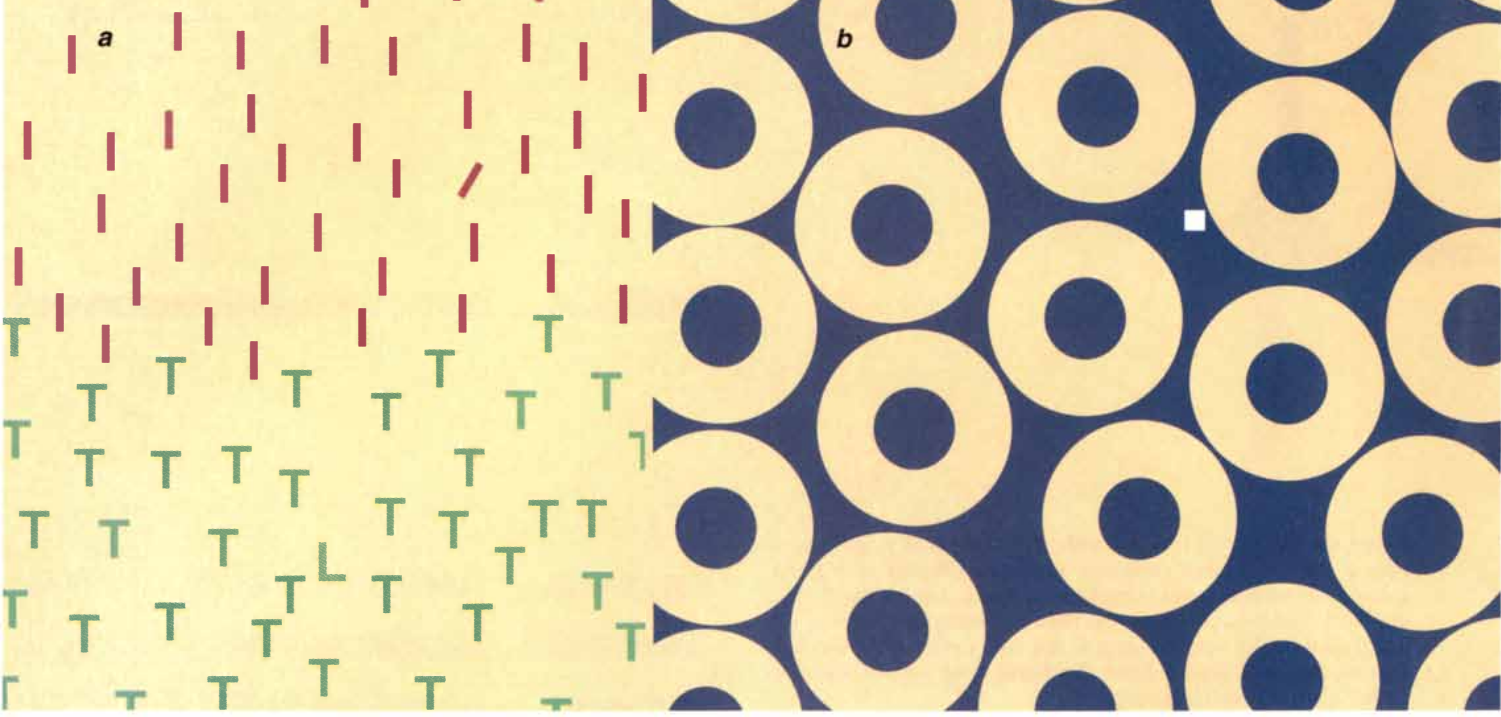
that generates a perceptual effect known as pop-out. The visual system tends to direct attention to certain so-called elementary features in the visual environment. These features appear conspicuous when displayed next to many distracting forms that differ from the targets in such characteristics as color or orientation. Indeed, some psychologists have suggested that pop-out can occur only for features extracted relatively early in visual processing.

My collaborators and I wondered whether filling in occurs before or after the process that produces pop-out. To explore this, we generated an image consisting of several rings and asked the volunteers to place the center of one of the rings in their blind spots [*see illustration on next page*]. Interestingly, the subjects commented that the ring surrounding their blind spots was filled in and was transformed into a homogeneous disk. They also noted that the disk stood out among the other rings.

This observation has two important implications. First, the filling-in process must occur quite early in visual processing since it actually precedes pop-out. And second, filling in must involve the generation of a perceptual representation. If no such representation was formed, the subjects would not experience pop-out.

William Aiken and I then examined the relation between filling in and motion detection, which occurs during the earliest stages of visual processing. We exploited a familiar illusion known as apparent motion. If two identical parallel lines are displayed rapidly one after the other, for example, the brain tends to perceive a single line in motion. Indeed, apparent motion is the illusion that allows us to perceive continuous movement when a series of images is flashed on a movie screen.

For our experiments, we devised two images, each containing a line interrupted by a small gap [*see illustrations at top right corner of this page and page 91*]. We positioned the gaps in such a way that when the images were displayed in rapid succession, the gap appeared to move diagonally. To start, we presented a subject with the first image and asked him to aim his blind spot at the gap. When the individual commented that the line appeared complete, we switched it off and flashed the second shifted image. We had expected that if filling in followed motion detection, the subjects would con-



DIAGONAL LINE is conspicuous among a field of vertical segments, but an L in a group of Ts is somewhat more difficult to find. The diagonal line stands out because of a perceptual process known as pop-out. Likewise, in illustration *b*, if the center of one of the rings is placed within the blind spot, the ring will fill in and pop out against the other rings. If you fix your gaze on the square in illustration *c* for several seconds, the colors will fill in the disk from either side.

tinue to see diagonal motion. But, in fact, they reported that the lines appeared to move vertically. These experiments and others have led us to conclude that the filling-in process precedes the detection of motion.

Careful observations of the blind spot are sometimes difficult because the spot is always at the periphery of the eye's field of view. In an attempt to overcome this problem, Sir Richard Gregory of the University of Bristol and I found a harmless way to induce an artificial blind spot near the center of the eye's field of view.

The reader can perform our experiments at home by using a television set. Choose an open channel so that the television produces "snow," a twinkling pattern of dots. Then stick a very tiny circular label in the middle of the screen. About eight centimeters from the label, tape on a square piece of gray paper whose sides are one centimeter and whose luminance roughly matches the gray in the snow. To produce the same visual effect, Gregory and I used a computer to generate the shapes and a twinkling pattern of dots.

If you gaze at the label very steadily for about 10 seconds, you will find that the square vanishes completely and gets "replaced" by the twinkling dots. We suspect that this filling-in process is analogous to that associated with the true blind spot and that it may be based on similar neural mechanisms. The fading of the square is probably caused by overstimulation and fatigue of neurons that signal the presence of the square. Such fading does not normally occur, because the eye usually moves around, preventing overstimulation.

These results are consistent with physiological experiments performed recently by Charles Gilbert and Torsten Wiesel of the Rockefeller University. By studying primates, they have made a remarkable discovery: the cells of the retina surrounding a damaged light-insensitive area can very quickly start influencing the primary visual cortex in the region associated with that same area. This observation—and others made by Ricardo Gatas of the National Institutes of Health and John Kaas of Vanderbilt University—might explain the filling-in process that we observed.

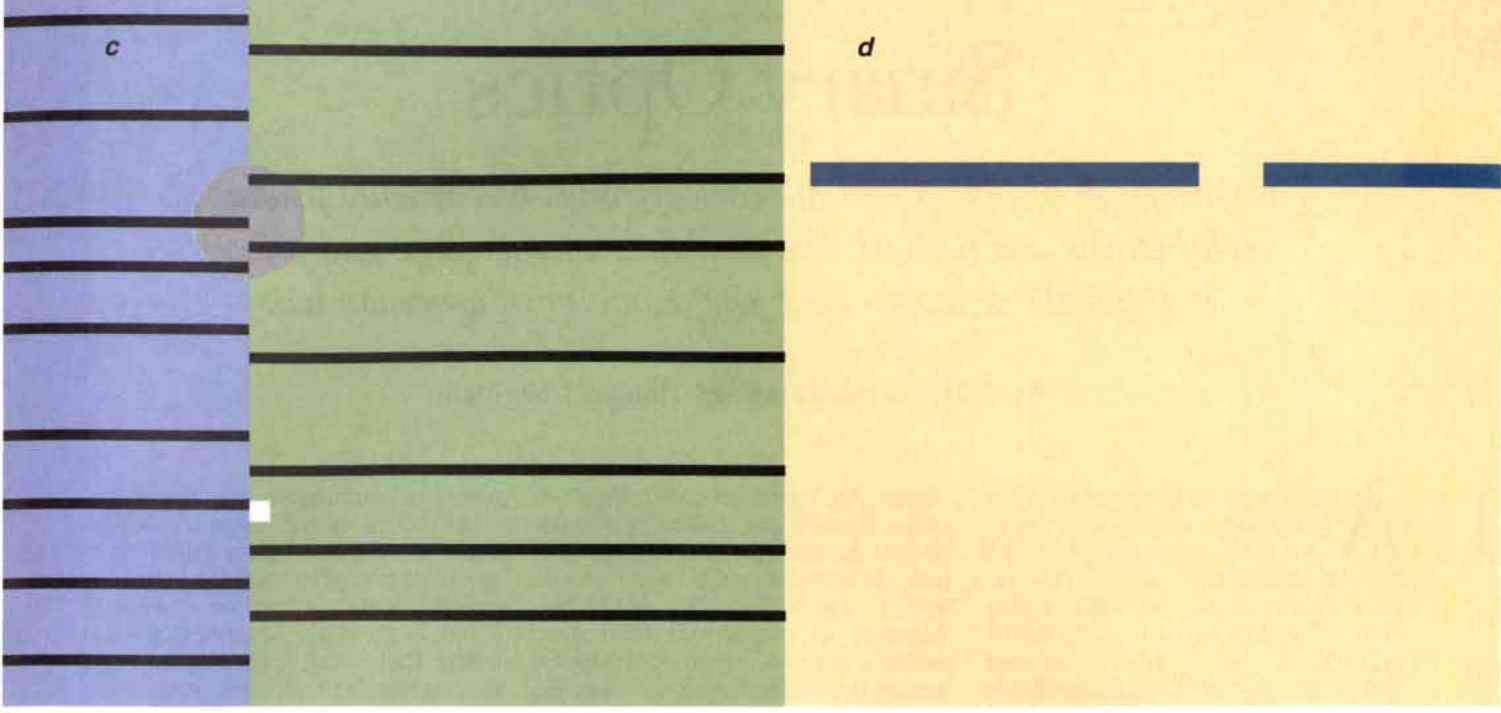
Recently we came up with an interesting variation of the original "twinkle" experiment. When a volunteer indicated that the square had been filled in with twinkling dots, we instructed the computer to make the screen uniformly gray. To our surprise, the volunteers reported that they saw a square patch of twinkling dots in the region where the original gray square had been filled in. They saw the patch for as long as 10 seconds.

The observation suggests that a set of neurons actually generates a representation of the region that was filled in with twinkling dots. Furthermore, the evidence implies that the representation can persist even after the surrounding dots have disappeared.

Filling-in effects can also be observed in static, nontwinkling patterns. For example, color borders tend to fade when the subject fixates on a particular image. (This has been studied intensively by A. L. Yarbus of the Russian Academy of Sciences in Moscow and Thomas Piantanida of SRI International.) My son, Chandramani Ramachandran, and I experimented with a pattern in which a gray disk straddles a vertical boundary between two colors, green and blue, of equal luminance. We asked subjects to gaze at the disk for several seconds. They reported that the disk was filled in with the two colors, but they could not make out a border between the colors. Instead they saw a diffuse, nebulous haze.

Next we altered the image somewhat by adding several black horizontal segments [*see illustration on opposite page*]. Our intention was to create an illusory contour that coincided with the color border. After the subjects gazed at the pattern for a few seconds, the colors filled in the disk from the two sides. But unlike the previous experiment, they formed a crisp color border along the illusory contour. This result is surprising because most vision researchers have assumed that the filling-in process depends only on such simple factors as the presence of edges defined by changes in luminance.

During the past year, we have begun investigations of one of the most interesting kinds of blind spots. If a person injures a tiny area of the visual cortex because of an accident,



illness or surgery, he may have a scotoma, that is, he may be blind in a small section of the visual field.

A person is often completely unaware of a scotoma. If she gazes at a pattern on wallpaper, for example, she does not perceive her scotoma as a change in color or a break in the pattern. Indeed, the design will appear uniform. Yet if a disk of any color or pattern is pasted against the wallpaper in the area corresponding to the scotoma, the individual will not notice the disk and will continue to see only the wallpaper.

My colleagues and I examined two patients who had scotomas near the center of their field of view. (Hanna Damasio and Leah Levi assisted us by proving that the visual areas in the brain were indeed damaged in these patients.) We first presented the patients with a large circle so that it partially overlapped their scotoma. They reported that after about eight seconds the obscured part of the circle emerged, completing the figure. This effect contrasts sharply with similar experiments done on the natural blind spot. When a part of the circle fell within the blind spot, it did not fill in.

Why is there a difference? Most cells in the undamaged visual cortex receive input from retinal cells of both eyes, but the cortex contains a patch of neurons that corresponds to the left blind spot and that receives signals only from the right eye. (A similar arrangement exists for the right blind spot.) Therefore, if a circle falls partially within the blind spot of, say, the left eye, the right eye can usually compensate by signaling the presence of the part of the circle invisible to the left eye. The visual system perceives a complete circle. But if the right eye is shut, it does not signal the presence of the obscured piece, and the visual system simply assumes that a piece of the circle is missing.

On the other hand, if the visual cortex is destroyed in some region, it cannot process signals from either eye, and the visual system seems to adapt by filling in the missing piece.

We then generated an image of a vertical line interrupted by a disk. The patients reported that when the scotoma was aimed at the disk, the line was completed, although, curiously, the process took about five seconds. (A delay of this kind is never seen for the natural blind spot.) We then shifted the upper section of the line horizontally so that the parts on either side of the disk were no longer collinear. The patients reported that the lines initially looked misaligned but that they soon started moving horizontally toward each other until they became collinear and connected across the scotoma. They told us that the sensation of movement was very vivid.

We can only guess as to why the lines seem to become collinear. One of the higher visual areas may get a few clues that the segments on either side of the scotoma are part of the same line. When this area does not receive conflicting signals from the primary visual cortex (because it is damaged), the visual system may ultimately interpret the image as a single vertical line.

Finally, Kerrie A. Maddock, Daniel Plummer and I asked one of the patients to look at a television screen that displayed twinkling red dots. At first, the patient said that only the red color filled in his scotoma; after about eight seconds the twinkling red dots seemed to fill in as well. This experiment suggests the visual area responsible for filling in color may be different from the area associated with the filling in of motion. (The visual cortex of monkeys has such distinct areas, as shown by Semir Zeki of the University College, London.)

In time, we hope to elucidate the similarities and differences between scotomas and blind spots. Perhaps we will learn exactly how the filling-in process is related to surface interpolation and where such processes occur.

Some readers may contribute to this research or, at least, continue to experiment with the blind spot. With a little bit of practice, one should be able to aim the blind spot, making any small object disappear. According to folklore, King Charles II of England used this trick to amuse himself. He would visually decapitate his ladies-in-waiting. But I hope readers will find more pleasure in examining their own heads than in obscuring those of others.

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Binary Optics

This marriage of optics and microelectronics has already produced useful lenses one fortieth the thickness of this page and arrays of 10,000 telescopes each the diameter of a human hair

by Wilfrid B. Veldkamp and Thomas J. McHugh

A visit to a precision optical shop seems like a flashback to another era: the scene is replete with heavy machines, belts, pulleys, tin cans, paintbrushes, spattered sinks, makeshift stoves and garden hoses. Skilled artisans use grinding wheels and then cast-iron tools coated with successively finer grades of abrasives to shape lenses for telescopes, optical signal-processing equipment and other systems. Although such methods can yield lenses of exquisite quality whose shape is precise to a small fraction of a wavelength, production is slow and painstaking. Furthermore, traditional grinding and polishing can produce only spherical shapes, which do not focus light as efficiently as possible.

Binary optics (named for its close alliance to the making of digital circuitry) is a new technology that eliminates almost all the steps of traditional lens making. Instead designers etch desired shapes directly into the surface of any optical material, using techniques originally developed for manufacturing integrated circuits. Binary optics produces lenses of high quality and permits rapid, inexpensive reproduction of optical elements whose focusing properties can be tailored in ways that were previously impossible.

Thanks to this technology, engineers are no longer constrained by the capabilities of conventional optics. They can create virtually any system or component within the bounds of human ingenuity, provided it can be manufactured by current microcircuit technology. Furthermore, as microcircuit fabrication methods improve, so will binary optics. Among the applications now under investigation are microlenses for computer vision, light multiplexers for optical communications and even binary optical microsurgery intended to improve eyesight. Many companies are engaged in binary optics research, and some have begun developing products. The scope of this new technology is so broad that designers have yet to explore more than a fraction of its potential.

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Binary optical devices not only are fabricated by methods alien to those used for producing most lenses, they also work according to a somewhat different set of principles: they control light by diffraction rather than refraction. A conventional lens brings light from a distant source to a focus because rays passing through the edge of the lens strike the surface of the glass at a more oblique angle and so are bent more strongly than those passing through the center. The bending is a necessary consequence of any passage of light between substances of differing refractive indexes. In contrast, a device based on binary optics breaks up the wave front of incoming light at each point on the lens surface and reconstitutes it as a wave traveling in the desired direction to the point of focus.

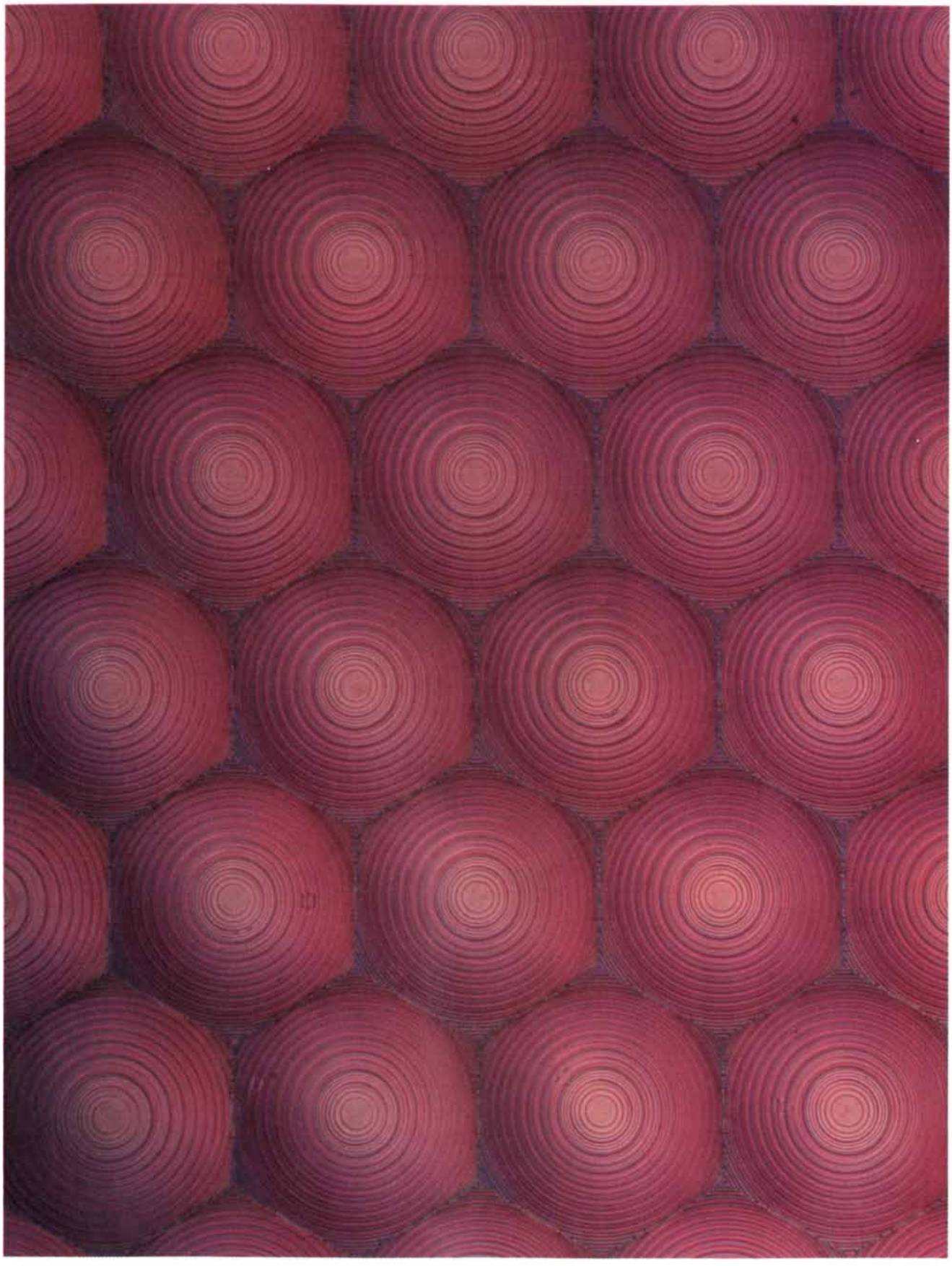
Most refractive optical systems (a category that includes almost everything except for astronomical telescopes, which employ reflection) suffer from a number of inherent shortcomings, such as spherical aberration. Light passing through different parts of the lens focuses at different points along the optical axis, causing a blurred image. Designers must often prescribe lenses of several different materials and curvatures to compensate for aberration.

Diffractive optical elements can be much thinner and lighter than refractive ones because they need to induce changes of only a fraction of a wavelength in the shape of an optical wave front. They work according to Huygens's principle: each point on the wave front of the manipulated light beam acts as a source of spherical waves whose constructive and destructive interference yields a new wave front. The shape of this wave front may be altered so that the path of the light is bent, converges to a focus or displays whatever other behavior the designer chooses.

Perhaps the simplest example of this phenomenon is the Fresnel zone plate, which employs diffraction to focus monochromatic light. Zone plates consist of a series of concentric light-blocking rings separated by slits. The spacing of the slits is arranged so that light waves coming from all the slits interfere destructively except at the plate's focal point, where they reinforce one another to create a bright spot. The lithographic and etching steps used to make integrated circuits are perfectly suited to make a structure such as the zone plate: regions destined for slits are etched away, and the rest of the material is left untouched.

Although they are simple to make, Fresnel zone plates are optically inefficient because less than half the light striking them passes through the slits. Binary optics produces similar effects more efficiently by etching different parts of an optical blank to different depths rather than just blocking light or allowing it to pass.

The simplest binary optical structure is the prism, which appears under the microscope as a series of tiny staircases. When a light wave falls on the prism's surface, the wave, in essence, is broken up into secondary wave fronts. Each wave front is delayed in proportion to the thickness of the staircase at that point (the maximum thickness is just



MICROSCOPIC LENS ARRAY was made by the same techniques used to etch integrated circuits on silicon wafers. Each lens is only 200 microns across. The authors predict that such arrays could help bring about a revolution in machine vision by focusing light onto tiny photodetectors surrounded by image-processing circuitry.

enough to delay a wave front by one full wavelength). When these wave fronts interfere, they produce a new wave front at an angle to the incoming one. Thus, in effect, the light is bent. Instead of the few millimeters of glass required to bend light in a conventional prism, however, the binary optical version requires as little as two microns of material.

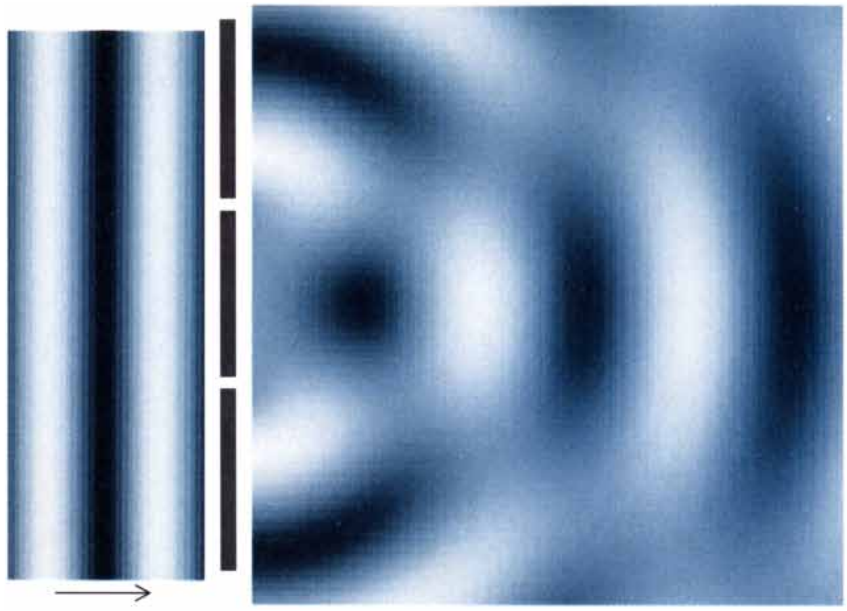
A lens is essentially a variable prism, capable of bending light through different angles depending on the part of its surface that the light strikes. Thus, the staircase technique can be extended to make a binary optical focusing device. A circular blank is etched with a series of concentric staircase patterns. Each staircase proceeding out from the center is made successively steeper and closer to its neighbor. The steeper staircases bend the light by ever increasing angles so that light passing through the edges of the lens is focused to the same point as light passing through the center. By choosing the steepness and spacing of the staircases properly, designers can eliminate spherical aberration completely.

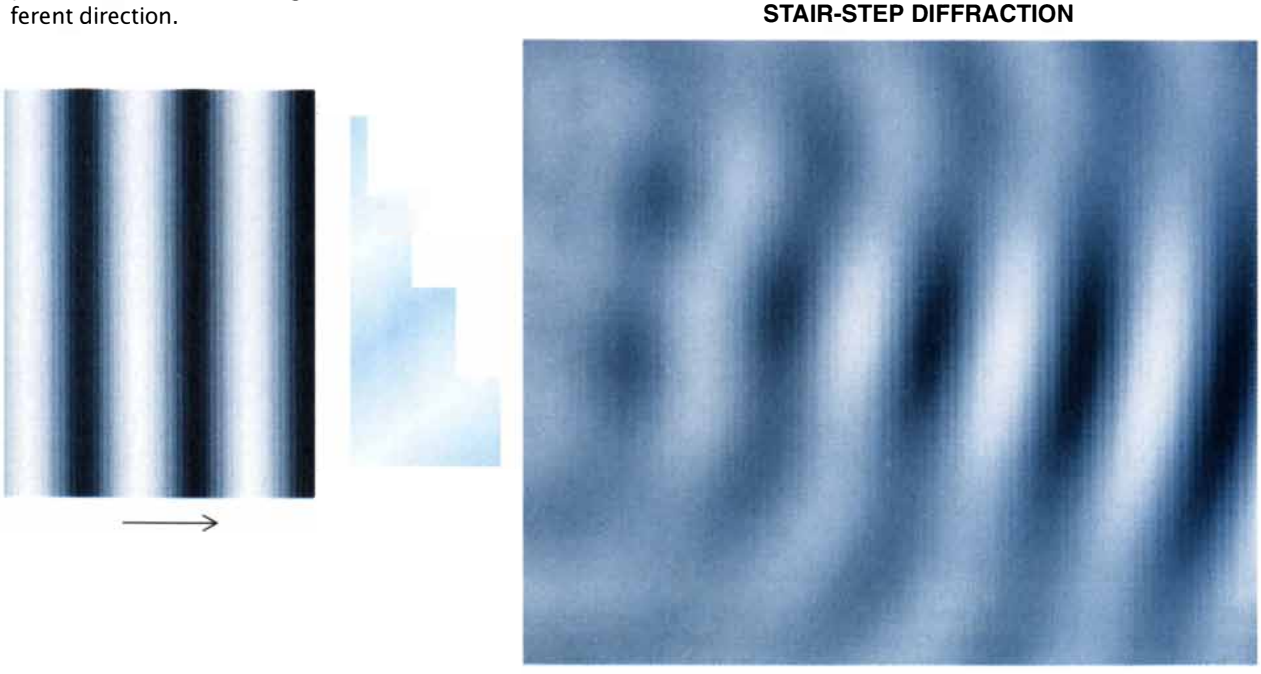
Many other types of stepped microstructures are possible. Lenses whose staircases are two wavelengths or more high can focus light over a wider range of wavelengths. They also scatter less light than one-wavelength-deep versions. Depths corresponding to fractions of a wavelength yield binary com-

Diffraction Is the Basis for Binary Optics

Interference effects permit binary optics to bend and focus light, achieving the same results as conventional refractive optics. The simplest example of diffraction is the two-slit experiment (*right*), in which the peaks and troughs of light waves passing through two small apertures combine to yield a pattern of light and dark fringes.

According to Huygens's principle, each point on an optical wave front can be considered as a tiny slit sending out a new spherical wave whose interference with its neighbors creates the next set of peaks and troughs. As such a wave front passes through a binary optical device (*below*), each part of it is delayed by an amount proportional to the thickness of the device's staircase pattern. Interference among the different parts of the wave front yields a new wave traveling in a different direction.





ponents that act as beam splitters or beam combiners.

The techniques that produce today's state-of-the-art integrated circuits can reproduce patterns whose dimensions are as small as half a micron; pattern depths can be controlled to a single nanometer. Thus, binary optical devices can be made using current semiconductor manufacturing technology at minimal start-up cost.

Furthermore, lithographic fabrication of multilevel staircase patterns is inexpensive. Each fabrication step doubles the number of levels in the staircase. A single masked exposure and etching produces two levels. Repeating the process using another mask with feature widths half as large and etching to half the previous depth produces a four-level staircase pattern. A third cycle yields an eight-level staircase, and so on. Typical binary optical devices require no more than four etching cycles. They are thus easier to make than integrated circuits, which may require as many as a dozen cycles of etching interspersed with the implantation of ions and the deposition of polysilicon, metals and insulators.

The simplicity of repeated masking and etching makes it possible to fabricate complex binary optical elements cheaply and in volume, but the manufacturing technique does leave its traces in one significant drawback. It produces not the curved and angled surfaces of conventional optics but rather a series of flat steps that approximates the desired shape. Deviations from the ideal shape scatter light out of its intended path. Losses of even 5 percent at the surface of each binary optical element can seriously degrade the performance of optical trains containing half a dozen elements or more. Optical efficiency—the amount of light redirected in the desired direction—can be increased by using closer approximations to the ideal shape. Two levels are at best 41 percent efficient; four levels, 81 percent; eight levels, 95 percent; and 16 levels, 99 percent.

Although the growth of integrated-circuit manufacturing technology in the 1970s and 1980s has made binary optics feasible, diffractive optical elements are not new. Design concepts for many different kinds of diffractive optics had existed for decades. Among these devices were variable diffraction gratings, kinoforms (stepped lenses whose surfaces are cut back by precisely one wavelength of light every time their thickness increases by that amount) and holograms. (Although the best-known holograms manipulate flat optical wave fronts to produce images, holograms are also made simply to bend light efficiently through various angles without forming an image.) These diffractive components were not widely used, however, because they were too difficult to manufacture.

During the late 1970s, a group of researchers at the Massachusetts Institute of Technology's Lincoln Laboratory began work on diffractive optics for manipulating light in laser radar sensors, which use light to detect objects smaller than those that can be seen by conventional radar. The laser radar contained a linear array of detectors. Conveying the returning beam to the detectors by means of conventional optical elements such as partially reflecting mirrors proved impractical. The optical train resulted in painstaking, unreliable adjustments, and much of the light was lost.

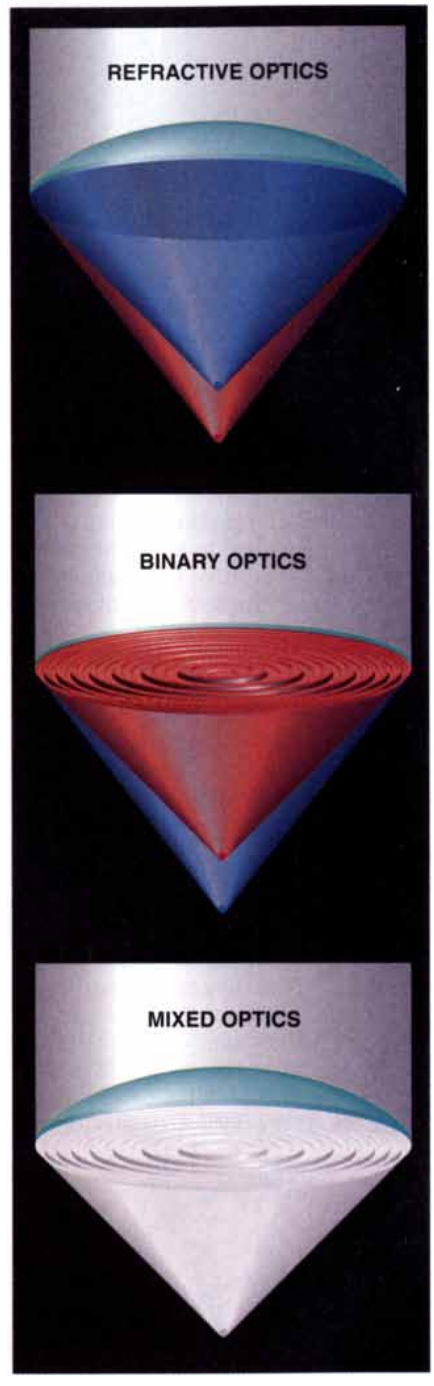
Instead the engineers designed a diffractive mosaic that could divide a single laser beam into 12 beams of precisely determined amplitude and phase. The microcircuit printing techniques employed to build the mosaic could produce only two levels rather than the multilevel staircase patterns used in later binary optics. Nevertheless, light striking the sinuous ridges of the mosaic's surface was diffracted in such a way that its interference pattern yielded 12 new beams, each leaving the surface at a different angle. By matching the beams precisely to the receiver's detector array, the diffractive element significantly improved the laser radar's detection efficiency and resolution.

The Defense Advanced Research Projects Agency sponsored additional work at Lincoln Laboratory as part of the Defense Department's efforts to develop low-cost infrared sensors. This research led eventually to the fabrication of multilevel optical microstructures.

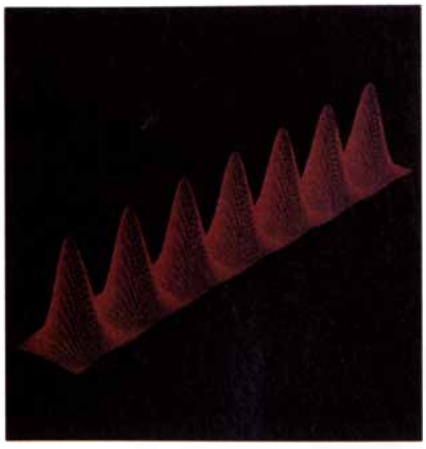
At about the same time, engineers at what is now Hughes Danbury Optical Systems were working to apply diffractive holographic elements to very large telescope mirrors. These elements were needed to divert a small amount of laser light into a sensor that monitors the system's optical performance.

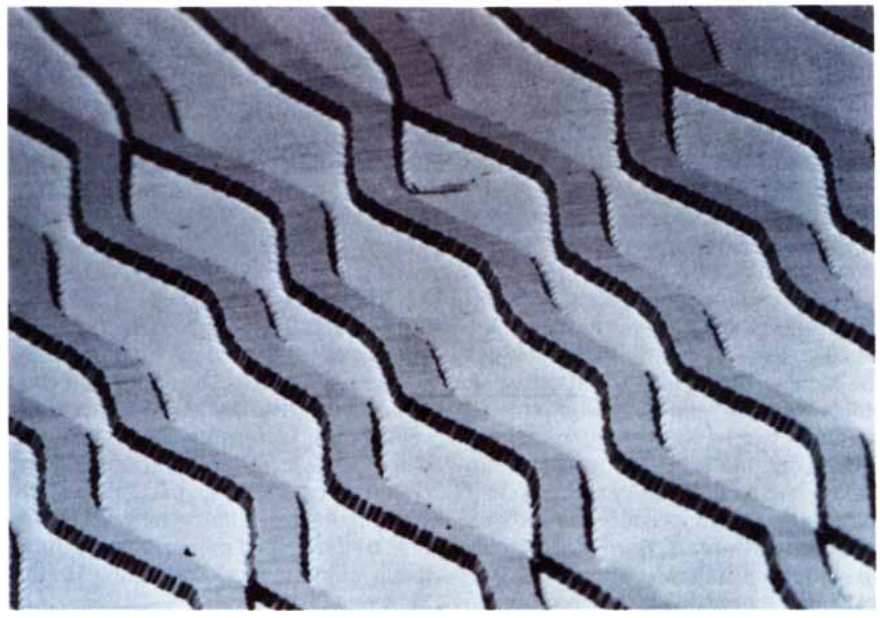
The mirrors were too large to place on an optical bench top where their surfaces could be coated with emulsion and holograms exposed by conventional methods. Instead the engineers decided to calculate mathematically the phase patterns of the desired holograms, then fabricate and etch them into the mirror surfaces using microlithographic techniques borrowed from the semiconductor industry. The success of this project has led to far-reaching applications. Not only can binary optics generate holographic patterns, but it also can generate virtually any transformation of an optical wave front.

Researchers at Hughes first tested their new capabilities by creating a bi-



CONVENTIONAL LENSES (*top*) focus blue light more strongly than red light; this phenomenon is known as chromatic aberration. Binary optical elements (*middle*), in contrast, focus red light more strongly than blue. By combining conventional and binary optics into a single element (*bottom*), it is possible to cancel the aberration over a modest range of wavelengths.





BINARY OPTICAL MULTIPLEXER (*right*) splits a beam of laser light into seven beams of equal amplitude (*above*), each separated by a precise angle. Such a task is impractical to perform with conventional optics.

nary optical component for possible use in a pattern-recognition system. The device was intended to make the overall system more sensitive to details of an object's shape and less sensitive to its size or rotational orientation.

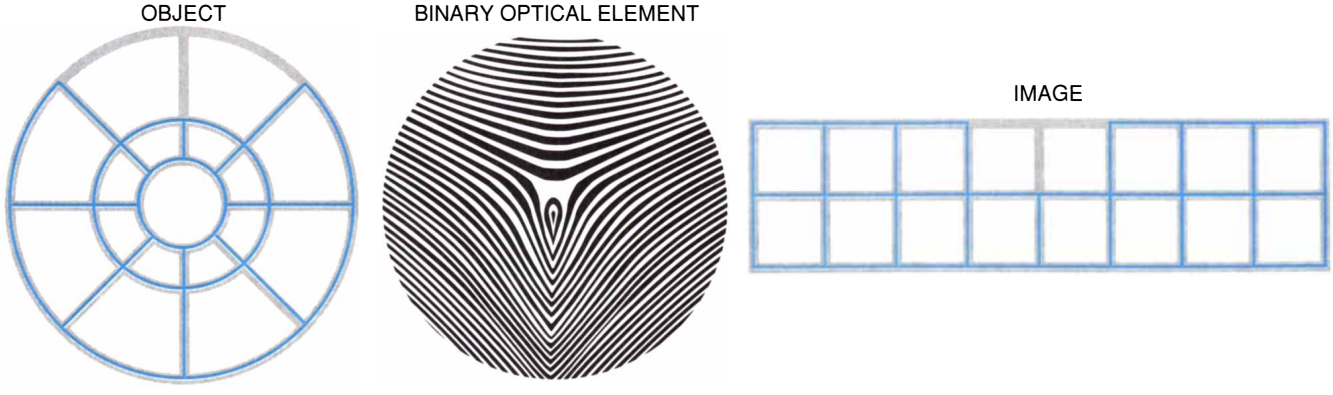
The device's optical properties transform concentric circles into straight, parallel lines. As a result, any object centered in the field of view is essentially sliced into thin annular rings and each ring transformed to a rectangular band. As an object's image is rotated about the center of the field, any distinguishing features slide from one part of the rectangular band to another. Most pattern-recognition systems can identify such translated features much more easily than they can rotated ones.

The concept for such a device is not new, but no optician could make the required component using conventional grinding and polishing techniques. Attempts to produce a similar device by means of computer-generated holograms were cumbersome and optically inefficient. The binary optical version outperformed all the others. Since then, lenses have been designed to correct astigmatism, spherical aberration and a number of other optical defects.

One of the few unavoidable obstacles to using diffractive optical elements is that they are highly dispersive: they tend to break light into its component colors. In some cases, however, lens designers have discovered how to turn this liability into an asset. They can combine binary optical elements with conventional lenses to reduce the chromatic aberration that arises from the dispersive character of glass and other refractive materials.

In traditional lens design, chromatic aberrations are minimized by cementing together lenses of materials having different dispersive properties. This technique increases the cost and complexity of the finished device. The dispersion of binary optics, fortunately, is opposite in sign to that of most glasses [*see illustration on preceding page*]. Thus, over a modest band of wavelengths the chromatic aberration of a binary lens will cancel that of a conventional lens into which it has been etched. The principles of diffractive correction have long been known, but they were impractical to apply. Computer-generated diffractive holograms were considered too inefficient, optical holograms were too difficult to produce, and holographic film or gelatin media were too unstable for highly precise work.

Binary optics overcomes these limitations by etching highly efficient diffractive elements directly into a selected optical material. In effect, a designer can synthesize new kinds of glass whose ability to bend light varies with wavelength as desired. This additional di-



OPTICAL TRANSFORMATION converts concentric circles (*left*) to straight lines (*right*). Such a "log-polar-to-Cartesian" transformation can improve pattern-recognition systems by making them less sensitive to the rotation of their targets. The center image is a contour phase map of the optical element that forms the image.

mension of flexibility can make it unnecessary to work with expensive or troublesome optical materials, reduce the number of optical elements in a system and improve overall performance.

Researchers at Lincoln Laboratory designed a binary optical lens and etched it onto the flat side of a plano-convex lens (a lens having one flat and one curved face). The hybrid lens, made of fused silica capable of transmitting ultraviolet light, was free of both chromatic and spherical aberration over a wavelength range of 2,460 to 2,500 angstroms. Chromatic aberration in that part of the spectrum is particularly intense: an uncorrected lens has less than one thousandth the diffraction-limited bandwidth of the conventional-binary optical hybrid.

Because binary optics and semiconductor chips are made by the same equipment, it will be possible to etch optical components directly onto integrated circuits. Designers can place on a chip arrays of microlenses or even fully integrated optoelectronic processing units. Therein lies the seed of a new era in smart, ultracompact sensor systems.

As a first step in this direction, researchers have already made binary optical lenses whose diameters are close to that of a human hair (50 to 100 microns). Such binary microoptics can be fabricated individually or in arrays of tens of thousands of lenses per square centimeter.

These lenses will not merely focus light on arrays of tiny electronic photodetectors; they will play an important part in shaping the architecture of future image-processing systems. Current machine vision architectures are based on arrays of detectors that produce cameralike images, from which intensive calculations extract features such as edges, surfaces and ultimately descriptions of the objects in a scene. Microscopic lenses that focus the light falling on a detector will make room for processing elements connected directly to each detector. Researchers can build detector arrays that mimic the structure of biological vision, which has thus far proved superior to artificial versions [see "The Silicon Retina," by Misha A. Mahowald and Carver Mead; SCIENTIFIC AMERICAN, May 1991].

This improvement will make possible image sensors that adjust to varying light levels, detect movement and automatically determine the position of object edges in a scene. One of us (Veldkamp) has coined the term "amacronics" for these circuits because they emulate the motion-detection, edge-enhancement, and dynamic-range reduction function of the amacrine cells of the retina.

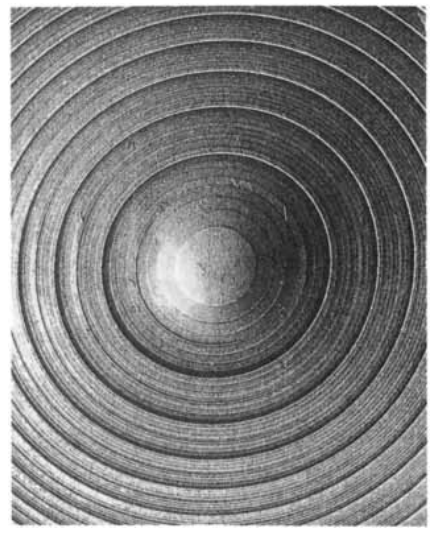
The biological model can be emulated in even more elaborate systems. Additional binary optical elements can interconnect the cells of arrays of photodetectors stacked in layers, as are the cells of the retina. An array of integrated light-emitting diodes and microoptics could pass the low-level image to another chip whose sensors might be sensitive, for example, to the orientation or texture of image features. A stack of image-processing circuits might ultimately convey a largely symbolic description of a scene in almost the way that the visual cortex conveys its information to the rest of the brain.

In addition to enhancing machine vision, amacronic devices will be useful in reducing bandwidth requirements for image transmission. Rather than sending a complete image, these systems will be able to extract and send key information from which a picture can be reconstructed at the other end. A number of Japanese companies have already begun developing amacronic systems for picture-phone applications.

The microelectronics revolution owes much of its success to high-quality optics. Without the sophisticated optical systems that project reduced images of circuit masks on silicon wafers, low-cost mass production of the microprocessor might have been impossible. Now, with the development of binary optics, microelectronics appears to be repaying its debt in a way that few could have foreseen. Computers and modern semiconductor processing equipment are being used to fabricate optical elements previously thought to be impractical.

Indeed, just as today's circuit designers sit at a computer terminal and manipulate electronic building block devices, so too may binary optics designers someday synthesize optoelectronic systems at the click of a "mouse" or the touch of a key. By creating designs that employ both binary and conventional optics, engineers can often halve the number of elements in a complex system.

Making such a vision into reality requires developing better techniques for binary optics design, perhaps revisiting methods abandoned years ago because high-quality, generalized diffractive optics were thought to be impractical. We have found that old books and forgotten technical papers can be a rich source of ideas for now feasible designs. Conventional optics and time-tested fabrication methods, of course, are not about to disappear, nor should they. Reflective and refractive optics will continue to be used in applications where they function best.



BINARY LENS on the surface of the cornea could correct visual defects such as nearsightedness, farsightedness or astigmatism. The lens shown here was etched by ultraviolet laser pulses into a cornea removed from a cadaver.

Binary optics offers such a wide array of light-manipulation capabilities that designers face the challenge of learning where not to use the new technique as well as where to use it. As the new lenses make their way into applications ranging from conventional image-forming optics to integrated-circuit interconnections and machine vision, designers are finding themselves in an unaccustomed situation: limited not by materials or manufacturing techniques but only by their own creative vision.

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Why American Songbirds Are Vanishing

An avian chorus still heralds the beginning of spring in North America, but the number of singers has declined sharply of late. The trend will be difficult to reverse

by John Terborgh

In 1813 the renowned naturalist John James Audubon was awestruck by a migratory flight of passenger pigeons, which blanketed the sky with birds for three days in succession. "The air," he later recounted, "was literally filled with pigeons. The light of the noonday was obscured as by an eclipse."

Based on such descriptions, ornithologists have estimated that passenger pigeons in precolonial America numbered two to three billion, making them perhaps the most abundant bird species on the earth at the time. Now, of course, they are only a memory, victim of the laissez-faire attitude toward the use of natural resources that prevailed during much of U.S. history.

Recent legislation, notably the Endangered Species Act, has been designed to prevent further needless extinctions of U.S. flora and fauna. Despite such major efforts to reconcile human needs with nature, it has recently been discovered that many migratory bird species are in steep decline. Increasingly, research is indicating that human activities have directly and indirectly altered the environment in ways that are detrimental to birds.

Birds first came to the forefront as indicators of environmental health during the 1960s, when the focus of concern was the pesticide DDT. At that time, only a small number of species seemed to be in trouble, among them several raptors, such as the peregrine falcon and bald eagle, and a number of water birds, including the brown pelican. In those years, there was little to suggest that songbirds might be in jeopardy. But early warning signals of a much broader phenomenon affecting perhaps scores of species began to be detected in the 1970s.

Ornithologists and amateur bird-watchers noticed that a number of songbirds had suddenly become scarce in haunts that had previously harbored abundant populations. The declines were most dramatic and pervasive in urban and suburban woodlots, but the causes were entirely mysterious. Especially affected were species that breed in northern latitudes but migrate to winter homes in the tropics—so-called long-distance, or Neotropical, migrants. Among these are some of our favorite songbirds, namely, thrushes, warblers, tanagers and orioles.

One of the sites that drew attention to the problem was Rock Creek Park in the District of Columbia. The park has been embedded in an urban environment for more than 100 years. Despite this fact, the first bird censuses to be conducted there in the 1940s documented a profusion of forest-dwelling long-distance migrants, including the eight most abundant species. Yet by the 1970s the total number of breeding birds had dropped to about a third of the 1940s level; long-distance migrants had plummeted almost 90 percent; and several once common species had become locally extinct.

Forest-dwelling migratory songbirds are not the only North American birds to have suffered recent declines. Ducks and other waterfowl have been drastically reduced by draining of the prairie wetlands in which they breed. Shorebirds, such as curlews, godwits and sandpipers, have dwindled because their breeding or wintering habitats have been appropriated for human use and because water quality has deteriorated along their migratory routes and on the wintering grounds. Finally, grassland birds have succumbed to the plowing of the prairies and, more recently, to the intensification of agriculture that is permitted by the application of chemical fertilizers, pesticides and herbicides. Through the liberal application of these agents, farmers can sow crops on the same land for many years in succession, a practice that deprives meadowlarks, bobolinks, grasshopper sparrows and others of their ilk of the fallow fields in which they formerly thrived.

But what is amiss in the forests, where birds were vanishing for no obvious reason? By the mid-1970s declines in the bird populations of woodlots had become so dramatic that they could not be attributed to normal fluctuations in number or to observer error. At about the same time as the problem in Rock Creek Park emerged, downward trends were also reported in New Jersey, Maryland and Wisconsin. Soon afterward, bird-watchers in Connecticut, West Virginia and Illinois detected similar patterns. More recently, drops have been detected farther afield, in such places as Ontario, Missouri and California. To date, the most marked losses have been documented east of the Mississippi.

As reports of these decreases accumulated, it was widely noted that the

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LEAST BELL'S VIREO, which breeds in southern California, is one of many migratory songbirds whose populations have dwindled in this century. The species is now close to extinction.

missing species could still be found in large continuous tracts of forest. The phenomenon of declining population seemed to be restricted to isolated tracts, and the smaller the tract, the more extreme the impoverishment of the bird community. In recognition of these observations, the dwindling numbers quickly became known as the forest fragmentation effect.

However logical, this designation was an unfortunate choice of terms, because it implied that fragmentation of habitat was somehow a root cause of the disappearances. Most investigators implicitly assumed the fragmentation effect was a response to the size of forest plots. Yet when researchers set about documenting the presence or absence of species in forest fragments of different size, they obtained mixed and sometimes contradictory results. For example, a species that regularly built nests and reproduced in 10-hectare (24.7-acre) woodlots in one state might require 100-hectare tracts for nesting in another state. The inconsistency of the findings suggested factors other than insufficient area must be involved.

The role of edges was among those considered. The environment of isolated woodlots differs from that of continuous forest in the proximity of all parts of the habitat to edges. Forest margins are brighter, warmer, drier and windier than the interior and support more shrubs, vines and weeds. Perhaps certain birds were averse to edges and rejected small tracts because none of the habitat was sufficiently far from edges.

Two studies quickly dispelled this idea as well. In 1984 Roger L. Kroodsma of the Oak Ridge National Laboratory reported on the distribution of nesting territories in Tennessee forests in which swaths had been cut to accommodate power-line rights-of-way. Species that normally resided in the forest interior used the habitat right up to the cuts. In a similar study in Maryland, David S. Wilcove, while a graduate student at Princeton University, examined the distribution of the same birds in a large forest surrounding a reservoir. Breeding territories occupied the wooded habitat all the way to the water's edge. Birds of the forest interior thus did not seem to have an intrinsic aversion to edges.

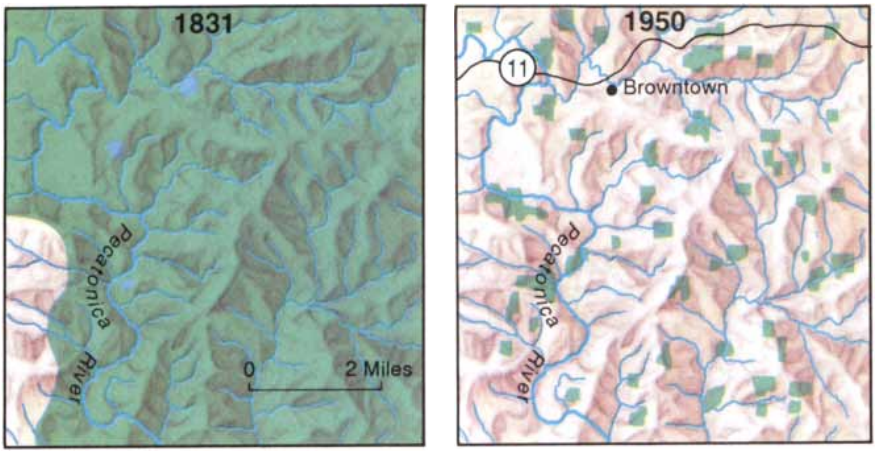
Some researchers wondered whether migrating birds were simply failing to discover forest fragments. After a population disappeared for whatever reason, other individuals might not reestablish the species's presence. One rationale focused on young males seeking territories for the first time. It was argued that the presence of experienced adults might be the best indicator of suitable habitat and that novice breeders might be loathe to settle where they could not hear males of their own species.

It was difficult, however, to reconcile this possibility with the fact that each spring and autumn migrating birds pass by the thousands through habitat islands such as Rock Creek Park. In the spring, males often stop and sing vigorously in these spots, as if claiming territories, but a few days later move on. One could not conclude that the empty forest fragments were being overlooked; for reasons best known to the birds, the fragments were apparently being rejected as unsuitable breeding sites.

Impressed by the consistency with which the missing species were long-distance migrants, other investigators eagerly jumped to the conclusion that tropical deforestation rather than fragmentation of the breeding habitat was to blame for the declines. But the facts simply did not jibe. Some species that winter in regions undergoing rapid deforestation appeared to be holding their own. Yet others that winter in relatively unscathed parts of the tropics had

dwindled to low numbers in forest fragments or had vanished from some tracts altogether. Tropical deforestation might have been affecting some species, but it could not account for all the observations of diminishing populations in fragments.

Another argument seemed to provide a better explanation of the pattern. Of all the birds breeding in eastern forests, long-distance tropical migrants appear to be the most vulnerable to disruptions of their breeding efforts. Compared with local residents and short-distance migrants (those wintering in the southern states), the long-distance migrants tend to arrive on the breeding ground later and to depart earlier. Their breeding seasons are consequently more restricted, so they are able to make fewer nesting attempts in a year. Moreover, many long-distance migrants have smaller clutch sizes: three or four eggs versus the five or six of other species. Therefore, any environmental changes that were to reduce nesting success indiscriminately across all species would hit Neotropical migrants first and hardest.



CADIZ TOWNSHIP, in Wisconsin, was mostly forest (*green*) in 1831. By 1950 only isolated patches of woodland remained. The excessive fragmentation of forests, which has occurred throughout much of the U.S., increases the exposure of bird nests to parasites, which lay eggs in other birds' nests, and to predators, which feed on eggs and nestlings. The maps were compiled by botanist John T. Curtis in 1956.

Declining Species in Rock Creek Park

SPECIES	MEAN NUMBER OF PAIRS		CHANGE	
	IN 1940s	IN 1980s	ACTUAL	PERCENT
RED-EYED VIREO	41.5	5.8	–35.7	–86.0
OVENBIRD	38.8	3.3	–35.5	–91.5
ACADIAN FLYCATCHER	21.5	0.1	–21.4	–99.5
WOOD THRUSH	16.3	3.9	–12.4	–76.1
YELLOW-THROATED VIREO	6.0	0.0	–6.0	–100.0
HOODED WARBLER	5.0	0.0	–5.0	–100.0
SCARLET TANAGER	7.3	3.5	–3.8	–52.1
BLACK-AND-WHITE WARBLER	3.0	0.0	–3.0	–100.0
EASTERN WOOD PEEWEE	5.5	2.8	–2.7	–49.1
AMERICAN CROW	2.0	0.6	–1.4	–70.0
KENTUCKY WARBLER	1.0	0.0	–1.0	–100.0
YELLOW-BILLED CUCKOO	0.8	0.0	–0.8	–100.0
CAROLINA CHICKADEE	5.0	4.3	–0.7	–14.0
TUFTED TITMOUSE	5.0	4.5	–0.5	–10.0
DOWNY WOODPECKER	3.5	3.0	–0.5	–14.3
WHITE-BREASTED NUTHATCH	3.5	3.1	–0.4	–11.4
NORTHERN PARULA WARBLER	0.3	0.0	–0.3	–100.0
TOTAL SPECIES IN CENSUSED AREA	**26.5**	**24.5**	**–2.0**	**–7.5**
DENSITY (PAIRS PER 100 HECTARES)	**90.1**	**34.9**	**–55.2**	**–61.3**

SEVENTEEN SONGBIRD SPECIES in a censused part of Rock Creek Park in Washington, D.C., declined in mean number of breeding pairs between the 1940s and 1980s, according to data published by the National Audubon Society. Most of the affected species were long-distance migrants (*shaded areas*), which winter in the tropics; six of them disappeared entirely (*red type*).

By the early 1980s the most obvious possible factors—the small size of forest fragments, the proximity of edges and the destruction of tropical wintering grounds—had all been tested and found wanting, at least as general explanations. The decline of songbirds in stable sites such as Rock Creek Park suggested that the environment in fragments had become hostile to migratory birds over the past few decades; that although the tracts were superficially unchanged, they had acquired some mysterious pathology.

Wilcove was among the first to try some detective work. He realized, as do many homeowners, that the suburbs are a haven for certain avian nest predators, such as blue jays, raccoons and opossums. Raccoons and opossums, for instance, are inveterate raiders of garbage cans. As a consequence, they abound in settled areas, where they occupy smaller ranges, grow faster and attain larger body size than they do in rural areas. Wilcove therefore wondered whether predators could be putting increased pressure on birds in suburban forests.

To test this notion, he stocked artificial nests with quail eggs and set them out in small, medium and large forests situated in both rural and suburban settings. Half the nests were placed on the ground and half at eye level in shrubs or trees. For an undisturbed control site, he chose the Great Smoky Mountains National Park, which boasts 200,000 hectares of mature forest.

The results were startling. In the Smokies only one nest in 50 was discovered and raided. In the suburban and rural woodlots, the predation rates were much higher. In some of the smaller tracts, nearly 100 percent of the nests were raided. Here indeed was a kind of pathology, and it seemed to be pervasive except in the largest remaining expanses of forest.

At about the same time, Margaret C. Brittingham and Stanley A. Temple of the University of Wisconsin found evidence of yet another type of ecological pathology affecting forest fragments: an abundance of nest parasites. Parasitic birds lay their eggs in the nests of other species, who often raise the resulting offspring as their own. A parasite's eggs typically hatch sooner than the eggs of its host, giving the hatchling parasite a head start over its nest mates. By the time the host's eggs hatch,

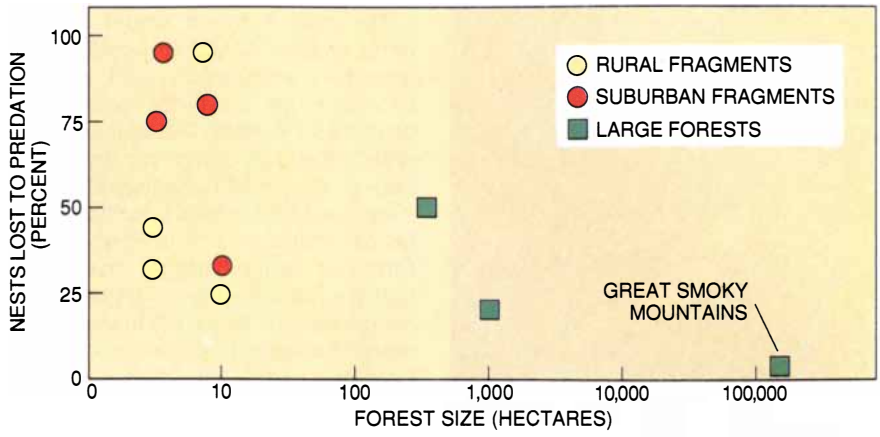
the parasite has grown to a size that allows it to obtain much of the food brought by the parents, so the host's own offspring often starve.

The nation's leading nest parasite is the brown-headed cowbird. The name derives from its habit of following bison and, later, cattle to scavenge seeds from heaps of dung. Two hundred years ago the cowbird was relatively uncommon. Its rise to pest status was promoted by the creation of open agricultural habitats in formerly forested sections of the country and by the availability of bountiful winter food supplies. In cold weather the species can find seeds at bird feeders and in fields where mechanical harvesters spill grain. Brittingham and Temple discovered that cowbirds parasitized 65 percent of nests located near forest edges in southern Wisconsin. Parasitism was recorded even at interior locations more than 300 meters from the nearest edge, although at lower rates.

Follow-up studies in several states have confirmed that unnatural numbers of nest predators and parasites are impairing the reproductive success of many forest-dwelling bird species. The most comprehensive results come from an effort led by Scott K. Robinson of the Illinois Natural History Survey. His team first investigated one of the largest contiguous areas of forested habitat in the central part of Illinois, an irregular strip of mature forest and second growth surrounding a reservoir near Shelbyville.

During the five-year period from 1985 to 1989, seven out of 13 Neotropical migrant species in the study area decreased by more than 50 percent. The birds at Shelbyville were having great difficulty nesting successfully. Of all clutches laid, 80 percent were lost to predation before any young fledged. Of the nests that survived predation, 76 percent were parasitized by cowbirds. Two thirds of the broods that fledged included cowbirds.

To assess the impact of such numbers on the songbird population, we can begin by noting that typically about 60 percent of adult birds of the kinds studied by Robinson survive every year. A pair of adults must thus produce at least 0.8 surviving young to replace the adults lost to the breeding population of the following year. But survivorship of hatchlings born in a given breeding season is only half that of adults, so each breeding pair must double the minimum number to guarantee maintenance of the breeding population. In other words, at the end of a breeding season, the ratio of hatching-year birds to adults should be 1.6 young for every mating pair, or 0.8 young for every mature adult. It can be assumed, then, that a group producing fewer than 0.8 young per adult is not maintaining itself.



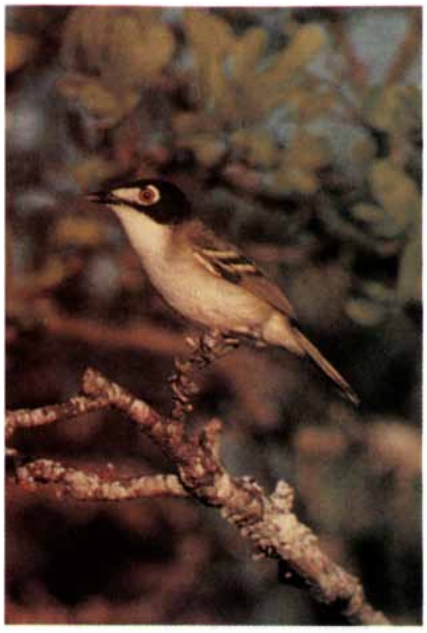
FRACTION OF ARTIFICIAL NESTS raided by raccoons and other animals that thrive near human civilization was measured by David S. Wilcove of Princeton University in 1985. His findings indicate that nest predation has become a serious problem for bird species in all but the largest U.S. woods.

YELLOW WARBLER is watching over a newborn brown-headed cowbird along with two smaller warbler babies. Many modern songbirds are victimized by cowbird parasitism, which is detrimental to the affected species because young cowbirds aggressively outcompete the hatchlings of the host.

Because hatching-year birds are easily distinguished from adults by plumage differences, the reproductive success of a breeding community can be estimated by trapping birds in fine, mist nests at the conclusion of the breeding season and determining the ratio of young birds to adults. At Shelbyville, Robinson and his co-workers found the number of young to be 0.1 per adult. The reproductive output of the breeding bird community therefore fell far short of the level required to sustain the population.

Banding studies, in which birds are marked by numbered bands, have shown that adults returning from winter territories often nest again in plots where they bred successfully before. For example, as many as 70 percent of adult wood thrushes generally follow that pattern. At Shelbyville, however, 16 percent of the thrushes returned.

Two conclusions can be drawn from such a finding. First, after failing to produce young at Shelbyville, many adults may try another location the next year. Second, because a number of poorly reproducing species continue to be present at Shelbyville, birds from somewhere else must be replenishing the adult populations. But from where?



BLACK-CAPPED VIREO, like the least Bell's vireo and the Kirtland's warbler, is on the verge of extinction. In all three cases, nest parasitism by cowbirds is the probable cause.

This question prompted Robinson to move his efforts to the Shawnee National Forest in the extreme south of Illinois. At 100,000 hectares, the Shawnee is by far the largest forest in the state. Some blocks are of substantial size, encompassing more than 2,000 hectares. Here Robinson expected to discover a healthy breeding population that might be producing surplus young to replenish the dwindling songbird numbers elsewhere in Illinois.

This hopeful expectation has now been dashed. In 1989 and 1990 Robinson and 18 co-workers located and monitored more than 1,000 songbird nests in the Shawnee forest. They found cowbirds to abound even in the center of the largest section of forest. Several long-distance migrants, such as hooded warblers, wood thrushes and red-eyed vireos, suffered parasitism rates between 80 and 100 percent. For these and other species, hatching-year bird to adult ratios at the end of the breeding season fell well below any reasonable replacement level. These results suggest that there may be no place in the state of Illinois where such species can nest successfully.

From where, then, are the birds coming to subsidize a deficit breeding effort? At this point, the answer is not known, but a good guess is the extensive forests of the Ozarks and Appalachians. When Wilcove was in the Great Smoky Mountains National Park, he did not detect a single cowbird.

The size a forest would have to be to support a source population of migratory songbirds is still a matter of conjecture. Cowbirds require open country for feeding, but females freely enter forests to search for host nests. Indeed, studies of radio-tagged females conducted by Stephen I. Rothstein and his associates at the University of California at Santa Barbara have shown that the birds will commute up to seven kilometers from feeding areas to search for nests to parasitize. A seven-kilometer radius describes a circle of 150 square kilometers, equal to 15,000 hectares. It is disturbing to think a forest that might offer at its center a haven from cowbird parasitism would have to be at least that size.

Robinson's results reveal that the ecological pathology afflicting migratory songbirds in the eastern U.S. is by no means confined to the small suburban woodlots where it was first discovered. It is a sickness that reaches across half a continent and affects a major fraction of the potential breeding habitat of more than a score of migratory songbird species. Already the Kirtland's warbler in Michigan, the black-capped vireo in Texas and Oklahoma and the least Bell's vireo in southern California have been driven to the brink of extinction by cowbird parasitism. Other species are sure to follow.

Despite the severity of stresses imposed by predators and cowbirds, the gravest long-term threat to forest songbirds is still over the horizon: deforestation of the tropics. More than 250 species that breed in North America can be found south of the U.S. border in the winter. Every country from Mexico to Argentina provides habitat for at least some species, although the greatest concentrations are in the "near" tropics—Mexico, Central America and the Antilles.

Although until recently there was little convincing evidence that destruction of wintering habitat was having a measurable impact, newer data are more impressive. The first red warning flag came in results of what is known as the Breeding Bird Survey. Organized in 1965 by Chandler S. Robbins of the Fish and Wildlife Service, the BBS engages hundreds of volunteer bird-watchers to count birds along 25-mile routes. The observers stop every half mile and record all birds seen or heard in a three-minute period. Every year volunteers conduct more than 1,500 such surveys, covering most of the U.S. and Canada.

In 1986 Robbins and two colleagues published a report on the first 15 years of results, spanning 1965 through 1979. The analyses gave no indication that birds wintering in tropical forests were in trouble. In 1989, however, Robbins and his associates published a second report covering 1978 through 1987. This time the trend was entirely different. Even though forest cover in the eastern U.S. had not decreased significantly during the interval, the populations of 75 percent of the species of forest-dwelling long-distance migrants had declined. Resident species and short-distance migrants, in contrast, seemed to be holding their own.

The trends detected in the BBS data may offer merely a taste of what is to come. In 1989 a symposium on the conservation of migratory birds was held at Woods Hole, Mass. The participants were already jaded by two days of bad news but were nonetheless left openmouthed on the third day by the report of Sidney A. Gauthreaux, Jr., of Clemson University.

Gauthreaux has pioneered the use of radar to detect migratory flights of small birds. With the collaboration of the U.S. Meteorological Service, he has access to radar records from a series of stations scattered along the Gulf coast. The area is particularly strategic for this kind of observation because many birds returning in the spring from South and Central America and the Antilles fly across the Gulf. Large numbers of northbound birds accumulate on the Yucatán Peninsula, awaiting propitious weather. When the right conditions arrive, birds of many species take off just after sundown, and a few hours later clouds of them appear high over the U.S. shore.

In his doctoral research, Gauthreaux had used radar to detect migratory flights over Louisiana during three successive springs in the mid-1960s. Twenty years later, appreciative of the impending threat of tropical deforestation, he decided to repeat the measurements for the springs of 1987 through 1989. To the astonishment of everyone at the symposium, he reported that only half as many migratory waves passed over the Louisiana coast in the late 1980s as in the 1960s. It seems hard to believe that migratory birds have declined so rapidly, but thus far there is no alternative explanation for the radar results. We can now count two red flags.

Now a third flag has been raised with the publication of two reports issued independently but nearly simultaneously in 1990 by Friends of the Earth and the World Resources Institute. Both reports are based on interpretation of satellite imagery, but the details differ somewhat because of application of slightly differ-

ent criteria—such as whether to view land carrying partially degraded forest or second growth as deforested.

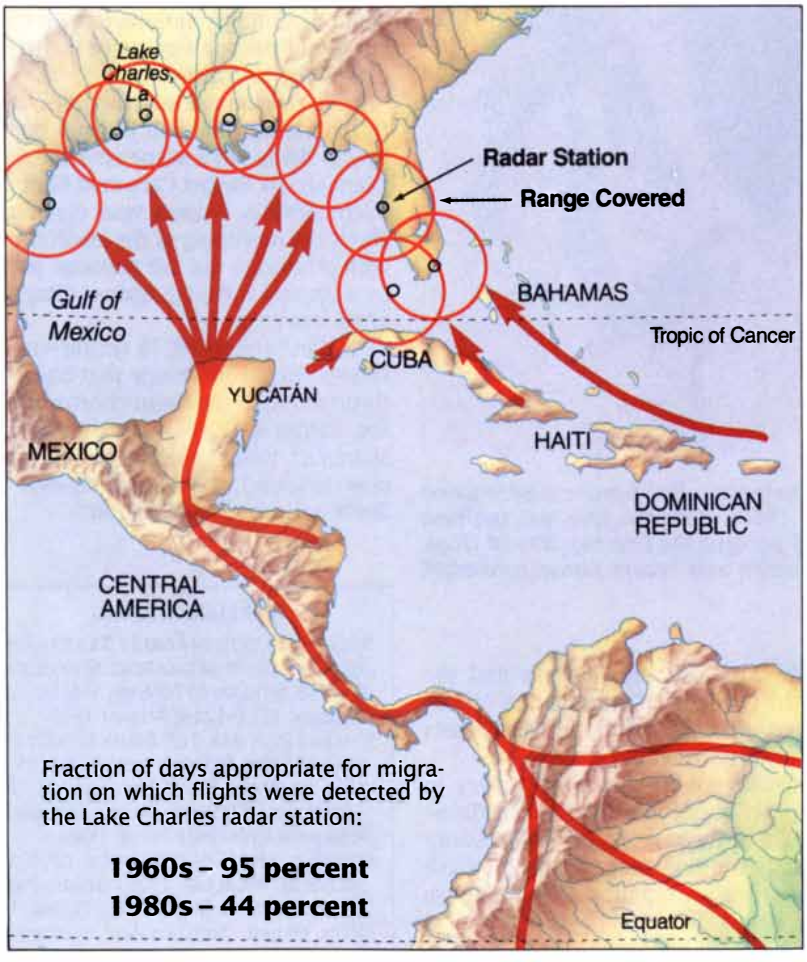
Friends of the Earth estimated the annual loss of tropical forest globally at 142,000 square kilometers, an area the size of Florida or Wisconsin. The World Resources Institute puts the annual loss at 160,000 to 200,000 square kilometers, roughly equivalent to the state of Washington. If one takes the lower estimate and simply extrapolates, the last hectare of tropical forest would be predicted to fall in the year 2045. This projection is likely to prove conservative, however, because both reports indicate that the rate of deforestation is not constant but accelerating. If the rate of loss continues to increase as it did between 1980 and 1990, the world's remaining tropical forests will be depleted by the year 2030.

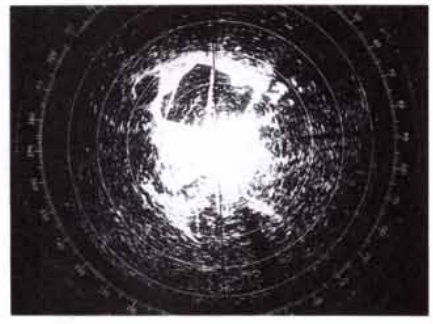
These disturbing trends can only bode ill for migratory songbirds and for much of the world's biological diversity. As waves of deforestation pass over the wintering grounds of migratory birds, reducing the area of suitable habitat, the populations of many species will contract. Not all species will be equally affected. Those that require mature forest will be hardest hit, but others can survive in man-made habitats, such as gardens, coffee plantations and second growth. Nevertheless, the total area of usable habitat will be greatly reduced, and we can expect to see populations contract in proportion. Many migratory species that are now common will become rare, although few are likely to disappear entirely, at least in the short run. I suspect we shall lose several species to cowbirds before we lose any more to tropical deforestation.

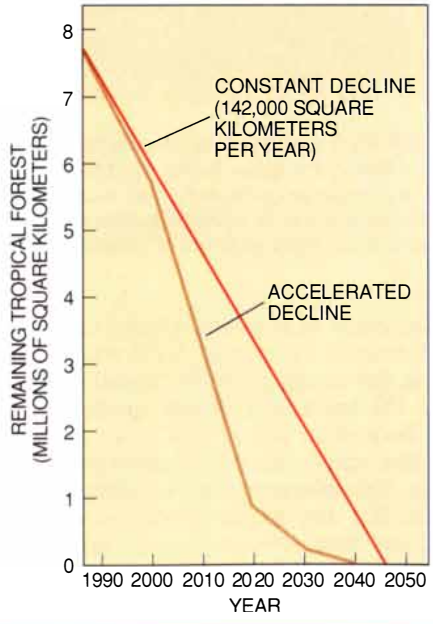
I say any more because the Bachman's warbler has already succumbed to the loss of its wintering habitat. Data on this always elusive bird are scanty, but it

Radar Reveals Decline in Northward Migration

In spring, many long-distance migrants follow routes (such as those indicated by arrows on the map) that pass over the Gulf coast of the U.S. There, radar stations capable of detecting small birds record flights. Each tiny dot on a radar plot (*photograph*) represents about 20 birds; the large white mass reflects scattering of signals by structures on land. When Sidney A. Gauthreaux, Jr., of Clemson University examined records from Lake Charles, La., he found that the number of flights fell by about half between the 1960s and 1980s, which implies that the number of all birds returning from the American tropics also fell by half. The likely cause, razing of tropical forests (*graph*), promises to become an increasing stress. A projection based on a conservative estimate of forest loss in 1990 shows that if the rate of deforestation is constant, the world's tropical forests will vanish by 2045. If the rate accelerates, as it did between 1980 and 1990, the winter homes of many birds will vanish even sooner.







was known to occupy an expansive breeding range in the southeastern U.S., from Virginia to Missouri and thence to the Gulf coast. Its only known wintering ground was in Cuba, which lost 95 percent of its forests to the burgeoning sugar industry in the first half of the 20th century. Never a common bird, the Bachman's warbler quietly vanished. The last sightings were in the 1960s.

My best guess as to why the Bachman's warbler disappeared begins with the assumption that severe contraction of its wintering habitat forced a drastic reduction in its numbers. Once a critical threshold was passed, birds returning in the spring probably fanned out over the immensity of the Southeast and became so diluted that males and females simply failed to locate one another. This interpretation is supported by the fact that the last few Bachman's warblers ever seen were adult males that sang for weeks on end in apparently futile efforts to attract females.

What can be done to prevent this scenario from repeating itself again and again? Some of the threats to bird life here in North America seem more intractable than others. Probably little can be done to reduce the hordes of blue jays, raccoons, opossums and cowbirds that have degraded the habitat of rural and suburban areas. It thus seems inevitable that long-distance migrants are going to continue to decline in neighborhood parks and woodlots. Conservation efforts should therefore be directed toward consolidating and expanding the largest tracts of forest, such as the Smokies, Adirondacks and the North Woods of Minnesota and Maine, to maximize the habitat in which birds can nest successfully.

Farmers would help by returning to the practice of fallowing their fields every two or three years, but it seems unrealistic to think they might. The Bush administration's policy of "no net loss of wetlands" is certainly a good one, but it should be implemented in good faith, without altering the definition of wetlands. It would be useful to prohibit the subsidized clear-cutting of our national forests and to curtail the systematic overgrazing of federal lands in the West. And reducing pollution in lakes and streams would help restore habitat for ducks and other waterfowl.

But even if all these goals were achieved in the U.S., more than 250 species that migrate south of our borders would face jeopardy in their winter homes. Stanching the tide of tropical deforestation hardly seems possible as long as 90 million people are being added to the world's population every year, nearly all of them in the tropics. Millions of new families needing a place to settle create an insatiable demand for land. Poor nations burdened by debt have only their natural resources to sell for foreign exchange. Consequently, the economies of many of our southern neighbors are being developed with the same laissez-faire attitude toward natural resources as we held in our own past.

It is hard to imagine how these pressures can be relieved in time to save the tropical forest. Nevertheless, it would be valuable if the U.S. were to demonstrate some leadership in the prudent management of natural resources. We could begin by calling a moratorium on clear-cutting of the last expansive virgin forests of the Northwest.

If we fail in enacting the needed reforms, Americans will be well on the way to living out a scene envisioned 30 years ago by Rachel Carson in her book *Silent Spring.* Carson was concerned about the poisoning of the environment with pesticides, but her message stands as a general warning against disregard of the environment.

"It was," she wrote, "a spring without voices. On the mornings that had once throbbed with the dawn chorus of robins, catbirds, doves, jays, wrens, and scores of other bird voices there was now no sound; only silence lay over the fields and woods and marsh."

BACHMAN'S WARBLER in a flowering *Franklinia* (once called *Gordonia pubescens*) was painted by John James Audubon in the 1800s. Both the tree and the bird are now gone from the wild, the warbler being perhaps the first casualty of tropical deforestation. It vanished after Cuba, the bird's only winter home, converted most of its forests to fields of sugarcane.

FURTHER READING

NEST PREDATION IN FOREST TRACTS AND THE DECLINE OF MIGRATORY SONGBIRDS. David S. Wilcove in *Ecology,* Vol. 66, No. 4, pages 1211–1214; August 1985.

WHERE HAVE ALL THE BIRDS GONE?: ESSAYS ON THE BIOLOGY AND CONSERVATION OF BIRDS THAT MIGRATE TO THE AMERICAN TROPICS. John Terborgh. Princeton University Press, 1989.

ECOLOGY AND CONSERVATION OF NEOTROPICAL MIGRANT LAND BIRDS: PROCEEDINGS OF A SYMPOSIUM. Edited by John Hagan. Smithsonian Institution Press (in press).

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Heisenberg, Uncertainty and the Quantum Revolution

At 32, Werner Heisenberg was one of the youngest scientists to receive the Nobel Prize. Ambition and fierce competitiveness inspired him to formulate one of the best-known principles of science

by David C. Cassidy

Of the many achievements of 20th-century science, perhaps the most fundamental is quantum mechanics. Devised by a small group of highly gifted European physicists, the science of the atom entails profound and controversial transformations in our understanding of nature. Matter can be waves or particles, depending on how one observes them, and cause and effect are no longer closely related. This interpretation of quantum mechanics—prescriptions for how and when it is to be used and what it tells us about the physical world—was developed in 1927 in Copenhagen. Because of the propagation by its originators and the astonishing success of its practitioners, the Copenhagen interpretation had by the 1930s attained the preeminence it enjoys today. But an interpretation is only that. Its origins, defense and acceptance can be in important respects the products of historical circumstance and personal preference as well as of scientific validity.

The role that human attributes play in science is perhaps best demonstrated by one of the prime inventors and more active supporters of the Copenhagen interpretation, Werner Karl Heisenberg. It was in February 1927 that the 25-year-old postdoctoral assistant to Niels Bohr formulated his most well-known contribution to physics and a key element to the Copenhagen interpretation: the uncertainty, or indeterminancy, principle. Like the Copenhagen interpretation, it can be regarded as a result of the search for a consistent means of linking the everyday world of the laboratory with the strange new world of the minuscule atom.

Briefly put, the uncertainty principle states that the simultaneous measurement of two so-called conjugate variables, such as the position and momentum of a moving particle, entails a necessary limitation on precision. The more precise the measurement of position, the more imprecise the measurement of the momentum, and vice versa. In the most extreme case, absolute precision of one variable would involve absolute imprecision regarding the other.

This indeterminacy is not the fault of the experimenter: it is a fundamental consequence of quantum equations and a feature of every quantum experiment. Furthermore, Heisenberg declared, the uncertainty principle will never be overcome whenever and as long as quantum mechanics is valid. For the first time since the Scientific Revolution, a leading physicist had proclaimed a limitation to scientific understanding.

Along with the ideas of luminaries such as Bohr and Max Born, Heisenberg's uncertainty principle formed the logically closed system of the Copenhagen interpretation that Heisenberg and Born proclaimed complete and irrevocable before a meeting of the world's leading quantum physicists in October 1927. That meeting, the fifth of the famous Solvay congresses on basic physics held in Brussels, followed by only weeks Heisenberg's appointment to the chair for theoretical physics at the University of Leipzig. Only 25 years old, he was Germany's youngest full professor.

Heisenberg's extreme youth at the time of his most significant work indicates an important characteristic that impinged on this and all his early research: his nearly insatiable drive for academic success and for distinction as the best at everything he did. Not surprisingly, much of this desire can be traced to his family heritage.

The Heisenbergs were a highly cultured, ambitious family that was making its way into the upper middle class of German society. The unification of Germany under Otto von Bismarck during the late 19th century and the subsequent powerful growth of the economy had created a strong need for bureaucrats, diplomats, judges, lawyers and managers. Consequently, the new nation's universities and schools rose dramatically in importance. So did the prestige and material rewards of academicians and their successful students.

Both Werner's father, August, and his maternal grandfather, Nikolaus Wecklein, had risen from humble origins to the top of the German high bourgeoisie through academic achievement. Wecklein had a rectorship in a renowned Munich gymnasium (high school), and in 1910 August became professor of Byzantine philology at the University of Munich. Both men also married within their new stations.

Right from Werner's birth in 1901, his elders were determined that he, too, would achieve high social status through scholarship. Believing that competition would foster academic success, August fueled an intense rivalry between Werner and his older brother, Erwin. Over the years the two boys often

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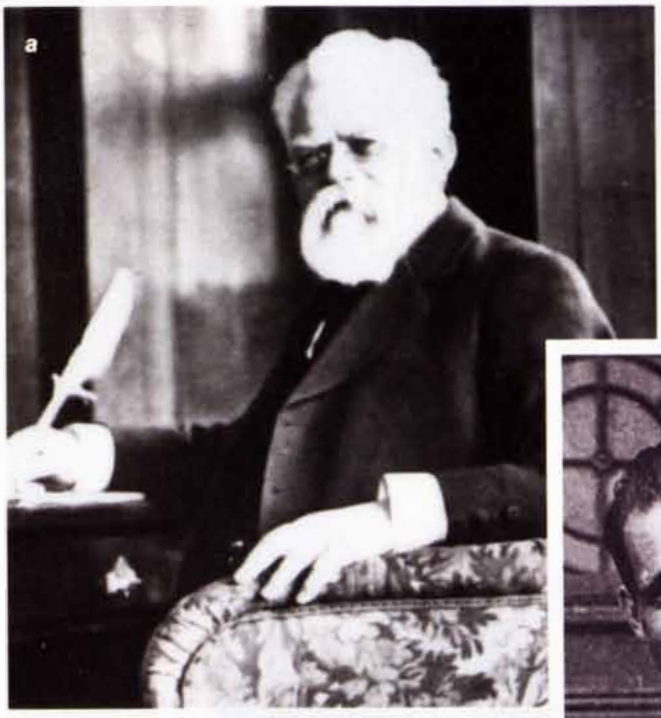
WERNER HEISENBERG made his most important contributions to physics while still in his twenties. The photograph was taken in about 1924 at the University of Göttingen, where he delivered the lecture that qualified him for a university chair.

The Early Years of Werner Heisenberg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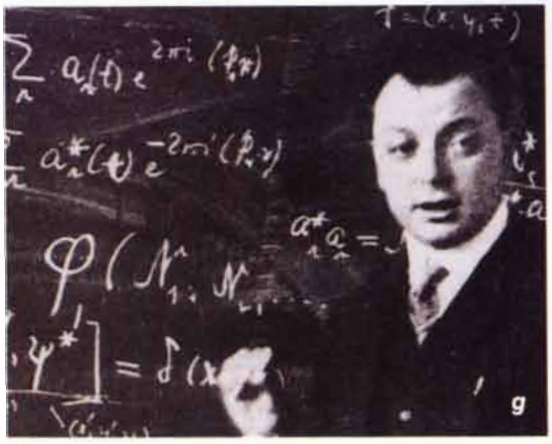
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fought fiercely, their competitiveness culminating one day in a bloody battle in which they beat each other with wooden chairs. As adults, each went his separate way—Erwin moved to Berlin and became a chemist—and, except for occasional family gatherings, they had little contact.

Werner's ambition to reach the top is especially evident in the period between July 1925, when he and his colleagues Born and Pascual Jordan developed a mathematical description of quantum mechanics, and February 1927, when he formulated the uncertainty relations. What made the impact of such drive so significant during this time was the confluence of two developments.

First, several chairs for theoretical physics suddenly became vacant in German-speaking central Europe. These positions meant great opportunity for an ambitious academic such as Heisenberg, who had already habilitated, that is, qualified for a university teaching chair, at the University of Göttingen.

Second, and perhaps more important, was the appearance of a new, rival mathematical description of quantum mechanics. Heisenberg and his colleagues had developed a formalism for quantum mechanics in 1925 that was based on the abstract mathematics of matrix calculus. To its authors, this "matrix mechanics" incorporated their preference for relying only on laboratory observables. They adhered to such essentials as the existence of quantum jumps and discontinuities within atoms and rejected the idea of *anschaulich,* or visualizable, atomic models.

Erwin Schrödinger, a 39-year-old Viennese physicist then working in Zurich, approached the puzzles of atomic physics from a quite different direction and with quite different aims. In a series of papers published during the first half of 1926, Schrödinger presented a quantum wave equation based on a hypothesis propounded by the French doctoral candidate Louis de Broglie. The idea, accorded favorable notice by Einstein, was that all matter in motion can be regarded as waves. Schrödinger used the notion to claim that electron "matter waves" set up harmonic modes of vibration inside atoms. These modes replace the stationary atomic states of matrix theory; discontinuous quantum jumps are instead continuous transitions from one harmonic mode to another. If true, Schrödinger had just rendered the fundamentals of Heisenberg's matrix mechanics irrelevant.

Most physicists gladly welcomed Schrödinger's more familiar approach and said little about his interpretation of it. That situation changed abruptly in May 1926, when Schrödinger published a proof that the two rival formalisms were, in fact, mathematically equivalent. Heisenberg and his matrix colleagues immediately rallied their cause, and in terms that on both sides assumed an increasingly emotional tone.

Schrödinger did not help matters. In his equivalence paper, he argued not for the equal appreciation of the two opposing schemes but for the superiority of his own. In a famous footnote to his paper, he stated: "No genetic relationship whatsoever [between Heisenberg's work and my own] is known to me. I knew of his theory, of course, but felt discouraged, not to say repelled, by the methods of transcendental algebra, which appeared difficult to me, and by the lack of *Anschaulichkeit* [visualizability]."

Heisenberg responded in kind in a letter to his close colleague Wolfgang Pauli: "The more I think about the physical portion of the Schrödinger theory, the more repulsive I find it .... What Schrödinger writes about the visualizability of his theory 'is probably not quite right' [an echo of Bohr], in other words it's *Mist* [manure]." The only advantage to Schrödinger's method, he said publicly, was that it enabled a simple calculation of atomic transition probabilities, or the probabilities of quantum jumps, for plugging into the matrices of quantum mechanics. Pauli agreed.

A closer look at the timing of these remarks indicates it was not the equivalence that provoked the conflict (Pauli had proved it privately a month earlier and without much ado) but what each side made of it. Heisenberg and the matrix school had spent their entire careers struggling with properties of nature that they believed to exist and to be embodied in their matrix mechanics. They had bet their futures on this approach. Schrödinger had staked his reputation on the banishing of seemingly irrational discontinuity and quantum jumps through a revival of the physics of continuous, causal, rational wave motions. Neither side was willing to concede superiority or its likely consequence—professional predominance—to the other. The nature and future direction of quantum mechanics were suddenly in dispute.

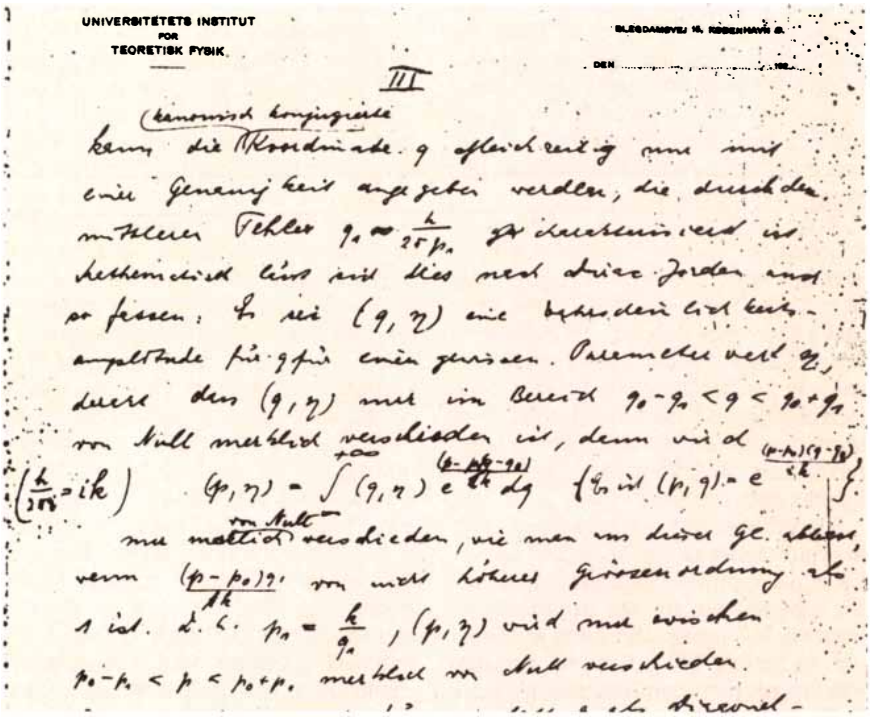
The discord further intensified Heisenberg's career ambitions. Just weeks before Schrödinger published his equivalence proof, Heisenberg had turned down a professorship in Leipzig for an assistantship with Bohr in Copenhagen. Werner's incredulous grandfather, Wecklein, hastened to Copenhagen in an attempt to dissuade his grandson from taking that post just as Schrödinger's equivalence paper appeared. Wecklein's renewed pressure and Schrödinger's challenge to the underpinnings of matrix physics redoubled Heisenberg's efforts to produce work of such high quality that it would attain wide professional acceptance and ultimately land him some other vacated chair.

But at least three events in 1926 impressed on him the vast intellectual gulf between his own ideas and Schrödinger's point of view. The first was Schrödinger's lectures on his new physics in Munich at the end of July. There the young Heisenberg argued from the crowded audience that Schrödinger's theory did not explain several phenomena. He failed to convince anyone and left the conference despondent. Next, during an autumn conference of German scientists and physicians, Heisenberg witnessed the overwhelming—and to him, wrong-headed—support for Schrödinger's views.

Finally, there was the intense though ultimately inconclusive debate between Bohr and Schrödinger in Copenhagen in October 1926. The upshot of the debate was the recognition that no available interpretation of either quantum formalism was entirely acceptable. Whoever, or whichever side, found such an interpretation would be able to realize, as Bohr reportedly put it, his "wishes" for a future physics.

With these various motivations—personal, professional and scientific—at work, by February 1927 Heisenberg believed he had suddenly hit on the needed interpretation: the uncertainty principle. His intellectual route to that idea in late 1926 and early 1927 lay in the research of his closest colleagues, especially Jordan and Paul A. M. Dirac, who together formulated "transformation theory," an amalgamation of the wave

INFLUENCES ON HEISENBERG'S LIFE began with his grandfather, Nikolaus Wecklein (*a*), and his father, August, shown with his wife, Anna, and sons, Erwin (*standing*) and Werner (*b*). Both men fostered a desire for academic achievement in the boys. Heisenberg studied under Niels Bohr (*c*), with whom he later developed the Copenhagen interpretation. One of Heisenberg's earliest rivals was Erwin Schrödinger (*d*), whose wave formalism challenged the matrix mechanics that Heisenberg developed in 1925 with Max Born (*e*) and Pascual Jordan (*f, right*). Wolfgang Pauli (*g*) was a prime impetus in helping Heisenberg develop the uncertainty principle in 1927. In 1929 Heisenberg embarked on a world lecture tour to spread the "Copenhagen spirit," reaching the U.S., Japan, China and, finally, India (*h*).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LETTER WRITTEN by Heisenberg to Wolfgang Pauli derived the uncertainty relations for p and q, where $p_1 = \sqrt{2}\,\Delta p$ and $q_1 = \sqrt{2}\,\Delta q$. This excerpt, part of a 14-page letter, was the basis for Heisenberg's uncertainty principle paper.

and matrix mathematics. The objective for Heisenberg and his allies, then, was to find an irrefutable way to incorporate discontinuity into Dirac and Jordan's formalism.

A prime impetus for the new interpretation came from Pauli. In his letter of October 19, 1926, in which he informed Heisenberg of an available chair in Leipzig, Pauli applied stationary atomic states to Born's earlier study of free electron waves. Continuous variables for momentum p and position q of an atomic electron must be chosen, he found, but their quantum behavior manifested a "dark point": "The p's must be assumed to be *controlled,* the q's to be *uncontrolled.* That is, one can calculate only the probabilities for definite changes of the p's for given initial conditions and *averaged over all possible values of the q's.*" Thus, one cannot speak of a definite "'path' of the particle," Pauli wrote, nor "can one inquire simultaneously about the value of p and the value of q."

Heisenberg responded that he was "*very* enthused" by Pauli's letter and dark point, on which Heisenberg frequently reflected during the following months. Heisenberg's enthusiasm culminated in a 14-page letter to Pauli on February 23, 1927. In it, he presented nearly all of the essential features of a paper submitted exactly one month later under the title, "On the *anschaulich* Content of Quantum Theoretical Kinematics and Mechanics": Heisenberg's uncertainty paper.

Heisenberg, having derived the uncertainty relations from both mathematics and thought experiments, regarded the agreement between the two as proof for the universal validity of uncertainty. The mathematical argument began with a wave function that was conceived to be a bell curve, or mathematically speaking, a Gaussian probability distribution, for the variable q. The error in knowing the exact value of q (called the standard deviation) is delta q, written as Δq. Using the formalism developed by Dirac and Jordan, Heisenberg transformed the Gaussian distribution into the conjugate variable p.

In so doing, he discovered that as a mathematical consequence the standard deviations of the two distributions—that is, the imprecisions in the values of q and p—are inversely related to each other. This reciprocity can be extended and expressed by the relation

$$\Delta p \bullet \Delta q \geq \frac{h}{4\pi},$$

where h is Planck's constant. He then showed that this result is not merely abstract but fully compatible with every imaginable experiment involving the simultaneous measurement of conjugate pairs of variables, such as position and momentum or energy and time.

The compatibility with experiment relied, however, on several innovations Heisenberg introduced for the purpose of incorporating discontinuity and particles. One of these was a redefinition of the German *anschaulich* in the title of his paper to mean "physical" or empirically meaningful rather than visualizable or pictorial. This change was intended to counter Schrödinger's criticism that a discontinuous particle physics is essentially irrational and *unanschaulich.* It was closely related to a second innovation: a redefinition of such classic concepts as position, velocity and path of an atomic particle in terms of the experimental operations used to measure them, a form of operationalism. Only what the physicist can measure has any real meaning, and these measurements always manifest the uncertainty relations.

For the young Heisenberg, the uncertainty principle constituted the culmination and completion of the quantum revolution, a revolution that incorporated his commitments to foundations that he himself had helped to lay. And, as if to silence any objection to this point of view, he concluded his published paper with several claims that went far beyond mathematics and thought experiment. With the Dirac-Jordan transformation theory, he declared, the quantum formalism is complete and unalterable; the uncertainty relations are true and irrefutable, because they are a direct consequence of the formalism. All previous and future experimental observations of atomic phenomena are thus subsumed under this interpretation.

Moreover, he argued, although quantum physics contains a basic statistical element, that element is not a property of nature itself. It enters because of the disturbance caused by the physicist's attempt to observe nature. Finally, he presented his first explicit statement on a most profound consequence of uncertainty—a challenge to causality.

The causality principle requires that every effect be preceded by a unique cause. This idea had served for over a century as a basic assumption of practically every form of rational research. The French mathematician Laplace is credited with perhaps the simplest definition of causality as applied to Newtonian mechanics: if the position and momentum of a particle are accurately known at a given moment, then, with a knowledge of all the forces acting on the particle, its motion is fully determined by the mechanical equations for all future time.

The uncertainty principle, Heisenberg asserted, denies this: "In the strict formulation of the causal law—if we know the present, we can calculate the

future—it is not the conclusion that is wrong but the premise." The initial values of the momentum and position cannot be measured simultaneously with absolute precision. As such, one can calculate only a range of possibilities for the position and momentum of the particle at any future time. Only one possibility will result from the actual motion of the particle. The causal connection between present and future is lost, and the laws and predictions of quantum mechanics become merely probabilistic, or statistical, in nature.

Heisenberg's uncertainty principle paper was profound and far-reaching in nearly every respect. Besides satisfying his goals so closely, Heisenberg's paper was in character. When his mentor, Bohr, confronted him with an error in the argument, Heisenberg stubbornly defended his position in a battle that degenerated in the spring of 1927 into what Heisenberg called "gross personal misunderstandings." The error involved Heisenberg's overreliance on discontinuity and the corpuscular features of light quanta in one of his basic thought experiments, the so-called gamma-ray microscope [*see box below*].

Bohr, who had been on a skiing vacation, returned to his institute to find Heisenberg's paper already in draft. Forwarding the paper to Einstein at Heisenberg's request, Bohr complained privately to Einstein that Heisenberg's entire approach was too narrow and his gamma-ray microscope was all wrong, although the outcome was correct. For Bohr, the uncertainty relations arose not merely from formalism, redefinitions of basic concepts and the primacy of discontinuity and corpuscles over continuous waves. The wave-particle duality and, in the gamma-ray microscope, the scattering of light waves by the electron into the microscope lens were also crucial.

The wave and particle pictures are "complementary" to each other, mutually exclusive yet jointly essential descriptions. Bohr argued that the experimenter must choose either the wave or the particle picture with which to analyze the experiment. The price one pays for such favoritism engenders a restraint of what can be learned from the experiment, and this limitation is represented by the uncertainty relations. Heisenberg's argument was, for Bohr, only a special case of what Bohr was now calling complementarity.

Heisenberg vehemently disagreed. Insisting on the primary use of particles and discontinuity, he absolutely refused Bohr's suggestion that he withdraw his paper, which he had in the meantime sent to press. Heisenberg could not tolerate extensive use of waves or of wave-mechanical notions, nor could he fail to publish his own major contribution to the interpretation debate. The subsequent battle with Bohr grew so intense that Werner reportedly burst into tears during one meeting and even managed to wound the usually unflappable Bohr with some sharp remarks. Obviously,

The Gamma-Ray Microscope Thought Experiment

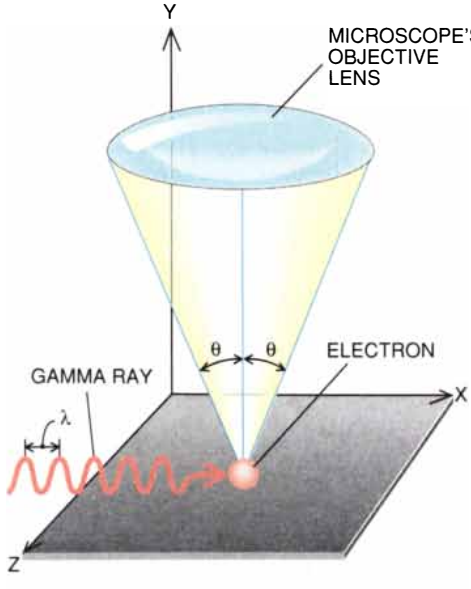
To demonstrate the uncertainty principle, Heisenberg offered a thought experiment. Using a microscope whose resolution was high because it relied on gamma rays for illumination, he tried to show that the electron's position and momentum obeyed the uncertainty principle. Although Heisenberg achieved the right results, Bohr pointed out that the original experiment neglected two essentials: the resolving power of the microscope and the wave-particle duality.

In the correctly performed version, a free electron sits directly beneath the microscope's objective lens. The circular lens forms a cone of angle 2Θ from the electron. The electron is then illuminated by a gamma ray traveling from the left. According to a principle of wave optics, the microscope can resolve objects to a size of Δx, which is related to Θ and to the wavelength of the light, λ, by the expression

$$\Delta x = \frac{\lambda}{2} \sin \Theta .$$

At the moment the light is diffracted into the microscope objective, the electron recoils to the right. After the collision the observed gamma ray could have scattered into any angle within the cone 2Θ. In the extreme case of scattering to the forward (right) edge of the lens, the momentum in the x direction would be

$$p'_x + \frac{h}{\lambda'} \sin \Theta ,$$



where p'_x is the momentum of the electron in the x direction, λ' is the wavelength of the deflected gamma ray, h is Planck's constant (which relates the frequency of the photon to its energy) and $\frac{h}{\lambda'}$ is the gamma-ray photon's total momentum, as defined by quantum principles. In the other extreme, the gamma ray scatters backward, just hitting the left edge of the lens. In this case, the total x momentum is

$$p''_x - \frac{h}{\lambda''} \sin \Theta .$$

The final x momentum in both cases must equal the initial x momentum; therefore,

$$p'_x + \frac{h}{\lambda'} \sin \Theta = p''_x - \frac{h}{\lambda''} \sin \Theta .$$

If Θ is small, then $\lambda' \sim \lambda'' \sim \lambda$, and

$$p''_x - p'_x = \Delta p_x \sim \frac{2h}{\lambda} \sin \Theta .$$

Since $\Delta x = \frac{\lambda}{2} \sin \Theta$, there is a reciprocal relation between the minimum uncertainties in the measured positions of the electron along the x axis and its momentum in the x direction:

$$\Delta p_x \sim \frac{h}{\Delta x} .$$

For more than minimum uncertainty, an inequality may be introduced,

$$\Delta p_x \cdot \Delta x \gtrsim h,$$

which approximates Heisenberg's uncertainty relation.

much was at stake for the 25-year-old: his new insights, his academic plans and perhaps even his desire for intellectual equality with his mentors. His paper appeared unrevised in May in a leading German physics journal, but it did contain a short postscript admitting the microscope error and alerting readers to some essentials of Bohr's argument.

About four months later Heisenberg had dried his eyes and completely changed his tune: he seemed to be grateful for Bohr's criticism. After Bohr made his first presentation of complementarity to an audience assembled at Lake Como in Italy in September 1927, Heisenberg, previously so certain of uncertainty, offered the first of his generous acknowledgments to Bohr. In the published version of the discussion following Bohr's Como paper, Heisenberg thanked him for clarifying uncertainty "in every detail" and for enunciating what became known as the Copenhagen interpretation.

Heisenberg's change of heart may have been initiated by the realization of his ambition. For in the same month as the Como conference, Heisenberg had learned of his impending call to the Leipzig chair. That goal had at last been achieved.

As Heisenberg's desire to emphasize his abilities and contributions to quantum mechanics subsided, another emerged that now included Bohr: the need to build up a permanent, first-class research program at Leipzig on the basis of the physics. In addition to buttressing ill-argued uncertainty, Bohr's explanations provided a rallying point for the Dane's followers, who, like Heisenberg, were eager for a completed physics to propagate from their freshly acquired chairs and to exploit in their papers. Heisenberg and other Bohr disciples no longer lent their allegiance to individual programs and discoveries, matrix mechanics or uncertainty but to the "Copenhagen spirit."

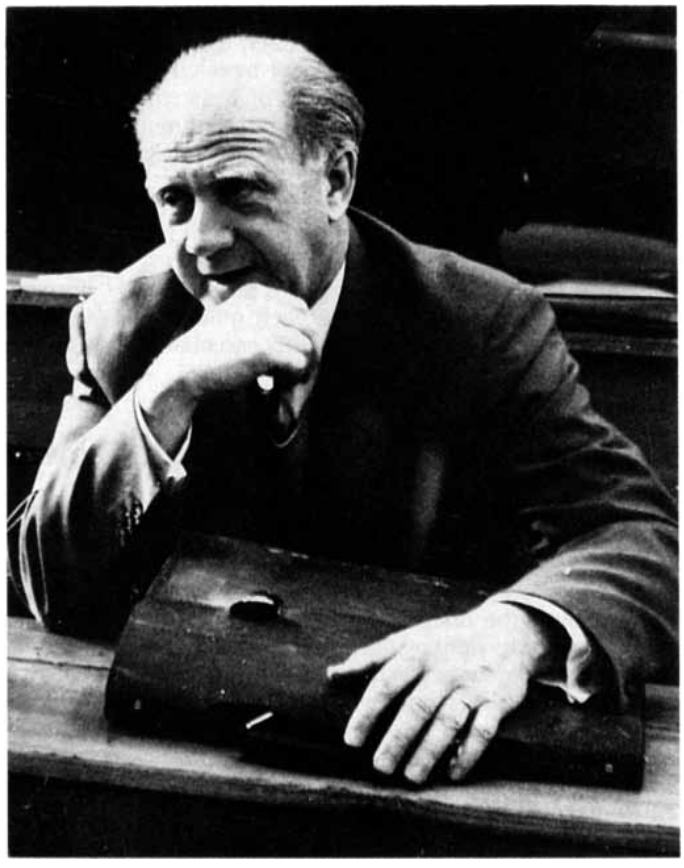
Heisenberg and others managed to ensure the acceptance of their interpretation, despite the lingering objections of such leaders as Einstein and Schrödinger. During the half decade after the Como meeting and, later, the Solvay congress, Heisenberg and his institute produced major quantum theories of solid state crystals, molecular structure, radiation scattering by nuclei and the neutron-proton structure of nuclei. With other theorists, they made enormous strides toward a relativistic quantum theory of fields and laid the foundations of high-energy physics research.

Such successes naturally attracted many of the best students to institutes such as Heisenberg's. These students, nurtured by the Copenhagen doctrine, formed a new and dominant generation of physicists who carried the ideas with them as they dispersed around the world in the wake of Hitler's rise to power during the 1930s.

Heisenberg and other Copenhagenites wasted little time in bringing their doctrine to those who did not travel to European institutes. Heisenberg in particular found the U.S. a fertile field for proselytizing. During a round-the-world tour with Dirac in 1929, Heisenberg presented tremendously influential lectures on the Copenhagen doctrine at the University of Chicago. In the foreword to his lectures, Heisenberg wrote: "The purpose of this book seems to me to be fulfilled if it contributes somewhat to the diffusion of that *Kopenhagener Geist der Quantentheorie* ... which has directed the entire development of modern atomic physics."

The purveyor of that *Geist* returned to Leipzig with his earlier scientific commitments now widely accepted by a profession that accorded him prominent positions in both institutional and scientific respects. In 1933 the profession conferred on Heisenberg, with Schrödinger and Dirac, the crowning recognition of his work: the Nobel Prize.

Although Heisenberg is rightly celebrated today as one of the greatest physicists of modern times, he has also been criticized for many of his actions after Hitler's rise to power. Heisenberg never joined the Nazi party, but he held prominent academic positions and became a spokesman for German culture in occupied territories. Repeatedly refusing offers of emigration, he headed the main research effort on uranium fission for the Third Reich. After the war, he offered various explanations for his actions, which further tarnished his reputation abroad. The puzzling juxtaposition of such questionable behavior and brilliant physics reflects the larger predicaments of the scientist and science during a turbulent and sometimes brutal century. A loyal son of Germany, Heisenberg, who saw so deeply into nature, found it difficult to discern and accept how tragically his country had strayed. He died of cancer of the kidney and gallbladder in his Munich home in 1976.



HEISENBERG AT 65 returned to the University of Leipzig to deliver guest lectures. He became ill a few years later and died of cancer in 1976.

FURTHER READING

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UNCERTAINTY: THE LIFE AND SCIENCE OF WERNER HEISENBERG. David C. Cassidy. W. H. Freeman and Company, 1991.

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ELOQUENT REMAINS

by Philip E. Ross, *staff writer*

Nucleic acids and proteins trapped in ancient mummies and still more ancient bones can serve as time capsules of history. Molecular biologists are beginning to unlock their secrets.

The poor man's relatives will want to know his fate, thought vacationer Helmut Simon as he snapped pictures of the corpse he and his wife, Erika, had found protruding from a melting Tyrolean glacier last summer. Simon was right: the body has reliably been dated to between 5,000 and 5,500 years ago, making it the possible ancestor of millions of living Europeans. Scholars scrambled for access to the mortal remains and tools of the Iceman, the only known mummy from the Stone Age.

Yet for all the drama attendant on the discovery of the Iceman, he is but a single pixel in a slowly forming picture made of thousands. Uncannily true to life, sometimes accompanied by clothes, weapons and victuals, the contents of their last meal often still discernible in their stomachs, ancient bodies regularly crop up in certain propitious sites, from the deserts of North Africa, Peru and the American Southwest to the peat bogs of Denmark, Britain and Florida. Long regarded as curiosities or as raw material for the apothecary's mortar and pestle, multitudes of these mummified messengers from the distant past have been willfully destroyed or reburied. Those that remain are now undergoing intense scrutiny.

The silence of the grave has become a poetic anachronism. Far from being mute, ancient remains bear eloquent testimony to those who know how to listen. Within the past decade, biochemists have discovered how to wrest the molecules of life from organic residues one step removed from mere dust. Proteins and nucleic acids have been recovered from plants that lived millions of years ago and animals that lived tens of thousands of years ago. Most encouraging of all, workers now seek and find such molecular clues not only in preserved bodies but also in dry bones, providing a vastly greater vista of the past.

This young science of molecular archaeology provides the first absolute check on inferences drawn from the genetics of modern populations. Together with comparative studies of language and of artifacts, it promises to unravel the tangled skein of human biological history, its divisions and migrations, extinctions and expansions. Molecular archaeology has already illuminated more mundane concerns—the climates early peoples braved, the diseases they contracted, the foods they ate, the way they reared their children. Ultimately, the new field will enable biologists to walk Darwin's theory step by step through history. "We can now dream of catching molecular evolution red-handed," exulted the late Allan C. Wilson of the University of California at Berkeley, a pioneer in the field.

No one knows how far back the DNA sleuths can hope to look,

PREDYNASTIC EGYPTIAN MUMMY from the fourth millennium B.C. appears in a reconstruction of the grave in which it was found. Mummies provided the first direct view of genetic affiliations of early peoples.

but there are grounds for optimism. A still green magnolia leaf has preserved DNA for more than 17 million years, and workers speculate that residues of hominid DNA may survive in bone at least until the bone becomes its own mineralized facsimile. The oldest human remains analyzed reach back only 8,000 years, but that record may already have been broken.

In the three years since researchers at the University of Oxford first recovered DNA from old bones, there have been persistent rumors that groups were seeking such clues in the remains of archaic hominids. No one, however, would admit to using unproved analytical techniques to ravage priceless relics. "A lot of people have held back in examining rare materials, although there are quite a lot of Neanderthal specimens," says Bryan Sykes, a member of the Oxford group.

But there was truth in the rumors. Erik Trinkaus, a paleoanthropologist at the University of New Mexico, says he has provided a bit of Neanderthal bone to biochemists at Los Alamos National Laboratory, who are now trying to recover DNA from it. The bone, a fragment of a vertebra from a skeleton found at Shanidar, Iraq, dates to about 50,000 years ago. Trinkaus was willing to part with the specimen because its fragmentary nature did not even allow him to identify the vertebra from which it came.

As of late March, the Los Alamos group would not discuss its work. But sources close to the project say preliminary studies show that DNA is present, that it appears to be damaged—as if by age—and that it comes from a primate. Sources cautioned, however, that rigorous tests would have to be conducted to rule out the possibility that the DNA derives from modern contaminants, and not from the ancient bone. Only then would the scientists submit their findings for publication.

Whether or not the Los Alamos group sets the record for recovering the oldest hominid DNA, the experiment is just one example of the rapid progress being made by molecular archaeologists. Until recently, most research on the human genetic past had centered not on the skin and bones of mummies and of skeletons but on the blood of living people. No good alternative presented itself for the analysis of purely hereditary traits. At first, workers studied the blood proteins themselves, especially the polymorphic antigens (such as the Rh, or Rhesus, factor) and immunoglobulins. Then, about 10 years ago, the development of new biochemical techniques shifted the focus from proteins to the nuclear DNA that encodes them.

In 1984 Wilson and his team at Berkeley became the first to identify genes in old tissues. They cloned DNA from skins of the quagga, a zebralike beast that went extinct in Africa a century ago. A year later Svante Pääbo, a Swede who now teaches at the University of Munich, cloned DNA from an Egyptian mummy who lived more than 4,400 years ago. Then in 1988, while working in Wilson's laboratory, Pääbo became the first to apply the polymerase chain reaction (PCR) to ancient human remains. By amplifying mitochondrial DNA from a brain preserved in Little Salt Spring, Fla., he pushed the horizon 2,600 years deeper into the past. Finally, in 1989, Sykes and his colleagues Erika Hagelberg and Robert E. M. Hedges of Oxford became the first to amplify DNA from human bone.

Scouring ancient remains for traces of DNA was all but impossible until the development in 1983 of PCR, an astoundingly sensitive copying machine for DNA [see "The Unusual Origin of the Polymerase Chain Reaction," by Kary B. Mullis; SCIENTIFIC AMERICAN, April 1990]. The process works in two steps: first the double helix of a sample of target DNA is split into its two single strands, then enzymes build a new second strand from a bath of free-floating nucleic acid bases. Through repetition of the process, a single molecule of DNA becomes two, then four and so

SVANTE PÄÄBO of the University of Munich proved the feasibility of molecular archaeology in 1985 by cloning DNA from a mummy. Here he poses with a sample in his ongoing genetic survey of Egyptian history.

on—geometric amplification that can in principle turn out a bucketful of product for analysis. As a result, DNA samples that would have eluded all detection 10 years ago now leave satisfying solid electrophoretic bands—the traces left by materials of varying molecular weights, after they have migrated through a gel substrate.

The very sensitivity of PCR makes it devilishly tricky. If you should shed a single skin cell into the bath, PCR will amplify the DNA blindly and, because of its superior state of preservation, preferentially. After a few doubling cycles, you will see in your test tube not the secrets of Neanderthal Man but of yourself. "Most DNA from old materials is so degraded that when people tell me they get great bands in a gel, I just don't believe it," says Rebecca L. Cann, a former student of Wilson who is now at the University of Hawaii at Manoa.

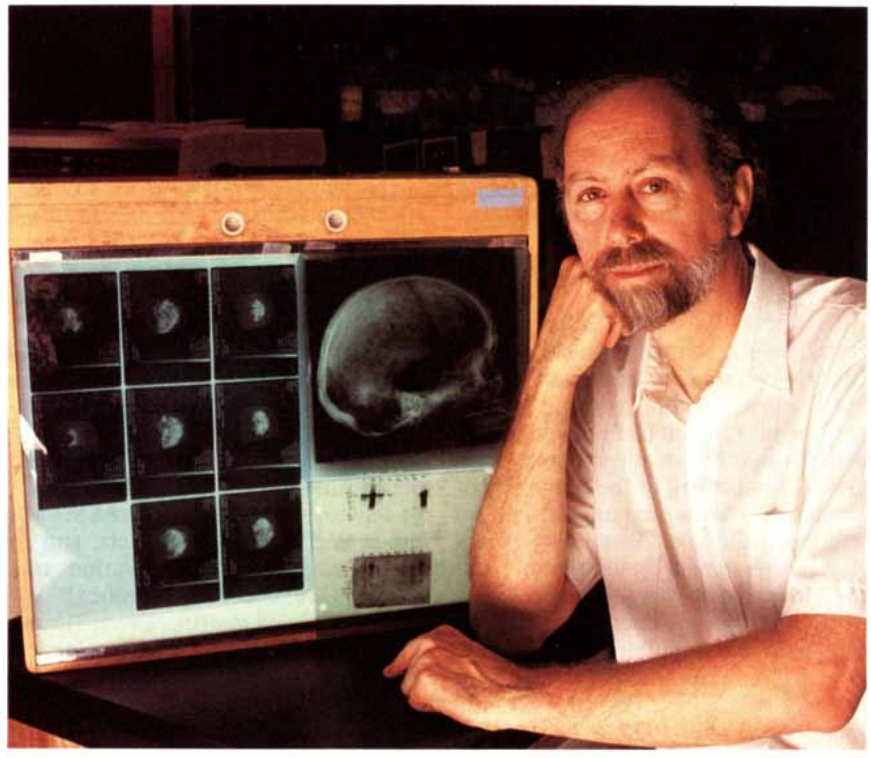
Pääbo has promulgated laboratory protocols that minimize the confusion of new DNA with old. Researchers continually refine such clean-room techniques while working on another black art: overcoming inhibitors, the shadowy substances that often insulate old DNA from PCR. Bovine serum albumin, for example, will sometimes loosen the gunk that ties old DNA into knots.

Some frustrations remain. During the world's first paleo-DNA meeting, held last summer in Nottingham, England, workers found they could do some things with fresh DNA they could not do with old samples. "We've tried to sex a series of bones that had been sexed by morphometric anthropologists," Sykes says. "But in a blind series of 20 skeletons, we never got it exactly right. It should be really easy."

Bog Brains

Nor is it an easy task to find ancient DNA in the first place. Workers first obtained their DNA from soft tissues preserved by drying, as in Egyptian mummies. But they ruled out those bodies that had been pickled in peat bogs, despite their astounding degree of preservation. Bog people, such as the Iron Age sacrificial victims dredged up decades ago in Denmark and a possible Druid found seven years ago in Britain, show slashes on their throats, tattoos on their bodies, food in their gut and even crow's-feet around their eyes. Unfortunately, they are intact precisely because they have been cured by tannic acid, which destroys DNA, itself an acid.

The freeze-dried Iceman is a notable—and highly unusual—exception. His remains were not destroyed by tannin; all indications are that his DNA is well preserved. Researchers are even optimistic that they may discover bacteria and other disease organisms, perhaps even viable spores, in his tissues [*see box on pages 122 and 123*].



WILLIAM W. HAUSWIRTH of the University of Florida at Gainesville finds striking genetic homogeneity in the DNA of prehistoric brains from central Florida.

But occasionally, even a bog can turn up a surprise. At a peat pond in Windover, Fla., dribbling limestone springs that buffer the acid have preserved the oldest human DNA yet sampled. Construction workers who dug up the pond found a foot-thick stratum—a millennium's worth of sediment—that harbored skeletons, some of which had intact skulls and well-preserved, if shrunken, brains. The oldest date back 8,000 years, the youngest, 7,000.

In the early to middle 1980s Glen H. Doran of Florida State University led anthropologists in an ambitious project to excavate the bog, section by diked section, while pumps bailed out the encroaching water. They found some skeletons still framed by stakes crossed over them at an angle, possibly to keep the bodies from floating into the view of scavengers.

After recovering 177 skeletons and 91 brains, the archaeologists closed the dig, deliberately leaving another 60 or so skeletons untouched. "It was hard at first to talk the archaeologists into doing that," says William W. Hauswirth, a microbiologist at the University of Florida at Gainesville. "But we know for sure that the genetic material is quite stable in situ. When I pointed out that we didn't yet know how to analyze such material—they had thought we knew exactly what we were doing—they agreed."

For four years, Hauswirth struggled with the frustrations of old-style cloning and, later, with the unforeseen intricacies of newfangled PCR. Finally, a year ago, Hauswirth and Cynthia D. Dickel, also of Gainesville, together with David A. Lawlor and Peter Parham of Stanford University, identified particularly significant DNA segments from a 7,500-year-old Windover man. The segments came from the major histocompatibility complex (MHC), which regulates the immune system. The MHC contains many sites carrying either one or the other of a pair of alternative genes, or alleles. "We can characterize what MHC alleles the ancient populations had, and we may eventually be able to infer what diseases they were and were not resistant to," Hauswirth says.

Hauswirth's group found that the genetics of the Windover population changed little in the burial ground's 1,000-year history, so few outsiders can have married into the community. "Things are cropping up that are very different from modern populations," he says. "We looked at three genetic loci and found they're much more homogeneous than in contemporary tribes that have been studied."

That homogeneity may mean the pop-

ulation was very inbred. If this trait was general—if early Americans all stayed at home and married neighbors—the isolation could have given rise to a multiplicity of languages, a pattern now found in the highland valleys of New Guinea. This scenario might explain why the New World in 1492 held as much linguistic diversity as the Old World, as well as why New Guinea still hosts a fifth of the world's language families.

To check on such reasoning, researchers can compare genetic diversity between men and women in the old burial sites. "Within a single village, you'd expect that at birth males and females would be equally variable," says Lyle W. Konigsberg of the University of Tennessee, who is studying the mound builders of Illinois. "You'd also expect each village to be a little different from the others. So if women, say, came in from other places, they would be less similar to one another than the men were." That is the pattern Konigsberg noticed when he looked for exogamy among the mound builders.

On the other hand, the Florida tribe may simply have passed through what is known as a genetic bottleneck. A bottleneck occurs when pestilence, famine or war ravages a community when a handful of emigrants establishes a colony. In either case, the new population will be less genetically diverse than the original one was, and genes will appear in different ratios. The genetic shuffle produces what evolutionists call a founder effect. Such effects, perhaps coupled with natural or sexual selection, may explain why so many Irish have red hair or why Samoans tend to be so robust.

Several research groups are now applying genetic methods to seek evidence of the bottleneck that Asians must have faced when they immigrated to the New World. Pääbo and others at the University of Utah plan a comprehensive genetic survey of living peoples as well as of such ancient populations as the 900-year-old mummies from the American Southwest. "We're trying to reconstruct the population history of North and South America," Pääbo says. "We want to see how populations related to each other, and eventually to Asia, and to check whether the population tree matches linguistic classifications."

Meanwhile Hauswirth, Noreen Tuross, a biochemist at the Smithsonian Institution, and others will establish three ancient-DNA data bases to study the effects of measles and smallpox, which killed most Native Americans within a few generations of their first contact with Europeans. The data come from Windover, Indian Knoll, Ky., which claims 1,200 well-preserved skeletons, and Arroyo Seco, Argentina. The last site was included for both its wealth of material and its distance from the other sites. "This would be the first genetic analysis of pre-European contact with Native Americans," Hauswirth declares.

Such examinations of paleo-DNA should confirm, or weaken, recent theories about early man that are based on genetic comparisons of modern populations. When Luigi Luca Cavalli-Sforza of Stanford and his colleagues cast population-wide genetic patterns into family trees, those trees turned out to correlate well with a genetic classification of languages [see "Genes, Peoples and Languages," by Luigi Luca Cavalli-Sforza; SCIENTIFIC AMERICAN, November 1991]. The work focuses on recent prehistory—the period since the emergence of modern-looking *Homo sapiens*.

Father's Irrelevance

Most important, the study of paleo-DNA promises to test the theory of Wilson and his colleagues that all living humans are descended from a single woman, dubbed Eve, who, they concluded, lived in Africa. Wilson, Cann and Mark Stoneking analyzed DNA from mitochondria, organelles that turn glucose into a more easily used form of energy. Unlike the DNA in the cell nucleus, mitochondrial DNA passes from mother to child as a unit. (Although mouse studies last year proved that the odd paternal mitochondrion may leak into the next generation, even then it will not mix its genes with the mother's.) The father's irrelevance makes lineages distinct, so analysts can explain genealogy as the result of mutation alone.

Wilson and his group compared mitochondrial DNA of people from around the world to estimate genetic distances. They represented the distances in a family tree and rooted the tree by comparing it with data from a chimpanzee. Because the longest branches were in Africa—which would suggest the mitochondrial DNA had begun differentiating there—they placed Eve in that continent. Although no one disputes the preeminent diversity of African genes, some scholars have recently found fault with the tree itself. They have shown that alternative statistical treatments can construct equally plausible trees with Asian roots.

Even more controversially, the Wilson group inferred a "molecular clock" from genetic differences accumulated by humans and chimps in their five million–odd years of living apart. Mitochondrial DNA lends itself to such chronometry because its fast rate of mutation makes it a fine-grained index of time. The clock dated Eve to about 200,000 years ago, leading the group to conclude that her descendants—the early modern humans—later fanned out of Africa to replace other hominids

BRYAN SYKES and his colleagues at the University of Oxford expanded the scope of paleogenetic data by recovering DNA from dry bones.

with little or no interbreeding [see "The Recent African Genesis of Humans," by Allan C. Wilson and Rebecca Cann; SCIENTIFIC AMERICAN, April].

The "out of Africa" theory had been formulated independently, on purely paleontological evidence, by Christopher B. Stringer of the Natural History Museum in London [see "The Emergence of Modern Humans," by Christopher B. Stringer; SCIENTIFIC AMERICAN, December 1990]. It has since been attacked by other scholars who read the same fossils differently [see "The Multiregional Evolution of Humans," by Alan G. Thorne and Milford H. Wolpoff; SCIENTIFIC AMERICAN, April].

Ultimately, molecular geneticists hope to settle the debate with analyses of DNA preserved in ancient bone. Genetic data bases, such as those being proposed by Hauswirth, could calibrate the mitochondrial clock in absolute terms. Workers would have to find modern descendants of paleo-DNA, count the base-pair substitutions and compare them against radiocarbon dates for the bones in which the DNA was found.

As a starting point, Pääbo and Anna Di Rienzo, another graduate of the Berkeley laboratory, will study both mummies and modern people from sites along the Nile to search for signs of an out-of-Africa migration. "The Nile would facilitate the movement of people," Di Rienzo says. "I am confident that when we have more information we will find a gradient" from south to north. (A still more telling test could come from a single sample of Neanderthal DNA. If, for example, it carried markers found in only a few branches of Eve's family tree, the finding would refute the theory of total replacement).

NOREEN TUROSS of the Smithsonian Institution in Washington, D.C., freezes bones and grinds them to dust in her quest for ancient antibodies.

Other molecular archaeologists are turning to ancient remains to trace the effects of disease on human populations. Tuross of the Smithsonian seeks direct molecular evidence of pre-Columbian cases of treponematosis: infections caused by the spirochetes, or helical bacteria, that variously cause venereal syphilis, endemic syphilis (bejel), yaws and pinta. (She cautions that her tests cannot, in principle, distinguish one treponemal strain from another.)

Instead of probing DNA, Tuross seeks antibodies that may have soaked into the bones of severely infected individuals. So far she has identified immunoglobulins of the IgG class in two New World skeletal populations: that from Windover and another from a 16th-century site in the northern Great Plains. A comparative molecular study of treponemal infections in the Old and New Worlds might finally resolve the question of whether syphilis was brought back to Europe by Columbus's crew.

Tom D. Dillehay, an archaeologist at the University of Kentucky, is trying to trace disease bottlenecks that may have confronted the first Americans after they arrived in this hemisphere. He believes the chilly passage southward, through Canada, might have cleansed immigrants of some Old World parasites. New ones, however, were surely lying in wait for them, especially in the humid climes of Mexico and Central America. "I am convinced that disease ecology may be important archaeologically," he says, "but it has been a damn difficult thing to figure out."

Among the most interesting bottlenecks created by infectious agents are those that select for genetic diseases. A family of blood disorders, called thalassemias, arose in independent mutations in Asia and the Pacific. Prehistoric sites in Thailand have just provided historians of thalassemia with their earliest hard evidence—bone. "We believe we're seeing evidence that 4,000 years ago they had thalassemia," says Philip Houghton, a surgeon turned anthropologist at the University of Otago in New Zealand. "In the bones of infants and young people, you see signs of abnormal growth" deriving from the thalassemic overproduction of blood cells.

By grounding evolutionary processes in time, such finds help workers refine the models they use to test whether other genes arose by chance or through selection. Even the inability of many adults to digest lactose, the sugar in fresh milk, has been so explained. Although no ancient molecular evidence has yet been brought to bear, biological historians believe they can infer selective patterns from contemporary data.

Lactase, the enzyme that digests lactose, is generally retained into adult-

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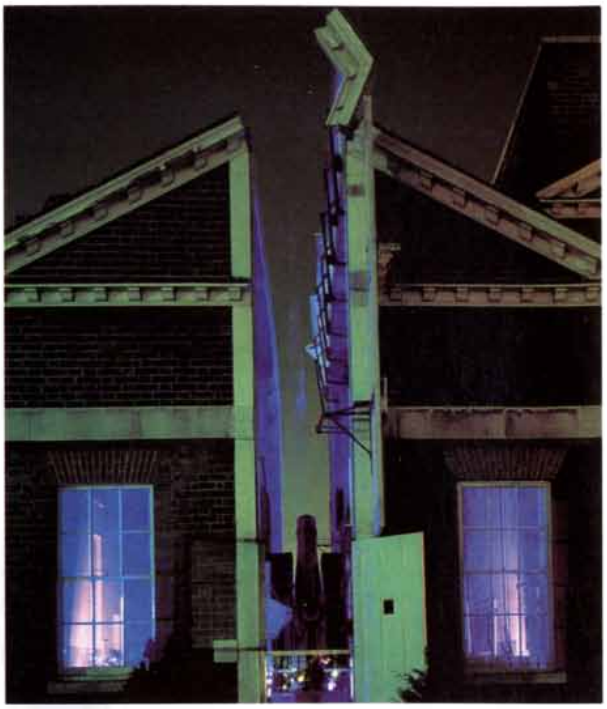

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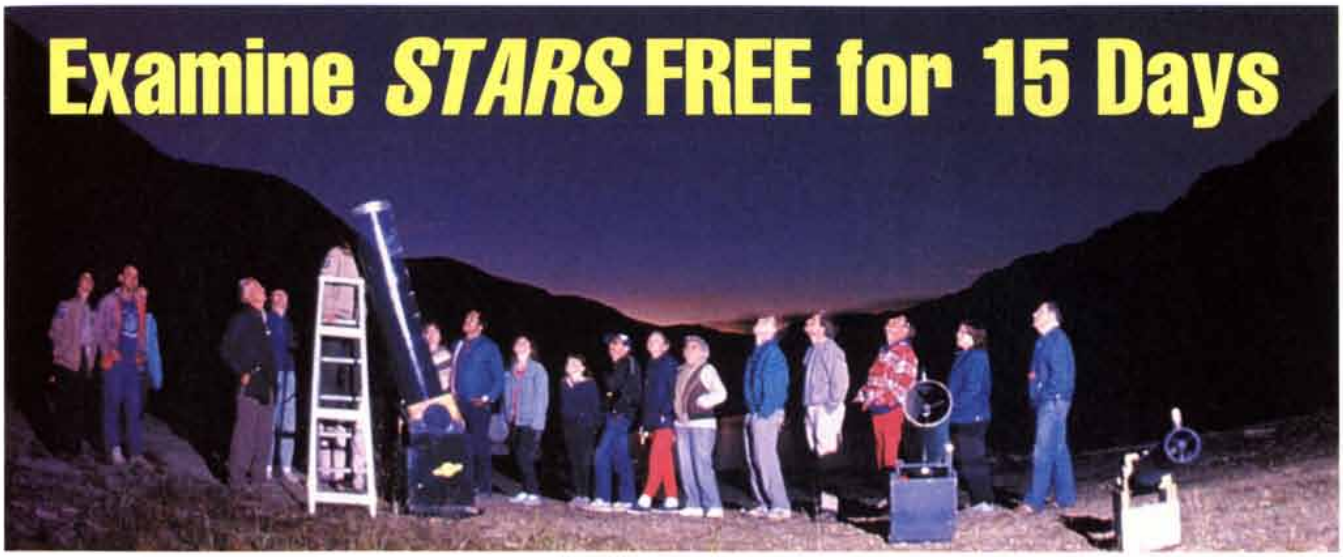

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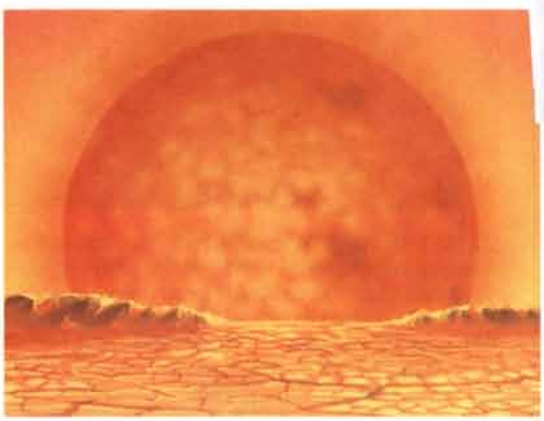

This artist's rendering is what the earth may look like 5 billion years from now as it is scorched by a brighter sun.

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hood by members of ethnic groups descended from dairying societies. It is usually absent, however, in adult members of groups that support themselves by hunting and gathering. One exception to the rule has attracted attention: among the San-speaking foragers (sometimes called Bushmen) in Africa's Kalahari Desert, about 10 percent of the adults digest lactose. "Fresh milk–drinking San can never have been genuine hunter-gatherers," concluded Michael J. Casimir of the University of Cologne in a 1990 article for *Current Anthropology*.

Instead, Casimir suggests, the foragers split off from neighboring Hottentots, renouncing the pastoral way of life the Hottentots follow to this day. But G. Eichinger Ferro-Luzzi of Rome objects to Casimir's argument, pointing out that "it is most unlikely that the Danes, for instance, with one of the lowest percentages of lactose malabsorption in the world, could ever have been under such dietary stress that drinking or not drinking large quantities of fresh milk made a difference to their survival."

Milk, of course, is the beverage of babies, and just when human infants were weaned might have astonishing implications. Mothers in modern foraging cultures typically breast-feed for years, during which lactation suppresses their fertility. But Jane E. Buikstra of the University of Chicago has suggested that early farmers might have sped

A Messenger from the Stone Age

When the police on both sides of the border between Austria and Italy first heard that a body had been discovered on an Alpine glacier, they reacted with a certain indifference. After all, glaciers periodically yield up their dead; in 1991 alone, the unusually warm weather had thawed about a dozen corpses. Meanwhile the weather had turned nasty, and the weekend was nigh. Why rush the rescue of a dead man?

But then a pair of topflight climbers, intrigued by the initial report, made their own investigation and brought back startling news: the body, now half awash in a newly formed pool, had four parallel blue-black lines on its back. Beside the body lay strange implements, including a shoe and an unstrung bow. Now a little rushing was in order. Rainer Henn of the Institute of Forensic Medicine in Innsbruck scrambled to the scene, immediately recognized the body for the mummy that it was and packed it in ice for a helicopter trip to his laboratory.

Score one for Austria: although Austria and Italy would later spend months haggling over jurisdictional rights to the Iceman, both with each other and with their own Tyrolean provinces, possession is nine tenths of the law. Austrians now head the two international teams that have parceled out the study of the Iceman and his effects. Werner Platzer, an anatomist at Innsbruck University, heads the team that analyzes the body itself. Konrad Spindler, an archaeologist at Innsbruck, heads the team that studies the body's markings and accoutrements.

The Iceman was preserved still wearing a necklace bearing a white marble pendant. "This little stone piece doesn't have any function, and so it must have a meaning outside of function," Spindler observes. "I think it was an amulet." The markings on the skin, which he says have been proved to be tattoos colored with charcoal, "are the oldest tattoos we know. The next oldest are only about 2,000 years old." They can signify almost anything, Spindler notes: membership in a particular family, tribe, village or social class.

On the last point, at least, there are clues that the Iceman may have been fairly well off. He wore well-tailored leather clothes, lined with straw against the chill mountain air. He had a metal ax, also an expensive item. Experts at first thought the ax was bronze and that the Iceman therefore dated to about 4,000 years ago. Analysis then showed it to be copper, a softer metal characteristic of the late Neolithic.

This chronological hint found confirmation in radiocarbon dating of the clothing, which pushed the Iceman's date to about 5,000 years ago. Finally, in February, dating of the skin

AFLOAT IN AN ICY SEPULCHER, the Iceman appears as he did days after tourists first sighted his head and shoulders protruding from a glacier. Biologists checked the body for fungus (*left, top*), then stored it under conditions resembling those that had preserved it for more than five millennia. The wear patterns on the teeth

things along by supplementing breast milk with grain mash. The primeval pabulum would have let mothers cease lactating and begin making babies sooner, enabling farmers to outbreed foragers living about them.

In the space of a few millennia, then, the agricultural cultures would have swamped the foragers by force of numbers, putting their hunting grounds under the plow, replacing their languages with their own rapidly differentiating dialects. They would thus have seeded vast swaths of territory with the germs of the Indo-European, Sino-Tibetan, Austronesian and Afro-Asiatic families of languages. That theory is championed by Colin Renfrew of the University of Cambridge (Indo-European) and Peter Bellwood of the Australian National University (Austronesian).

Why explain the spread of farmers in this way? Because other arguments no longer seem sound. Many workers agree with the view of Jared Diamond, a physiologist at the University of California at Los Angeles, who suggests agriculture may have been "the worst mistake in the history of the human race." These workers see agriculture as a second-best expedient, adopted to supplement the heartier fare hunting could no longer provide, perhaps because of the depletion of herds in the prairies. Rather than spreading, the people became tied to the land. Diamond cites mounting evi-

and bone fixed the Iceman's age at a few centuries earlier still.

There is little experience in studying the DNA of freeze-dried humans, but workers expect it should survive at least as well as that in Egyptian mummies and in the brains from the Florida bogs. Moreover, the Iceman may also preserve parasitic organisms whose DNA can still be sequenced. Some researchers even hope to find dormant spores that they may then bring to life.

The first results from the Iceman should have come by April, although the search for possible genealogical links with modern populations will surely take much longer. For now, Spindler says, they know only that the Iceman, like nine tenths of the world, had dark eyes and hair. (The hair, which fell out after death, measured about 3.5 inches, or nine centimeters long, enough for it to have gotten in the man's eyes.)

The researchers are making informed speculations about some of the conundrums posed by the Iceman:

▪ **What was he doing in the mountains?** He might have been hunting with his bow and quiver, which contained a few arrows ready to shoot. He might have been prospecting for copper. Perhaps he was herding sheep and goats down from their summer grazing grounds in Alpine meadows. "We know he died in late summer," Spindler says, "because he had with him a small type of plum that ripens in September."

▪ **How did he die?** He had no bruises or cuts, and CT scans show no abnormality in the bones or organs. His teeth are worn, but this reflects the diet of the day: bread laced with abrasive grit from the crude millstones then in use. He is now believed to have been between 20 and 30 years old.

Finally, the Iceman left behind a good store of food, including some meat. He did not starve, so he must have died of exposure. "I think he died from the cold, at night," Spindler asserts. "It is very dangerous in these mountains at this altitude. If you are tired and you lie down to sleep, it takes only a few hours to die—every year we have some accidents."

▪ **How did his body survive?** A sudden squall might have forced him to take shelter in the small rocky depression where he was found. The cold killed him and then preserved his flesh while the sun and wind dried it out. Next a propitious snowfall might have obscured the body from scavenging birds, who got in only a few pecks. Finally, the snow and ice piled up scores of meters high, but not high enough to crush the hardened body. It stayed where it was because the rocky depression shielded it and the surrounding snow from the glacier that ground slowly overhead.

Archaeologists will excavate the area when winter snows stop flying, but no one actually expects to find any companions in death, if indeed the Iceman had any. He might say, in the words of Job's servant, "And I only am escaped alone to tell thee."

(*left, bottom*) reflect a gritty diet, probably based on grain ground in stone mills. The blue tattoos on the back (*right, top*) as yet defy interpretation. Because the body's raiment and tools (*right, bottom*) come down to us unfiltered by funerary rites, they provide an unparalleled view of workaday life in the Stone Age.

dence that the monoculture diets of early farmers, as well as their crowded living patterns, left their bodies scrawnier, their teeth more cavity ridden and their lives shorter than those of contemporary foragers roaming ranges nearby.

In his recent book, *The Third Chimpanzee,* Diamond writes that when agriculture came into what is now Greece and Turkey some 6,000 years ago, men dropped seven inches in stature, to an average of five feet three inches, and women dropped five inches, to five feet one inch. "By classical times," he adds, "heights were very slowly on the rise again, but modern Greeks and Turks have still not regained the heights of their healthy hunter-gatherer ancestors."

Weaning patterns might therefore be a way to document the shift from foraging to agriculture. The challenge is to find chemical markers that distinguish nursing infants from those that have been weaned. Tuross and Marilyn L. Fogel of the Carnegie Institution of Washington have devised a technique that tests not the mineral matrix of bone but rather the fibers of collagen that run through it, toughening it as straw toughens adobe. Collagen, like all proteins made in the bodies of animals, concentrates ^{15}N, the heavier isotope of nitrogen. Those animals that eat animals concentrate the isotope still further. "The nursing infant is a carnivore—it's eating Mom," Tuross ex-

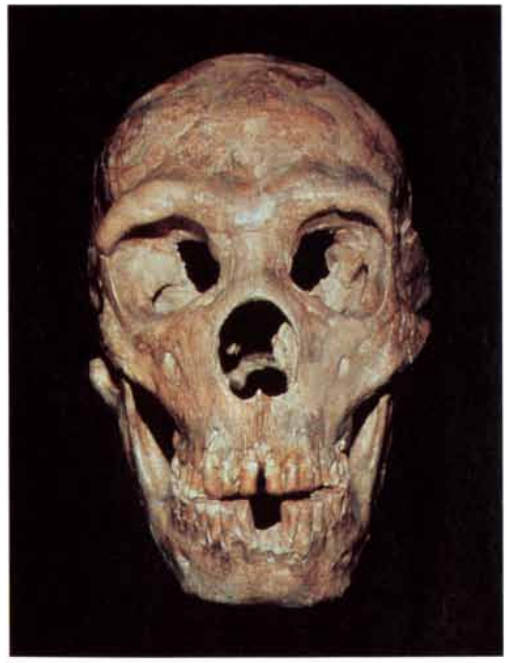
Will Neanderthal Genes Be the Test of Eve?

In the nine years since biochemists began to amplify vanishingly small traces of DNA into quantities that geneticists can study, the horizon of molecular archaeology has pushed ever deeper into the past. Many projects now under way seek to study materials from recent prehistory; other, quieter efforts seem within months of attaining their first successes in unraveling the genomes of archaic hominids. The availability of ancient DNA, possibly even from Neanderthals, will allow anthropologists to test a number of theories of human origins more directly than had once been deemed possible.

Perhaps the most prominent such theory uses genealogy to determine where and when modern-looking humans emerged. A family tree, proposed in 1987 by a group led by the late Allan C. Wilson of the University of California at Berkeley, traces mitochondrial DNA along its maternal line of descent to the unique common ancestor of all living people.

Because the tree's deepest branches divided Africans from non-Africans and because genetic diversity was greatest in Africa, the Wilson group traced Eve, as she is called, to Africa. Then, using a human-chimpanzee comparison as a chronological index, the workers dated Eve to between 150,000 and 200,000 years ago, long after archaic hominids had settled most of the Old World. The results suggested that early modern humans from Africa had replaced other hominids without breeding with them.

Some paleontologists welcomed the theory; many others opposed it bitterly. But by far the most serious criticism has just been leveled by geneticists. Some of them now say the Wilson group failed to notice that the computer program they employed to build their tree can produce thousands, possibly millions, of equally plausible trees, many of which are rooted in Asia. "It is likely that the Eve hypothesis would never even have been proposed if a proper phylogenetic analysis had been performed on the original data set," declares Alan R. Templeton of Washington University.



NEANDERTHAL from Shanidar, Iraq, dates to about 50,000 years ago. A bit of bone from a nearby skeleton has been given to biochemists, who are now trying to recover DNA from it.

Mark Stoneking, a member of the Wilson group who now teaches at Pennsylvania State University, says the greater genetic diversity of Africans continues to support the Eve hypothesis. But he concedes that the new statistical arguments remove the main leg of the original argument. "We need to get away from tree analysis," he says. One alternative, he adds, would be to comb the data for traces of a sudden demographic increase, such as would have followed a great expansion out of Africa.

"You can also find the genes that control for morphological variation," Stoneking adds, such as the physical traits that differentiate modern human subpopulations, or races. "You can then compare such genes in ancient DNA with those in modern DNA." If such genes are found—and if they show that the archaic hominids of Europe, Asia and Africa do not resemble the modern inhabitants of those respective regions—the theory of recent African origins would be supported.

The humblest success in recovering genes from Neanderthals and other archaic hominids would certainly feed on itself, by inducing paleontologists to put more of their bones at the biochemists' disposal. The resulting avalanche of paleogenetic data could immediately enable workers to construct far better family trees than can be derived from the DNA of living people.

Moreover, the information would go beyond that provided by even the most perfect genealogy because it would suggest not only what happened, but why. Workers armed with ancient molecular data could hope to estimate the selective advantages conferred by particular genes or complexes of genes. The role that blind chance has played in the survival or extinction of lineages could also be weighed. Together, the new research will surely give anthropologists their clearest view ever of the evolution of our bodies, our brains and perhaps even our minds.

plains. "So it's isotopically distinct from the mother; when you wean it, it becomes isotopically congruent with her."

The researchers examined two archaeological samples: one from a preagricultural Tennessee site dated between 6,000 and 5,000 years ago, the other from a South Dakotan site where maize was grown from A.D. 1650 to 1733. An anthropologist calculated the age of infant bodies from each site by their dental development. Tuross dissolved the ribs, leaving the collagen behind in a gelatinous sludge.

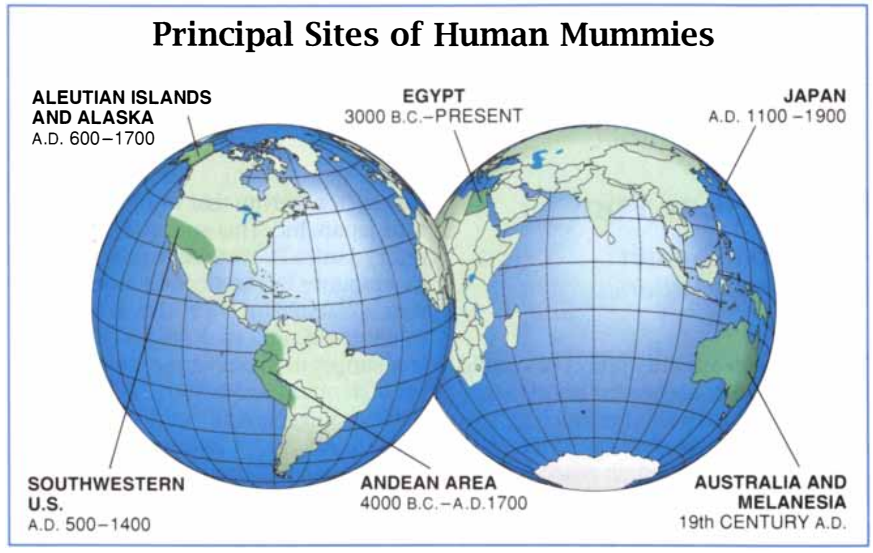
According to this analysis, the introduction of maize farming in the Great Plains did not effect weaning times. Isotopic analysis of the collagen indicated that heavy nitrogen reached peak concentration at the age of 1.1 years in both foragers and farmers, before falling to adult levels during the next two years of life. The next step, Tuross says, is to test specimens from the principal centers of agricultural innovation—South America, the Fertile Crescent, China and New Guinea. Should any of these regions produce evidence that weaning ages declined with the appearance of agriculture, Buikstra's hypothesis will have been confirmed.

Polynesia has also become a focus for the geneticists' efforts, in part because its languages—offshoots of the Austronesian family—appear to reflect prehistoric migrations extraordinarily well. That makes it relatively easy to search for appropriate genetic markers. Moreover, geneticists like the pristine purity of Polynesian genes, especially those encoded on mitochondrial DNA. "Because they're maternally inherited, you don't get the picture complicated by European and Chinese immigrants, who were exclusively men," Sykes says.

"Ancient mitochondrial DNA matches one living lineage out of the two major groups we've found in Polynesia," Cann says. Similar deep lineages have been reported by Sykes among the Cook Islanders and by Stoneking in the highlanders of New Guinea.

The researchers also note that Polynesian genes vary less than those of other Pacific peoples, suggesting that their ancestors went through a recent bottleneck. "It's possibly because a single boatload, or a few, founded the settlement," says Stoneking, who now teaches at Pennsylvania State University. He cites, among other data, the "nine base-pair deletion" in mitochondrial DNA, a mutation that originated in Asia and is seen, to some degree, in most populations that derive from it. The deletion is particularly common in coastal New Guinea and, above all, in Polynesia.

From such evidence the molecular geneticists infer that emigrants from island Southeast Asia exchanged mates in coastal New Guinea and that some of the women then continued on into Polynesia. Cann wants to test the theory directly by sequencing DNA from skeletal remains throughout the region. In Polynesia, at least, such remains were often preserved by the practice of burying the dead in dry sand or in the cool, dry lava tubes of volcanic islands.



Speaking for the Dead

There persists, however, the vexing question of proprietary rights: Do the dead belong to the scientist who finds them or to the living people who descend from them? In parts of Polynesia, materials for the molecular archaeologist abound, Cann notes ruefully, if only scientists can obtain access to them. "Right now we have good data on one skeleton from Hawaii, but we're not allowed to publish," she says, citing native Hawaiians' opposition to such research. "The university has become so sensitized to it that the osteologists who do this kind of work are not even allowed to have such material in the university." Similar difficulties afflict Australian archaeologists, who have just watched the skeletons from Kow Swamp go back into the ground. They were the earliest dated human remains on the continent.

The molecular archaeologists protest that they seek precisely what native-rights activists desire: a picture of early man and his achievements. To that they add the health benefits that will flow from research into the origins of genetic predispositions to disease.

But for many native peoples, the benefits of science tend to pale when set beside the sometimes ghoulish record of colonial "scientists." When the last Tasmanian man died in 1869, rival teams of physicians fought over pieces of his body. One learned doctor made some of the skin into a tobacco pouch. These disgraceful exploits so horrified the last Tasmanian woman that she asked to be buried at sea. Her wish was flouted and her skeleton displayed until 1947. Many years later it was finally cremated, and the ashes were scattered in the ocean.

Perhaps charges of disrespect for the dead themselves will die when workers begin to study their own ancestors or those whom they would gladly claim as such. "Ah, Lincoln—an interesting phenotype," Cann said last year, when asked about a proposal to sequence the Great Emancipator's DNA. Historians want to know whether Lincoln's gaunt face, lanky stature and loose joints marked him for Marfan's syndrome, a disorder of the connective tissue that can cause potentially fatal aneurysms. If blood from Lincoln's deathbed linen proves to harbor the causative gene, then Marfan's patients will walk even taller, and historians will wonder whether Booth murdered a doomed man.

But to honor the dead, we must know who they were and whence they came. These questions, which every child asks and every culture must answer, spurred the development of modern science. Renaissance scholars first applied reason and experiment to restore original texts from their corrupt copies. Later, philologists went further by reconstructing extinct languages from evidence presented by their daughters. These genealogical methods, at once scientific and historical, reached full flower in evolutionary biology, whose youngest child—molecular genetics—now comes to serve the historians.

Electric Car Pool

Automakers consort on advanced batteries

The Bush administration has made a fetish of eschewing policies that tell industry what technologies to pursue. But the government of the state of California has no such reservations. In 1990 it promulgated regulations that require 2 percent of all cars sold in the state to run without any polluting emissions by the year 1998, a figure that is to be increased to 10 percent five years thereafter.

The California rules amount to an unequivocal directive for deployment of electric cars. By inference, they are also an edict to find a battery that can outdo the lackluster power, range and lifetime of the conventional lead-acid battery. (For lack of something better, GM is using an improved lead-acid battery in its new electric vehicle, the Impact.) "We want to get electric vehicles out of the golf-cart stage and into a vehicle that really does something," says Bob Scheffler, an engineer at Southern California Edison, the electric utility.

With the California mandate in hand, the automobile industry managed to prod administration bureaucrats, normally averse to industrial policy, into an unusual orchestration of public- and private-sector activity that would be a credit to Japan, Inc. This spring, Energy Secretary James D. Watkins was scheduled to announce the first contracts in a four-year, $260-million effort that is intended to allow U.S. automakers and a few select suppliers to gain a technical and legal lock on critical battery technology.

The contracts will fund research by the U.S. Advanced Battery Consortium (USABC), a collaboration that marks the first time that Ford, General Motors and Chrysler have together undertaken research with the federal government. The electric power industry is also supplying money and expertise.

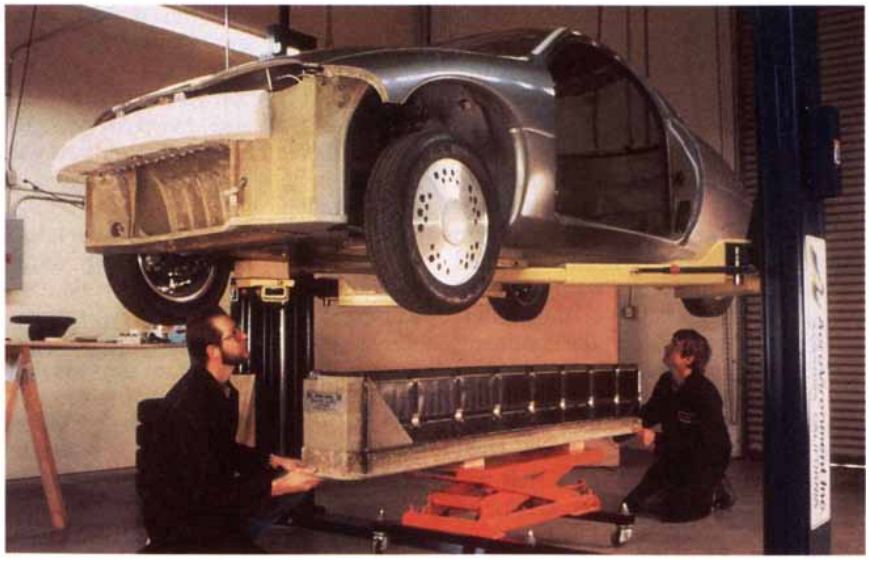
The consortium has succeeded in galvanizing the Department of Energy's battery development program for electric vehicles, which had been apportioning dribs and drabs to some dozen technologies. Funding has about doubled to $27 million from the previous fiscal year, and most of those funds are expected to be applied to the accelerated development of just four battery technologies. "Any research we do is in support of the USABC's overall goals and objectives," says Kenneth F. Barber, director of the DOE's electric and hybrid propulsion division.

Besides giving a bit of a post–cold war mission to the Energy Department's national laboratories, the effort is a plum for the beleaguered automakers, who may end up paying less than a fifth of the development cost. The DOE is picking up half of the expenses, and subcontractors who do the actual work will ante up most of the rest. Whether the automakers chip in for the hundreds of millions of dollars needed to build full-scale production plants for these risky technologies remains to be seen. "This is the best-leveraged job I've ever seen," says an executive with one prospective subcontracting firm.

Automakers see the program as more than just a good deal. GM executive Frank Jamerson, the crusty chairman of the USABC's technical advisory committee, compares the effort to the Apollo program and the Manhattan Project, while invoking the benefits of Japanese-style collaborative management.

The USABC's program specifications called for companies to work together in "integrated teams." But importing real Japanese managers was out of the question. Overtures by both Japanese government and industry to share in the cooperative venture were rejected by the USABC.

As stated, the technical goals for the program are highly ambitious—and given the short deadlines may border on hyperbole. The USABC has established two sets of objectives. By 1994, with enough time to meet the California standards, the consortium wants its subcontractors to set up pilot plants that will demonstrate the feasibility of mak-



IMPACT, GM's new electric car, is powered by a state-of-the-art lead-acid battery, shown below the car at left. But Canada's Hydro-Quebec, teamed with 3M, is vying for a contract from a consortium of automakers to devise lighter, more powerful batteries from lithium and other thin films **(right).** ***Photos: GM and Y. Beaulieu/Publiphoto.***

ing tens of thousands of batteries with roughly double or triple the energy capacity of lead-acid ones. By the turn of the decade it wants the battery that will enable an electric car to accelerate like a roadster, go nearly from Los Angeles to San Francisco without a recharge, and last the lifetime of the vehicle.

That is asking a lot. Even the most advanced batteries under development store less than a fifth of the energy per unit weight of gasoline. "The laws of nature limit the capability well below what you find in gas in terms of energy and power density," says David E. Cole, director of the Office for the Study of Automotive Transportation at the University of Michigan.

Two kinds of advanced batteries are slated to meet the initial goals: nickel metal hydride and sodium sulfur. Nickel metal hydride is a long-lived power source capable of storing large amounts of energy. It also does not have the toxicity of the cadmium found in its heavy-metal cousin, the nickel-cadmium battery. Ovonic Battery Company in Troy, Mich., and SAFT America, the U.S. subsidiary of a French company, may be asked by the USABC to make this battery power something bigger than a portable personal computer.

Sodium sulfur is by far the closest to the commercial marketplace. In the mid-1960s General Electric and Ford pioneered the technology for this high-temperature battery, in which molten sodium and sulfur function as electrodes and the ceramic tube that holds the sodium serves as the electrolyte.

Despite the consortium's patriotic overtones, sodium-sulfur batteries are now solidly a European technology. Britain's Chloride Silent Power (which is likely to get a USABC contract) and Swiss-headquartered Asea Brown Boveri (ABB) have been involved in setting up pilot plants in Europe. The batteries are being tested in BMWs, Volkswagens, Fords and other vehicles.

Even if the target price of $5,000 can be reached, the battery could become an Edsel maker for the Big Three if researchers do not find ways to stop corrosion of the sulfur electrode's casing and the cells' seals, some of the reasons the battery has only a two- to three-year life. Then there are the complex insulating and heating system required for the battery's more than 300-degree-Celsius operating temperature and the safety issues raised by the presence of liquid sodium and sulfur, both reactive chemicals.

Argonne National Laboratory may have a partial solution in the form of a battery with a lithium-aluminum alloy for the negative electrode and iron disulfide at the other pole. It will probably be slated by the USABC for its longer-term objectives. SAFT America was negotiating with the USABC to deliver prototypes of this high-temperature battery, whose solid electrodes are thought to be safer than molten sodium and sulfur. Although it may produce more power than any of the other technologies studied, the battery is still too new to know what its cost and lifetime will be.

Lithium is the material of choice for another USABC battery, one that relies on thin films. In the laboratory the battery's polymer electrolyte looks more like an oversized roll of color film than it does a power source. These batteries are made from paper-thin layers of lithium for the negative electrode, a high-energy density material such as a vanadium oxide for the positive electrode and a polymer electrolyte that is sandwiched in the middle. The films, which may achieve an energy capacity five times that of lead acid, might be rolled up and molded into any nook or cavity an auto designer leaves for them.

A lithium-polymer battery is closer to laboratory workbenches than it is to the recesses of a car chassis. W. R. Grace, 3M and Delco Remy each headed a separate team of companies negotiating for several available contracts. Meeting the deadlines will require a steady chain of technical breakthroughs—an increase in the conductivity of the polymer, for one. "You can't schedule innovation," says Sid Megahed, director of advanced technology for Rayovac, which dropped its negotiations with the USABC, partly because of the accelerated scheduling.

Negotiations for all the USABC contracts have dragged on well beyond the New Year's deadline, at least in part because of wrangling over who owns what. The issue of intellectual property was a sticking point for many of the companies that the USABC invited to submit proposals. Although it still wishes to sell to the U.S., ABB, the sodium-sulfur battery developer, broke off talks this year because it could not agree with the USABC on who would get the patent rights and manufacturing know-how.

Private battery developers and some government researchers are rankled by the USABC's hold on the Energy Department's purse strings. Funding for battery technologies not specifically targeted for the consortium is being cut. One firm, Arias Research Associates in Whittier, Calif., has wanted to continue to explore an advanced lead-acid battery design that might give an electric vehicle substantially better acceleration and lower costs than a sodium-sulfur battery. The money is not there. "The USABC acts like a sponge soaking up all the R&D dollars," says Jeff Arias, the company's president.

Echoing the views of some other researchers, Arias wonders whether the USABC may have set unreachable goals that will have the effect of undermining the California law altogether. But setting ambitious targets was part of the consortium's original strategy. Jamerson says stirring things up was the only way to commercialize technology that has been under the DOE's tutelage since the department was founded in the 1970s. "None of these batteries have ever gone into production—that's a perfect record," Jamerson storms.

Nor is the auto industry stopping at batteries. It has launched other consortia, such as one for developing lightweight structural materials. Meanwhile Japan, possibly in response to the USABC's rebuff, has set up its own battery collaboration. Let the best integrated team win. —*Gary Stix*

Goals for Advanced Batteries

	TODAY	1994	2000
	LEAD ACID	SODIUM SULFUR, NICKEL METAL HYDRIDE	LITHIUM POLYMER, LITHIUM ALUMINUM/ IRON DISULFIDE
ENERGY CAPACITY (WATT-HOURS PER KILOGRAM)	25–40	80–100	200
RANGE (MILES)	40–100	150–200	300
PEAK POWER (WATTS PER KILOGRAM)	110–150	150–200	400
RECHARGE TIME (HOURS)	6–8	<6	3–6
LIFE (YEARS)	3–5	5	10
COST (40-KILOWATT-HOUR BATTERY)	$3,000–$5,000	<$6,000	<$4,000

SOURCES: U.S. Advanced Battery Consortium, Idaho National Engineering Laboratory and the Electric Power Research Institute

Relative Lightweights

Plastics replace silica to make lower-cost aerogels

A few years ago proud researchers at Lawrence Livermore National Laboratory delighted in showing off the gossamer incarnations of silica known as aerogels. Likened to frozen fog, aerogels weigh some four times as much as air and are nearly transparent. Because of all the air captured in their lacy microstructure, aerogels have superior insulating properties. A slice half an inch thick will shield a hand from the flame of a blowtorch.

Although the developers could reel off a string of potential applications, from refrigerator insulation to energy-saving windows, aerogels have had difficulty finding their way into down-to-earth applications. Their only use so far is as particle detectors in physics research. As for many high-performance materials, the problem is cost. Now a Livermore investigator has come up with a lower-cost alternative: organic aerogels based on the monomers generally used to make plastics.

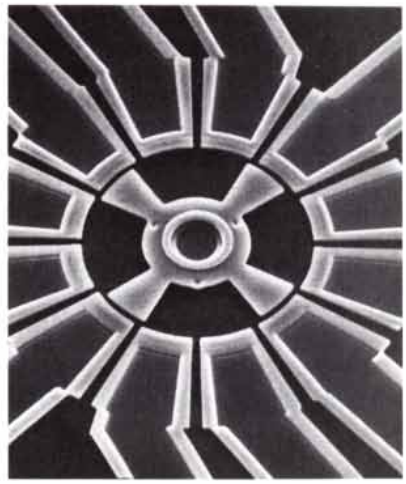
Organic aerogels have the same ability to insulate against heat as their relatives do—as well as some enticing traits all their own, says Richard W. Pekala, leader of Livermore's polymeric materials section and creator of the compounds. "The deep red one is the best thermal insulator in the world," Pekala declares, citing a report he and his colleagues recently published in *Science*. He also proffers varieties that are black and transparent. The clear form suitable for windows appears to be just as good an insulator as the red he says, although it is still being tested. Colored insulation would be no hindrance inside a refrigerator or stove.

The black aerogel is made by firing the red so that only pure carbon remains. Because this material conducts electricity most efficiently, Livermore researchers are testing it in capacitors to store electrical energy. The novel material's porous structure enables it to hold far more charge than solid carbon films used in conventional capacitors.

Frothing a Raindrop

What can anyone do with a working motor whose moving parts are no wider than the thickness of this page? Conjecture so far has focused on the human body. A 100-micron motor might mix, in situ, minute quantities of drugs that have very short lifetimes or, more optimistically, chip away at plaque in arteries. "These are the original micro Roto Rooters," says Mehran Mehregany of Case Western Reserve University.

Early this year Mehregany took his spinning motes a tiny step closer to confronting the fierce fluid flows of the body. For the first time, he and his Case Western colleagues proved that micromotors could overcome the heavy viscous drag of a liquid and continue to spin for several hours. The researchers proved an electric field could produce enough torque through two microns of insulating silicone oil or deionized water to turn a rotor whose diameter spans a hair's breadth. Their findings are scheduled to be presented at the Institute of Electrical and Electronics Engineer's Solid-State Sensor & Actuator Workshop in late June.



The Case Western team's success was by no means a certainty. When Mehregany's graduate student Vijay Dhuler first plunged a micromotor into water and applied a voltage to it last year, it refused to budge. Mehregany hypothesized that the liquid surrounding the motor had failed to penetrate the 1.5-micron gap between the rotor and the silicon substrate to which it is connected by a bearing. Surface tension between the liquid and the minuscule air pocket was enough to keep the water out and the rotor locked in place.

To get the liquid to diffuse into the gap, Dhuler sucked silicone oil into a micropipette. While watching through an optical microscope, he slowly let the liquid flow from one side of the rotor to the other. The rotor has subsequently worked for up to four hours in oil while turning at a lazy 15 revolutions per minute. Case Western investigators judge this achievement against the early micromechanical prototypes, which were so easily overcome by friction that they ground to a halt in less than a minute.

A micrograph of Mehregany's motor (*photograph*) looks like a machine from the early years of the industrial revolution. The motor begins to rotate when a voltage is applied to one or more of the 12 to 20 stator elements, or poles, that encircle the four-bladed rotor. These structures, only two microns thick, operate like a conventional electric motor except that they use static electricity, not magnetic forces. The field generated across the gap makes each of the rotor blades align with four of the stator poles. The process repeats itself as the voltage is switched to other poles, causing the rotor to spin.

By narrowing the part of the bearing that supports the rotor, Mehregany was able to reduce by a factor of three the amount of friction measured as a percentage of the motor's torque. Now machines that operate in air can spin for days at a time up to a more than respectable 15,000 revolutions per minute.

Similar gains in performance are anticipated for submersible micromachines. Liquids offer an advantage over air because their dielectric properties increase the energy in the electric field and hence the amount of torque. Unfortunately, this benefit is more than offset by the resistance from the viscous medium.

Real work from these machines is years away. Making motors turn in blood, whose high conductivity saps field strength, is still a dream. In air the maximum torque produced by Mehregany's micromachines is about 50 piconewton-meters. By comparison, an ant walking up a bare arm would feel like the footfalls of a *Tyrannosaurus rex*.

But the idea behind micromachines is not to compete with the V-8 engine. "If you consider things on the scale of the silicon wafer, micromotors produce plenty of torque," Mehregany says. Tinkerings by Mehregany and others may succeed in making micromotors into something more than a Jacuzzi for a paramecium.

—Gary Stix

"We're thinking these capacitors might work in electric vehicles," Pekala says.

Pekala makes organic aerogels by polymerizing monomers with formaldehyde mixed in water. Melamine produces a clear gel; resourcinol, red. The compounds condense from the solution into clusters that organize themselves into a stable latticework. "Think of pearl necklaces all sticking together," Pekala advises. But these pearls of cross-linked polymer are about one tenthousandth the width of a human hair. "There could be a basketball court's worth of space in a piece of aerogel the size of a sugar cube—there could be five courts' worth," he marvels.

The trick to making both organic and silica aerogels is getting the liquid out of the gel without collapsing its structure. Air drying is not possible, because the gel would shrink like Jell-O left out on the counter for a few days. The surface tension of the water being drawn away would crush the structure. Freeze drying is also out of the question, because the expansion caused by freezing would destroy the delicate framework.

The solution is the chemical equivalent of pulling a tablecloth out from under crystal and china. First the water is replaced by diffusion with an organic solvent such as acetone, which in turn is replaced by liquid carbon dioxide. Next the gel is placed in a vessel where high pressure transforms the carbon dioxide into a supercritical fluid that lacks surface tension because it is neither gas nor liquid. When the pressure is slowly released, the carbon dioxide gasifies harmlessly, leaving an unscathed aerogel.

"It's only been within the past six months that we've perfected and scaled up the process of drying," says Edwin L. Berkowitz, president of Thermalux L.P., a Richmond, Calif., company devoted to commercializing aerogels. The firm is drying Pekala's gels with technology developed by Arlon J. Hunt at Lawrence Berkeley Laboratory. It is also routinely producing slabs of silica aerogels 10 inches square and half an inch thick at a pilot manufacturing plant finished just a year ago. "Silica has gotten us only so far in the market," Berkowitz adds. "These organics are looking very, very interesting."

For his part, Pekala is still primarily interested in the science behind organic aerogels. "We think we've opened the door just part way. There are some rules that seem to apply to these gels that we think we can apply to other chemical starting materials people are more familiar with. Someday we'll see a polystyrene aerogel," he predicts. For aerogels, it seems the future may well be plastics. —*Deborah Erickson*

Demonic Toxin

A new shellfish toxin threatens fisheries

Now appearing in the Pacific Northwest and California: Horror from the Deep. Unfortunately, this is not a grade B movie. A mysterious toxin that kills nerve cells—particularly those in the brain—is showing up in mussels, clams, Dungeness crabs and other species. There is no known antidote for the potentially fatal poison. Nor are scientists certain where the toxin originally came from or how long it has been in the waters. The prime suspect is a type of microscopic marine diatom called *Nitzschia pungens.* Pray that it does not come to a shellfish bed near you.

The neurotoxin identified as domoic acid does not appear to harm the shellfish that filter it from the water, but humans can contract "amnesic shellfish poisoning." Symptoms such as vomiting, nausea, diarrhea and abdominal cramps may appear within 24 hours of ingestion. Neurological symptoms can crop up over 48 hours. They include headache, dizziness, confusion, difficulty breathing, loss of short-term memory and seizures. Some victims have died. Unlike illnesses caused by other algal toxins that shellfish inspectors routinely monitor, such as the paralytic shellfish poisoning (PSP) that accompanies "red tide" blooms, the effects of domoic acid can be permanently disabling.

"You bet all the Western states are now testing for domoic acid in a number of species," says Thomas J. Billy, director of the Food and Drug Administration's Office of Seafood. Public health is the primary concern, of course, but there is also business to consider. The Dungeness crab fishermen in Oregon, for instance, are still hurting from harvest interruptions. The 1991 take of some 4.9 million pounds brought in slightly less than $7.5 million, compared with the previous year's haul of $14 million for some 9.5 million pounds.

"Domoic acid means business," says Ann Drum, a technical specialist at the Battelle Marine Sciences Laboratory in Sequim, Wash. "That's why it's being taken seriously." Drum is the chair of a newly formed multiagency research committee charged with studying the toxin. "We don't know whether the toxin has been around a while and we're only now recognizing it, or whether this is brand-new. There are good arguments for both cases," Drum observes.

The first reported outbreak of domoic acid poisoning occurred in 1987 off

Prince Edward Island in eastern Canada. Physicians traced the toxin to locally cultured blue mussels. Ultimately, three people died of the toxin, and 107 other mussel-eaters reported symptoms. Drum tells of one physics professor who can no longer transfer a short-term memory such as where he parked the car to the long-term memory needed to find it at the end of the day.

In November 1991 the toxin made its first appearance in the Pacific Northwest during an annual razor clam harvest. "We were in the middle of the sport razor clam season when a sample being tested for paralytic shellfish poisoning came up with domoic," recalls Dan L. Ayres, a biologist for the Washington State Department of Fisheries.

The standard test for PSP, explains Mary C. McCallum, public health adviser to the Washington State Department of Health, involves injecting a mouse with ground-up shellfish. If it dies within 15 minutes, there is enough toxin present to hurt humans, and the beds are shut down. The person doing the test on the razor clams had just been to a conference on domoic acid, where he learned of a curious effect of the toxin on test subjects: the mouse takes longer to die, and before it does, it scratches behind the ear with its hind feet. The technician stepped away, and sure enough, when he came back the mouse was scratching.

After some more high-technology confirmation, the razor clam season was closed. Again this spring of 1992, the toxin has spoiled a beloved family tradition. All species in which domoic acid has been found will require monitoring for the foreseeable future, Billy adds. The FDA is considering an offshore phytoplankton monitoring system to give early warning not only of domoic acid but of all biotoxins of concern.

In the meantime, fisheries biologists will try to find answers to some of the questions posed by the mysterious toxin. Mussels are the only species contaminated in Canada, but they are not tainted in other regions where different species are carrying the toxin. Also, thousands of people in Canada and the U.S. ate the same mollusks as did the Prince Edward victims with no ill effects.

Some researchers speculate that there is a correlation between the algae's production of toxin and El Niño, the equally puzzling Pacific Ocean current. The shift in winds, currents and changing water temperatures may somehow have influenced the toxic bloom. Others blame fertilizer runoff from farmlands. Ayres says just one thing is sure at the monitoring stations where samples have come up positive: no one is sneaking bites. —*Deborah Erickson*

Business at Rio

An industrial agenda for the environmental convocation

If small is beautiful, the "earth summit" to be held in Rio de Janeiro this June will not win any prizes. The meeting, known formally as the United Nations Conference on Environment and Development (UNCED), could draw more than 7,000 delegates and 80 heads of state, which would make it the largest summit meeting ever. Landmark international conventions on protecting the environment will be signed, and delegates are expected to approve an "Earth Charter" as well as an ambitious plan for development called Agenda 21.

Environmental organizations have been lobbying to get strong commitments to conservation on the agenda for UNCED, which was inspired largely by the 1987 report of the Brundtland Commission that made "sustainable development" an essential term in the planning lexicon. But the business community has also had Rio on its radar screens. Scores of corporate executives will be on the jets that ferry UNCED participants into Brazil's second largest city in late May.

The mobilization is aimed at per-

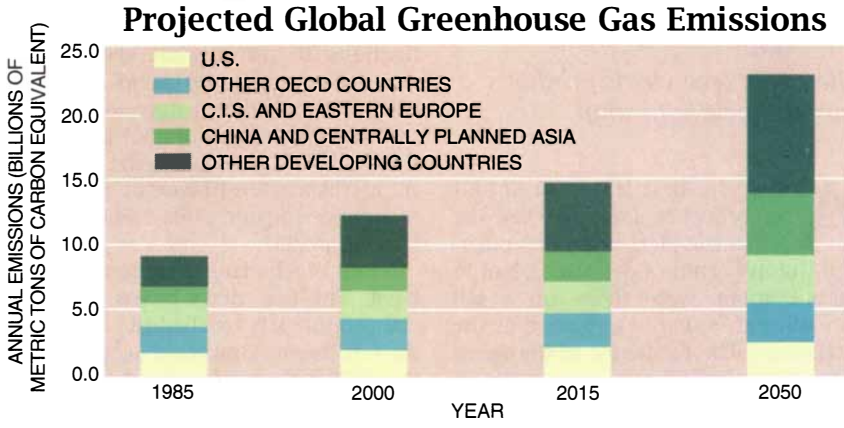
suading governments that business is willing to move toward sustainable development, but on its own terms and in its own time. A Shell International management brief neatly encapsulates the anxieties of many industrialists: "Environmentalists are likely to find a sympathetic audience at UNCED, while governments may be seeking ways to divert some of the resource demands away from themselves and toward the 'deep pockets' of business."

For the business world, one item looms especially large: the convention on climate change. Concerns about global warming have prompted the industrialized countries that constitute the Organization for Economic Cooperation and Development—with the exception of the U.S.—to commit themselves to curbing emissions of carbon dioxide. Business lobbyists have been working hard to persuade governments that inflexible commitments, which might require limits on new power plants or perhaps taxes on carbon emissions, will come at a high cost and bring no significant benefits.

Several corporate coalitions, both national and international, are active. The Business Council for Sustainable Development, established by the Swiss industrialist Stephan Schmidheiny at the request of Maurice Strong, the secretary general of UNCED, is one of those most willing to countenance change. The council, which is made up of 48 business leaders from around the world, supports a reform in energy-pricing policies, acknowledging that present patterns of energy use are "clearly unsustainable." But fearing "command and control" regulations, it argues for self-regulation of industry to ensure responsible corporate behavior.

Another of business's fears is that Rio may create pressure for a wholesale giveaway of environmentally friendly technology. In return for accepting environmental taxes—whose revenues would be recycled to increase business investment—Schmidheiny's council wants open markets and clearly defined property rights. The International Chamber of Commerce (ICC), the "world business organization," echoes the call, saying that "protection of patents and property rights of the developer" is an essential requirement for sustained technological cooperation.

The ICC has also issued a Business Charter for Sustainable Development, endorsed by more than 700 companies, that places environmental management "among the highest corporate priorities." Ross Stevens III of Du Pont, who is vice chairman of the working group that drafted the charter, says the first thing to emerge at Rio should be a "sound structure for future agreements, one that includes provision for flexibility and review" as well as commitments. But the ICC nonetheless opposes UNCED proposals for "internalizing" environmental costs, saying they "have theoretical relevance but may be ineffective and trade-distorting."



SOURCES: National Academy of Sciences, 1991, and U.S. Department of Energy, 1990

Many U.S. corporations have been working hard to ensure that the U.S. does not waver in its opposition to targets and timetables for reducing carbon dioxide emissions. Michael E. Baroody, chairman of the Global Climate Coalition, a broad-based industry organization, told the congressional Energy and Power Subcommittee in March that measures such as carbon taxes intended to reduce greenhouse gas emissions sharply "would impose massive costs on the U.S. economy."

Baroody also played the China card. He argued that although developed countries are now the largest source of carbon dioxide—roughly equivalent to the centrally planned economies and the developing countries combined—they are likely to contribute only a small fraction of the total by the year 2020. Baroody told Congressman Philip R. Sharp of Indiana, who chaired a hearing on climate change policy, that China plans to double its electricity generation in the next 10 years; 75 percent of the new capacity is to be coal-fired. Nothing the U.S. could do to reduce its emissions would offset such increases, Baroody noted.

Donald H. Pearlman, who lobbies for the Climate Council, a consortium of unnamed U.S. electricity, coal and railroad companies, says the companies he represents are "unalterably opposed to targets and timetables." He maintains that energy consumption per capita is higher in the U.S. than in Europe in part because Americans have greater distances to travel and larger homes. "It is not at all clear the U.S. is prepared to reduce its standard of living by downsizing its homes," Pearlman asserts.

Among economists the costs of measures to reduce carbon dioxide emissions are disputed: conclusions depend heavily on assumptions about growth and other factors. And even the two key government agencies in the issue, the Environmental Protection Agency and the Department of Energy, are at loggerheads on the question. The EPA believes it would be rather easier to reduce emissions than does the Energy Department. Meanwhile the Union of Concerned Scientists and some environmental groups have concluded that reductions in emissions could be achieved in a way that leads to savings of hundreds of billions of dollars over a time scale of decades.

Indeed, many manufacturing companies are finding it makes economic sense to reduce their emissions anyway. One example is 3M in St. Paul, Minn., a member of the Business Council for Sustainable Development. The company says it has reduced its energy use by 50 percent since 1973 by improving efficiency, and it plans a further cut of 20 percent by 1995. Others have similar records. Some utilities, including Pacific Gas and Electric and Southern California Edison, are moving in the same direction. Regulatory decisions have encouraged them to increase consumer energy efficiency and develop renewable energy sources. And the New England Electric System (NEES) broke ranks with many in the industry in March when its president, John W. Rowe, told Sharp's hearing that NEES had no objection in principle to carbon taxes.

The millennial flavor of the advance hoopla for Rio probably guarantees the event will disappoint the expectations of its cheerleaders. But the voluntary industry efforts might show the way to future agreements. By itself the Rio meeting will not save the planet, but it could mark the start of a move in the right direction. —*Tim Beardsley*

Village Pharmacy

The neem tree yields products from pesticides to soap

Among the first leaves to sprout on branches laid bare by the lethal chemical cloud that encircled Union Carbide's pesticide plant in Bhopal, India, were those on a tall spreading tree that is a relative of the mahogany. The resilience of the neem tree, as it is called, may have come as no surprise to Indian farmers, homemakers and folk healers, who have known of its remarkable properties for centuries. Its leaves are placed in books, beds or grain bins to discourage insects. They are used in a tea as an antimalarial agent. The tree is also ideal for use as firewood and for making soap, oils for lamps or lubricants to grease cart wheels. Documentation of the diverse attributes of what one monograph labeled "the cornucopia tree" has begun to pile up.

The earliest scientific reports, appearing in the 1920s, were published outside the normal purview of Western researchers. But interest began to build in 1959, when a German entomologist, Heinrich Schmutterer, noticed that neem trees remained unconsumed by a locust plague in the Sudan. Since then, hundreds of researchers from all over the world have launched studies on the neem and have occasionally even met at international conferences whose topic is dedicated to this versatile tree.

Helping to move the tree beyond folk nostrum status is a recent report from the National Research Council (NRC) entitled "Neem: A Tree for Solving Global Problems." This overview of existing research calls for more controlled investigations to prove what are still, in many cases, anecdotal claims about the tree. "We're saying it may solve these problems but not until a lot of science is carried out," asserts Eugene B. Shultz, Jr., a Washington University professor of engineering and policy, who chaired the NRC panel.

Neem is achieving acceptance by the West. The first neem-based commercial product has reached the market in the U.S. Neem extracts act against more than 200 arthropod marauders, including Mediterranean fruit flies, houseflies, fleas, head lice, Gypsy moths, the Colorado potato beetle, boll weevils and cockroaches. The U.S. Department of Agriculture has studied the tree since the early 1970s, and W. R. Grace & Company bought the rights to market a neem pesticide.

Grace has Environmental Protection Agency approval to market neem extract, which it sells as a pesticide to home gardeners as Bioneem and to greenhouses as Margosan-O. Grace is also seeking agency approval for use of the pesticide on food crops. One likely target would be the sweet-potato whitefly that has been decimating food crops in California.

Azadirachtin, neem's most active compound, bears a distant chemical resemblance to steroids and either repels pests or prevents their larvae from molting into pupae. Although it may take weeks to kill the pests, the substance does not commit "ecocide" in the process. Birds and bats eat neem fruits routinely, and neem leaves have been added to grain stores in India to keep weevils out. According to various research reports compiled by the NRC, neem's complex chemical makeup, consisting of more than 20 compounds, reduces the likelihood that insects will develop resistance.

NEEM TREES help with reforestation in Thailand. The tree bears flowers with a honey scent and fruits that resemble olives **(above).** ***Photos: W. R. Grace.***

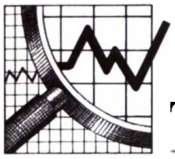
For now, W. R. Grace depends on a far-flung network, which sometimes begins with poor villagers in India who gather neem fruits that have fallen from trees lining the roadside to provide shade from the harsh sun. Because the trees take several years to mature and the tropics are a long way from the chemical maker's pilot plant in Maryland, neem extract will remain more costly than synthetic pesticides. With "green" products all the rage, though, Grace has had no trouble marketing its product. "If I had a little more, I could sell more," says F. Peter Boer, Grace's chief technical officer.

Less certain are neem's medicinal benefits. Thousand-year-old Sanskrit medical literature praises the tree called the *arishtha,* the Sanskrit word for reliever of sickness. Scientific evidence is more sketchy. Neem oil is reported to combat salmonella and staphylococci, and pastes are applied to the skin of victims of chicken pox and warts. Africans and south Asians scrub teeth and gums with neem sticks, which have been found to kill oral bacteria.

For centuries, neem leaf extracts have been ingested as an antidote for malaria. The most provocative claim, because it could presage a potentially affordable means of population control, is for neem oil's contraceptive properties. The oil has shown some promise as a spermicide and as a temporary means of blocking fertility in both men and women. The NRC concludes that controlled research is needed in every one of these areas before the neem can live up to its moniker: "the village pharmacy."

The most enthusiastic advocate of the neem at the NRC is Noel D. Vietmeyer, a program officer, who is described by one agency official as the "obscure plants and animals guru." During his 20-year tenure working for NRC's Board of Science and Technology for International Development, which tries to identify underexploited plants and animals, Vietmeyer has shepherded reviews of the jojoba, the amaranth and other supposed miracle plants. He even flirts with the expression "wonder plant" in the foreword to the neem report. But, he insists: "I've never come across a plant with the breadth of potential the neem has."

Even if pesticides from the neem do not prove a match for the other staples of agribusiness, spreading the word about the tree may help small farmers in tropical countries. "The neem tree brings pesticides within the reach of even the poorest people," Vietmeyer says. "People who couldn't conceive of purchasing pesticides can have a neem tree in their backyard." —*Gary Stix*



Overcoming the Short-Term Syndrome

During the past decade, the number of reports bemoaning corporate America's "lack of competitiveness" seems to have been exceeded only by accounts of congressional mismanagement. Among the reasons most often cited for the weakened grasp of U.S. enterprise on markets has been a myopic focus on short-term financial gain at the expense of long-term industrial success.

Pundits assert that managers have little choice. Corporate actions, they say, are dictated by the crushing cost of capital for future investments. Proposed remedies have consequently included lavish government-administered therapies aimed at lowering that cost through investment tax credits, lower capital gains taxes and so on.

Yet times and market conditions have changed. If investment decisions turn on the cost of capital, U.S. managers should now be pumping money into research and long-term capital projects, exploiting the downward slide in interest rates and the upward spurt in stock values. By and large, they are not.

Why the foot-dragging? A report issued by the National Academy of Engineering (NAE) this March offers a provocative explanation for the endemic corporate aversion to the long-term commitment: many managers have lost the expertise needed to assess the role emerging technologies can have in their businesses and so judge such projects to be enormously risky.

If a company stumbles in the marketplace because its investment horizon is barely a quarter or two away, the board of directors and the corporate managers—not just Wall Street financiers—are to blame, says Donald N. Frey, a professor at Northwestern University and former chairman of Bell & Howell, who chaired the NAE committee. (The other nine committee members included several board directors, company chairmen, a noted venture capitalist and a business school professor.)

Frey's group based its conclusions on the experiences of the committee members, as well as on interviews with the leaders of a diverse collection of small and large companies in competitive, capital-intensive industries. They found, for instance, that only five of 15 executives surveyed believe the cost of capital hinders their companies' performances. Tellingly, the profits of those five firms lagged behind the average profits of the other 10 companies surveyed.

Although the cost of capital is clearly important when evaluating projects, equally significant is management's assessment of riskiness, or "risk premium." Companies having a wealth of experience in a specific technology see less risk in new endeavors than do those lacking solid track records. Because veterans in these firms are more comfortable working with the technology, they have more confidence in their ability to see projects through.

Experience and success, in other words, help to pave the way to future successes. Consider, for instance, semiconductor companies that dropped out of the memory chip business a few years ago but are now entertaining proposals to jump back into that arena. Their leaders will judge such plans as far more risky than will those among their peers who have continued to compete in that marketplace.

Companies that jettison technology also lose managerial skills for reducing risk.

Precisely how far companies' investment horizons should extend differs from one industry to another, the NAE report points out. Some technologies mature faster than others and survive longer in the marketplace.

According to data assembled by committee member James Brian Quinn of the Amos Tuck School of Business at Dartmouth College, aircraft manufacturers boast long investment horizons because it takes eight years to develop a plane, which, in turn, will be used for more than 15 years. A software package, in contrast, may be developed in two years and have a product life cycle of only another two. To pick winning strategies, managers must have an intuitive feel for the rhythms of their industries—a sense best developed through extensive experience, the NAE says.

But even as they lay responsibility back on the shoulders of management, NAE committee members are quick to point out that the federal government could do more to protect companies from short-term profit whiplash. "There's a structural problem in the U.S., in that there is a big gap between the owners and managers of companies," asserts NAE committee member George N. Hatsopoulos, who is chairman of Thermo Electron Corporation. Large shareholders, such as pension funds, can push company managers to maximize short-term gains by threatening to sell large blocks of stock. When share values are depressed, corporate raiders may begin circling.

"There's no question that managers can themselves affect the environment," Hatsopoulos adds, particularly when they are technologically savvy and stay in close contact with their shareholders. But if institutional investors push for short-term gains, neither the company managers nor the board of directors will be able to withstand the pressure, he maintains. "How many heroes—or martyrs—do you expect to be on the board of directors?"

Other reports still in the offing will continue to call for structural changes. This spring Michael E. Porter, a professor at Harvard Business School, for example, was completing a study for the private-sector Council on Competitiveness that will describe how relationships between investors and corporate managers in the U.S. differ from those in Germany and Japan. In part, he argues, the U.S. equity markets have become too efficient. Whereas large shareholders in Japan and Germany are pretty well stuck with a company, U.S. investors can sell their holdings in seconds. When they disagree with management, U.S. groups usually choose to switch companies rather than grapple with management.

Will boards of directors take back their mandated role of nurturing long-term investments? Frey sees encouraging signs. "I'm now hearing directors say to company chairmen, 'You can revive this company, but if you chintz on R&D, you haven't created a viable company,'" he reports. "I find these statements stunning. I've been on boards for 25 years, and this is the first time other people are saying this."

—Elizabeth Corcoran and Paul Wallich

Watching the Death of a Star

When I look up at the night sky, the stars appear immutable. They never seem to change or age. But when I observe the array of stars across the heavens—even with the naked eye—I can see signs that they are slowly evolving from young stellar objects toward old, dim concentrations of matter.

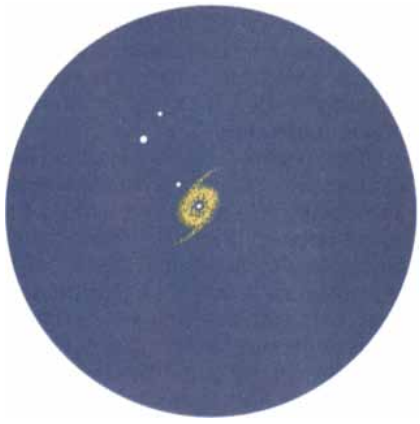
Recently I invited a group of amateur astronomers to observe stars at the end of their life cycles. Using our eyes and various telescopes, we scanned the sky for the senior citizens of the cosmos. In particular, we searched for the remnants of some of the oldest stars, known as planetary nebulae [see "Planetary Nebulae," by Noam Soker, page 78]. These shells of gas and dust are among the most beautiful objects in the universe.

JAMES B. KALER is professor of astronomy at the University of Illinois. He has written many popular articles and more than 100 scientific papers on the later stages of stellar evolution. His book *Stars* has just been published by Scientific American Library.

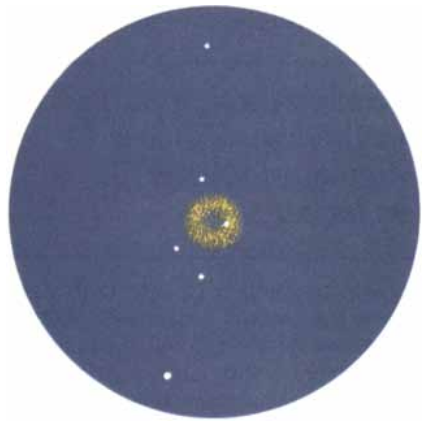
Let me begin the tour with a well-known, middle-aged star: the sun. Like most others, it is powered by thermonuclear fusion, releasing energy as hydrogen atoms fuse to form helium. After several billion years, the core of the sun will have exhausted its supply of hydrogen, and our star will begin to die. The core will shrink and heat as the fusion of hydrogen continues around it. Soon after, the sun will stabilize as the helium residue in the core begins to fuse. At that point, our star will be many times larger in diameter, it will appear 100 times brighter and it will turn orange or even red. The sun will become what astronomers call a red giant.

Fortunately, none of us will ever live to see the sun become a giant. But we have all seen such elderly stars. Most of the orange and red stars that can be viewed with the naked eye are giants. In spring, for instance, you should be able to find the bright, orange star Arcturus in the eastern part of the sky, and in winter you may see Aldebaran in the constellation Taurus.

As giants age, they burn up the helium in the core, leaving a central cinder of carbon and oxygen and outer shells of fusing helium and hydrogen. In the process the stars become even brighter,

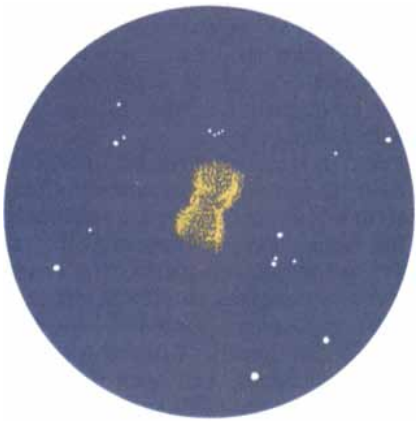


NGC 6543



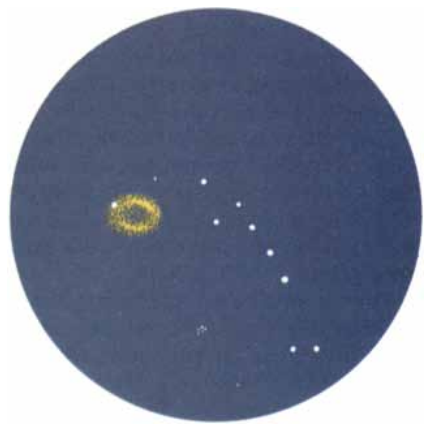
NGC 7662 (Blue Snowball)

NGC 650, 651



NGC 6853 (Dumbbell Nebula)

NGC 7293 (Helix Nebula)



Abell 80

bigger and redder than before. When the sun reaches this stage—known simply as AGB—it will likely envelop the orbit of the earth.

AGB stars are not as easy to find as ordinary giants. Still, a few can be seen with the naked eye, and with a small telescope many come into view. As an AGB star approaches its maximum size and brightness, it becomes unstable and begins to fluctuate in brightness. A fine example is the star Mira, "the amazing." Most of the time it is invisible, but every 11 months or so it appears as one of the brighter stars in the constellation Cetus. Mira is easy to locate with a good constellation map.

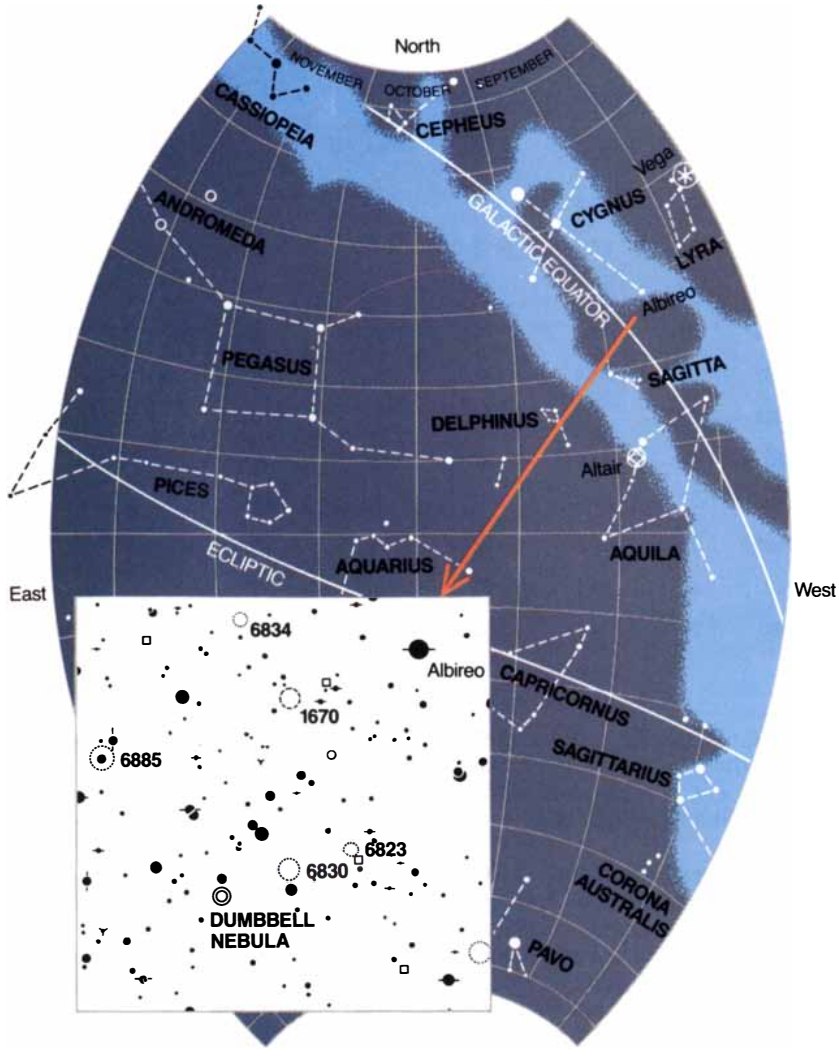
Because the outer region of an AGB star is tenuous and turbulent, it ejects matter at a high rate, as much as three times the mass of the earth a year. After tens of thousands of years, nothing will be left of the star but the hot, dense core and an enormous cloud of gas. The core will still have enough energy to generate a strong stellar wind that compresses some of the discarded matter into a shell. The central star will generate ultraviolet radiation that illuminates the shell. This event marks the beginning of the life of a planetary nebula.

After some 50,000 years, the nebula expands to interstellar dimensions, and its gases mix with those in space. At the same time, the central star starts to dim and becomes a dead, dense remnant called a white dwarf. Such will be the fate of most stars and the sun.

Unfortunately, no nebula is visible to the naked eye. A good pair of binoculars, however, will bring a few into view. For instance, the Dumbbell Nebula glows relatively brightly among the stars of the obscure constellation Vulpecula near the foot of the Northern Cross [*see illustration at right*].

To view dozens of other objects, you will need a telescope, a good set of star maps and a working knowledge of the sky. Before you dust off your telescope or borrow one from a friend, you might benefit from the experience of eight amateur astronomers who volunteered to search for planetary nebulae.

The amateurs were recruited by Wayne Wyrick, director of the Kirkpatrick Planetarium in Oklahoma City. They made most of their observations during the Okie-Tex Star Party, an event organized last fall by the Oklahoma City Astronomy Club. Together the eight volunteers had a variety of telescopes ranging from four to 24 inches in diameter. In preparation I had compiled a list of targets: some of my choices, I thought, would be rather easy to observe, whereas others, I hoped, would test the limits of the instruments and the talents of the observers [*see table on next page*]. To my amazement, all the nebulae on my list were viewed in some detail.



DUMBBELL NEBULA, easily visible with binoculars, lies just off of the star Albireo (Beta Cygni) in Cygnus, at the foot of the Northern Cross.

Young planetary nebulae are bright but small. As they age, they grow larger and easier to examine. The central star also heats up the gaseous cloud, which brightens and consequently obscures the star. Eventually the star cools and dims while the nebula continues to grow. An elderly nebula can be so large that it can be difficult to see against the background of the sky.

The youngest nebulae on my list were objects known as NGC 40 and IC 418. Larry Mitchell of Houston, Tex., and Phil Kuebler of Columbus, Ohio, searched for NGC 40 with a telescope 10 inches in diameter. They found the nebula easily and saw a slightly elongated halo and a prominent central star. With his 24-inch telescope, Mike Dennis of Oklahoma City could distinguish "a hint of a greenish cast." IC 418 is difficult to observe. At first, Kuebler could make out only an odd-looking star, but with persistence he found definite nebulosity.

We next took a look at NGC 6543, an extraordinary nebula, both visually and historically. In 1864 William Huggins observed the spectrum of light from NGC 6543 and discovered that it has mysterious features known as the nebulium lines. They were identified some 64 years later by Ira S. Bowen of the California Institute of Technology as doubly ionized oxygen.

Through a telescope, NGC 6543 looks ghostly green. "No mistaking this one," said Clive Cadle of Oklahoma City, peering through his 10-inch telescope. He could glimpse the central star by fixing his gaze at a region slightly to the left or right of the star. (This technique, known as averted vision, works because the outer regions of the retina are more sensitive to light than the center.)

When Barbara Wilson of Houston ob-

Planetary Nebulae

NAME	RIGHT ASCENSION		DECLINATION		ANGULAR DIAMETER	DISTANCE FROM EARTH
	HOURS	MINUTES	DEGREES	MINUTES	ARC-SECONDS	LIGHT-YEARS
NGC 40	0	10.4	+72	29	36	4,000
IC 418	5	27.1	–12	42	12	2,000
NGC 6543	17	56.8	+66	38	15	3,200
NGC 7009	21	2.2	–11	24	28	3,900
NGC 7662	22	23.5	+42	29	30	3,800
NGC 7027	21	6.7	+41	14	14	3,900
NGC 650	1	41.8	+51	31	140	3,600
NGC 6853	19	59.2	+22	42	360	800
NGC 6720	18	53.2	+33	1	70	2,600
NGC 7293	22	29.1	–20	50	800	500
ABELL 80	22	34.7	+52	24	240	5,700

served NGC 6543 using a 20-inch telescope, she thought the nebula looked "like a cat's eye, a green oval with a dark ovoid." She was easily able to see the central star.

The archetype of all nebulae is NGC 7009, in the constellation Aquarius. This lovely object is named the Saturn Nebula because of its faint projections, or ansae. Discovered in 1782 by William Herschel, it was the first known planetary nebula.

Through an eight-inch telescope, Beryl Cadle, Clive's wife, saw "a bright, large, bluish, oval nebula, hazy around the edges." Using a 20-inch instrument, Wilson observed its ansae and its double-shell structure. (Each shell may represent a different episode of mass loss.) The ansae may represent jets of material that has been ejected from the central star. No one, incidentally, saw the star itself. The bright nebula hides it from view.

We next examined the Blue Snowball, NGC 7662, in the constellation Andromeda. Using a 10-inch telescope, Kuebler could see "a small, bright blue nebula" with a "perforation" within the disk. Peering through larger telescopes, Wilson clearly observed a ring of gas and a bright clump of material on the southwest side. With a professional 40-inch telescope, I can make out two rings and the central star. Astronomers have studied this nebula intensely because of its triple-shell structure and hot nucleus (100,000 kelvins).

In NGC 7027 the star reaches 180,000 kelvins. To observe the star at all, astronomers must use sophisticated imaging systems. The nebula itself is rather compact and looks rather plain. Clive Cadle searched for NGC 7027 with a 10-inch telescope and passed over it several times because it looked like an ordinary star. Using a 24-inch telescope, Dennis clearly saw a "small patch of nebulosity with a greenish color… becoming more diffuse toward the edges." From these modest descriptions, it is hard to believe that NGC 7027 is the planetary nebula most frequently observed by professionals.

One of the older nebulae has two catalogue numbers, NGC 650 and 651, for its two lobes. Such a system, known as a bipolar planetary nebula, is created as the central star loses mass preferentially in some directions. Using 10-inch telescopes, both Kuebler and Mitchell saw the lobes.

The three best-known nebulae are the Dumbbell Nebula, the Ring Nebula in Lyra and the Helix Nebula in Aquarius. The Dumbbell, NGC 6853, is one of the most beautiful objects in the sky. It looks like a glorious mobile in an art gallery, hanging from a magnificent array of stars in the Milky Way. Using a four-inch telescope in suburban lighting, Linda McArthur of Moore, Okla., could see not only the dumbbell shape but also details along the edges. At 10 inches, Kuebler describes the nebula as blue-green and "an awesome sight."

Herschel did not even classify the Ring Nebula, NGC 6720, as a planetary because of its smoke-ring shape. With a 24-inch telescope, Dennis could see not only faint nebulosity but also the dim central star.

The last of the trio is the Helix Nebula, NGC 7293. The closest known planetary nebula to the earth, it is a mere 500 light-years away. Because it is so old, the nebula is enormous. Furthermore, because it so close, it covers a region of the sky almost half the angular diameter of the full moon. Consequently, it can be best observed with a low-power, wide-field telescope. But even with binoculars, Wyrick picked it out as a "grayish blob" and saw a hint of its ring structure. Using 10-inch telescopes, Clive Cadle and Mitchell clearly saw its ghostly ring set among the stars.

As a final challenge, I asked the group to look for Abell 80, a planetary nebula near the end of its life. Huge and faint, it will disappear from view altogether within the next 10,000 years or so. The only ones who could see the object were Wilson, Mitchell and Kenneth Drake of Houston, using telescopes 20 inches or more in diameter. Even then the feat proved difficult. They spent more than an hour at the eyepiece, applying every trick in the book of amateur astronomy: they covered their heads to keep out unwanted light, used averted vision and employed a contrast-enhancing filter that passes the oxygen nebulium lines.

The three described and drew the same image, so we were assured that they were actually viewing Abell 80. Wilson saw two narrow arcs. "At times it seemed that the entire planetary could be seen as a diffuse glow," she explained. "But I really feel it was an illusion, and only the western lobe could be described." Mitchell found a brighter, northwest edge, and Drake saw a faint, round diffuse glow that faded into the background.

Several years ago I observed Abell 80 through a 40-inch telescope, to measure its brightness. I never saw it directly and relied on electronic instrumentation. At the star party I got a second chance. I think I saw it. But afterward I wondered if it was just an illusion. I hope I did. It was an opportunity to see the last throes of a planetary nebula before it disappears forever into the void, before its gases help to give birth to another generation of stars.

FURTHER READING

PHYSICS OF THERMAL GASEOUS NEBULAE. Lawrence H. Aller. D. Reidel Publishing, 1984.

THE GUIDE TO AMATEUR ASTRONOMY. Jack Newton and Philip Teece. Cambridge University Press, 1988.

ATOMS, STARS, AND NEBULAE. Lawrence H. Aller. Cambridge University Press, 1991.

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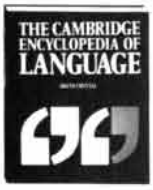

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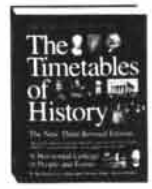

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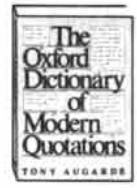

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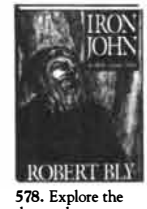

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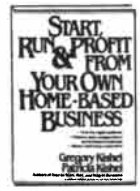

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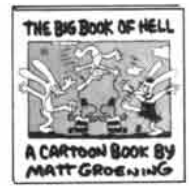

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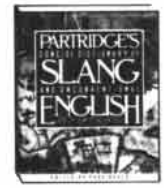

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BOOK REVIEWS by Philip Morrison

Random Visitors

COMETS: A CHRONOLOGICAL HISTORY OF OBSERVATION, SCIENCE, MYTH AND FOLKLORE, by Donald K. Yeomans. Wiley Science Editions, John Wiley & Sons, 1991 ($35).

COMET DESTROYS THE EARTH in this 19th-century French cartoon.

Comet Halley has come and gone, a shy flame in the city glow. It ought to be judged not for that uncertain visual display but for its wonderful recurrences, recorded for 20 centuries by watchers around the world. First to note it, moving from east to north in early June of 240 B.C., were the Chinese, who called it the "broom star."

The author, who wears his broad learning lightly, is an astronomer at the Jet Propulsion Laboratory of NASA. He has long been an assiduous tracker of Comet Halley's history. It was his official task to carry forward the work of a long line of past reckoners, to say just when and where that comet would leave the hidden domain of digital memory, to be recorded by a sensitive detector at Palomar one October night in 1982, still tailless. Yeomans's position proved correct to about 1/400 of one degree of arc, although the comet would fall for three years more toward the sun.

A graph shows more than 2,100 years of computed variations of the period with which Comet Halley repeats its long, slender path. The round-trip averages about 77 years, with a quite rhythmic variation from about 75 to 79 years. That timetable reflects the shifting position of massive Jupiter when the comet approaches close enough to feel the planet's pull. Edmond Halley knew enough Newtonian physics to expect that Jupiter effect; his first prediction of the object's return was based on three earlier observations at varying intervals. "I dare venture . . . ," he wrote in 1705, "that it will return again in the Year 1758." It was first seen by telescope on Christmas Day of 1758, years after Halley's death; his revision of his first prediction allowed for a return as late as January 1759. In fact, better calculations by Alexis-Claude Clairaut in 1758 missed the true date of closest approach by a month. We can now assign some sources of error: for example, six days for the effects of Uranus and Neptune, planets that had not yet been discovered, four days for wrong mass values for Jupiter and Saturn, and six more days due to neglect of the inner planets.

Planets are compact, dense, rocky masses, but comets are by no means firm and dependable orbiters. Two 1974 photographs show Comet Kohoutek, one in visible light, one in an ultraviolet light of atomic hydrogen. That modest comet's hydrogenic halo extended to four times the diameter of the sun. Local outbursts of gas and dust come from the comet core, more frequently as the body approaches the fierce sun. Each jet of gas imparts a small recoil to the nucleus and a minor disturbance in the motion, depending on jet strength, direction and duration. The recoils certainly cannot be computed by gravitational theory alone. They modify the passage time of a comet by a day or two out of a century in orbit. But even so irregular a phenomenon shows some averaged uniformity. An estimate of jet effects subtly modeled to fit Comet Halley's history since 1607 trimmed the final error in its 1986 arrival to about five hours.

The punctual traveler was met by an international welcoming party of half a dozen probing spacecraft. The comet's nucleus was photographed from distances of a few thousand miles—the closest image was made from about 1,700 miles—and the book shows the best composite shot of six images, with a helpful guide map. At heart, Comet Halley is a potato-shaped lump of dusty ices, its dimensions about $10 \times 5 \times 5$ miles, spinning once every few days. It has a jet-black, tarry crust, but about a tenth of that crust is missing from patches where dust-laden gas streams out to form the bright comet head and the grand sweep of tail. On its next return we will surely fetch a sample back for the analysts and their museums.

Less than half of the text is given to an up-to-date but nontechnical account of our contemporary understanding of comets. The rest of the text and its copious illustrations in black-and-white live up to Yeomans's subtitle. He knows the art of historical show-and-tell without the little elisions and deceptions of many storytellers yet with no ponderous burden of footnotes. (The lack of sources for many of the illustrations is one small flaw.) We are spared all those familiar portraits of heroes such as Ptolemy and Aristotle by old artists who had never seen their models or indeed any image of them. What illustrates this fine account of classical ideas is real. It is a comet image stamped on the silver denarius issued under Augustus, adopt-

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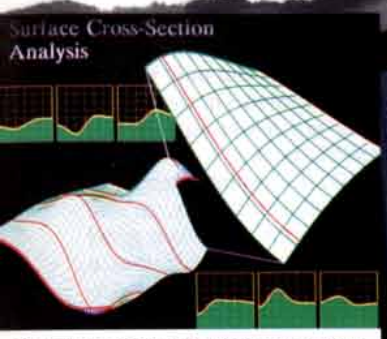

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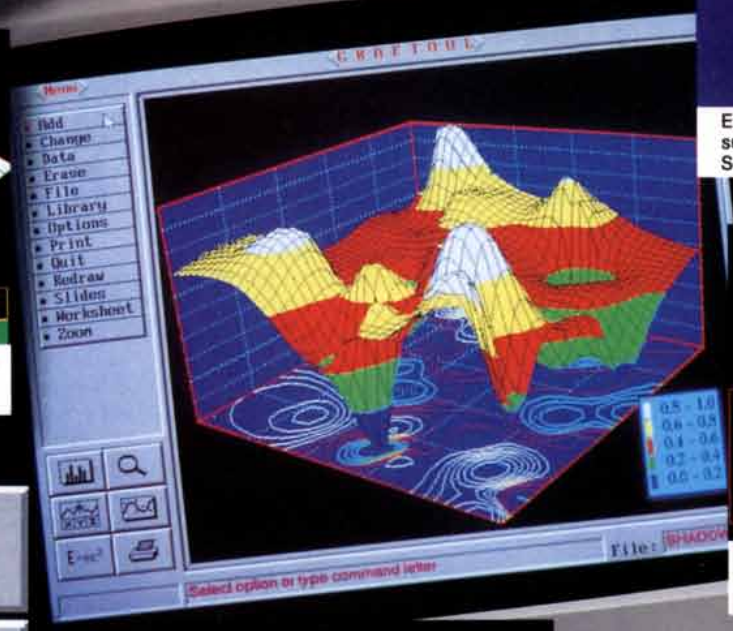

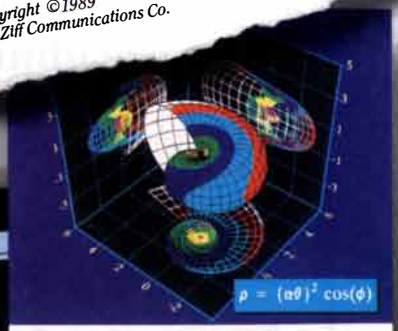

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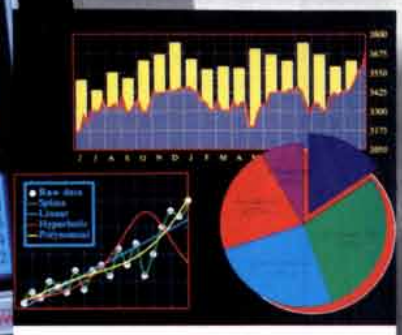

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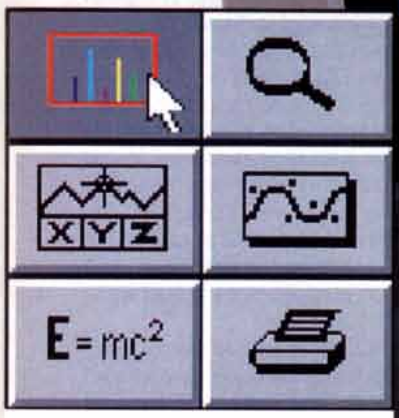

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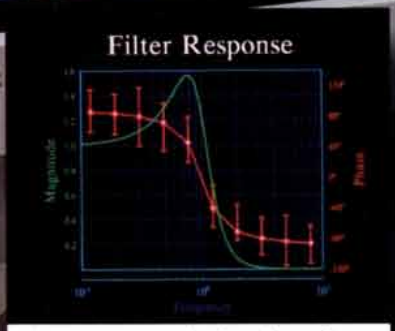

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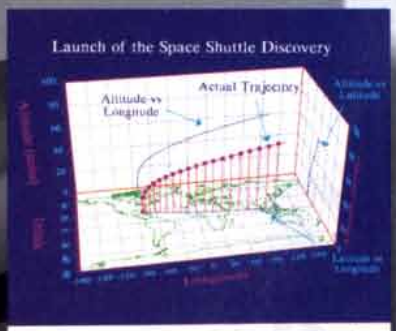

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ed son of Julius Caesar, to record the scene of 44 B.C., when it was widely held that "the heavens themselves blaze forth the death of princes."

The chronicle goes on. A Chinese book of the Han records on silk 27 types of comet tail and what each brings as an omen: a flamelike tail, say, presages a five-day rebellion. Soon enough this lore turns more matter-of-fact. Shifting schedules become orderly, although comet form remains protean. A wonderful six-tailed comet seen in the spring of 1744 is drawn with its head below the horizon, a symbol for the complex richness of comet physics.

Evidence for the bombardment of the earth by comets remains quite tentative. Recent findings show that Yucatán and Quebec each exhibit a dated scar from a killer comet. This new evidence strongly suggests that the half-dozen mass extinctions in the rocks signal not six but scores of intruders that must have arrived in million-year "swarms." Comets are as disorderly and ominous as the ancients held; we moderns concede that those random visitors helped to shape terrestrial life, itself a restlessness.

Ancient Creatures

ON METHUSELAH'S TRAIL: LIVING FOSSILS AND THE GREAT EXTINCTIONS, by Peter Douglas Ward. W. H. Freeman and Company, 1992 ($18.95).

Do maggots arise spontaneously in rotting meat? The physician Francesco Redi first put that question to nature in 17th-century Florence by means so simple yet so intellectually audacious that even the memory is a delight. Redi saw a way of Euclidean rigor that could *deny* the old conjecture. Screen butcher's meat behind a gauze. Neither any internal property nor the essential ambience of air, light and moisture could be much affected by the loose mesh. But since it kept out all the eager, buzzing flies, no eggs were emplaced in the meat, which putrefied but did not go wormy. Maggots must come from without.

A generation ago Bob Paine of the University of Washington first brought Redi's ingenuity to the seashore. Three bands of life are plain to even the most casual stroller along the Northwest shore. Lowest, longest submerged, many forms of mollusks live in the dark seaweed; above them runs a half-dry zone of mussels; least tide-washed of all is an uppermost zone of barnacles. The easy explanation was that those marine organisms had different tolerances for rhythmic exposure to the air.

Paine attached bottomless wire cages to a few rocks close to the tide line. Within a few weeks the species mix in the area enclosed by his cages began to change. Cages put where normally a diverse group of shells (none of them mussels) dwelled amid weed were eventually overgrown by one single species: the mussels. The wire cages had only one effect, just as for Redi; they excluded no air, no seawater, no tiny eggs or sperm, but they kept out all good-size predators. The mussels had not settled in their middle zone to avoid long dousing under the tide. They could thrive in the deepest tidal band, but only if their predators were excluded. On this shore, predation does not lessen species diversity but maintains it.

If in the small, the environment that counts is an organismic one, in the large, it can be cosmic. We have good reason these days to conclude that a shower of icy comets from the dim outer marches of the solar system now and again invades our bright orbital garden near the sun. Some of those comets chance to strike and shatter against the earth, to darken the sky, poison the seas, even kindle the forests. The great French paleontologist Alcide D. d'Orbigny, who was a traveling naturalist when Charles Darwin was on the *Beagle,* inferred repeated mass extinctions from the long stratigraphic record itself. He drew attention to the several profound "divisions which nature has delineated... across the whole earth." But he held the extreme view that at each great extinction all life on the earth had died out, to be created anew as it had been made in the first days.

Peter Douglas Ward has given readers a wonderful small book that tells all this and more. The book is lively with reminiscence, gossip and sharp argument. He, too, has made those long drives to the shore from his own Seattle campus, just where Bob Paine once worked. And he has sought out yellowed labels in d'Orbigny's hand in that savant's own dusty office. But this is no outsider's history of a science; it is the self-revelatory account of a paleontologist still hard at work, a joyous celebration of adventuresome field trips and lengthy experiments. Old Alcide left a rich collection in Paris; even today his ornately spiral fossil ammonites lie "scattered over every possible surface of the large room." Ward, too, has hammered many an outcrop in western Europe to seek out marine fossils at the very level of the great dying that parted the old sea life from new (called the Cretaceous-Tertiary boundary), when the reign of the dinosaurs ended.

In the dark shales below that bound-

ary near the western Pyrenees in France lurk many fragments of once showy ammonites, of abundant flat clams and of characteristic plankton. Inches above the interface, only lime-white rocks dazzle in the spring sunlight. The hammer discloses almost none of the fossils that are abundant below. Only one fossil form is found often on both sides of that contact plane: the round core of a sea urchin, much like living forms common today in the tropical Pacific. These urchins represent a morsel of marine life that has for 65 million years survived the calamity recorded below, one of Ward's Methuselahs.

We see a photograph of a piece of rock from a celebrated English shore. Two fossils, each a spiral, chambered shell of a sea beast a foot across, lie side by side. One is an example of adept but basic submarine engineering, a nautiloid. The other is an ammonite, optimized for economy of shell material, hence capable of much faster growth. Ammonite shell walls are thinner than nautiloid shells, cunningly strengthened by artfully curved partitions and ridges. Ever since Robert Hooke saw the shell of the still living nautilus brought back to Europe, the scholars have wondered how it is that none of the ammonites, so frequent and so similar to the nautilus, are still found alive. Although they have left no traces in any rocks above that boundary, Ward has traced ammonite parts right up to the terminal clay layer at the very top of the Cretaceous. They were "present for Armageddon," but never beyond.

Yet the chambered nautilus and four kindred species still swim today. Many dwell around the reefs in the Coral Sea, and they are known from Fiji westward to the Indian Ocean. Energetic Ward shelved his geologist's hammer to go fish up these Methuselahs in big, baited cubical traps. He brought some of the creatures back alive for rearing and study. His own volume on their natural history, reviewed here a few years ago, documents the extraordinary lifeway of these submersibles, who rise 1,000 or even 2,000 feet during the dark of the moon to feed in well-stocked shallow waters. They stay mainly hidden in the deep whenever the waxing moon might silhouette them. The thick pressure hull grows slowly, over 20 years or so. Every year the adult females deposit a dozen inch-long eggs in deep water; the hatchlings surface freely a year or so later.

The ammonites were fitted for life in the fast lane. They deposited thousands of millimeter-size eggs that developed swiftly, they matured very rapidly in the warmer shallows amid plenty of prey and they diversified easily into baroque

genera with hundreds of species. But they ended for good as soon as the comets fell. The prudent nautilus lineage dwelled in the cold, dark depths, where food was short and growth slow. It managed thus to survive the fall for a crucial first year deep under a sea surface soured by the acid rain made at the comets' entry. Here they are, the fortunate survivors. Survival is not always to the adapted, as the battle is not always to the strong, for time and chance happeneth to them all. But one year's grace was enough to carry this Methuselah species past the catastrophe.

There are half a dozen other such tales here. None is so fully worked out as the story of the spiral shells, but each is fascinating. Professor Ward shares most vividly the growth of his own understandings, but he presents very well the work of others. His story of the horseshoe crabs, most cited of Methuselahs, offers a drawing to illustrate how a single species of that antique genus once essayed life on land, if only on swampy land. The spiny crabs are found nestled against matching spiny trunks of big lycopods, common plants in the Illinois coal seams.

This loyal reviewer of the printed word foresees a future television version of these tales tall but true. Readers, get the book first.

Columbus's World

CLAUDIUS PTOLEMY: THE GEOGRAPHY, translated and edited by Edward Luther Stevenson. Dover Publications, 1991 (paperbound, $19.95).

This big volume is the unabridged reprint of a scholarly work issued in limited edition in 1932 by the New York Public Library. It is the first English version of the text by the famous Alexandrian, whose Greek manuscript dates from the middle of the second century A.D. Ptolemy was a tireless and encyclopedic writer. His astronomical manual, called by the Arab scholars the *Almagest,* defined the calculations of planetary motions for nearly 15 centuries. His famous astrology in four books is influential, unhappily, to this day, and this summing up of classical geography, largely compiled by his main source, Marinus of Tyre, was long celebrated.

The *Geography* was a source of major importance in the 15th century. The text is supplemented here by full-size black-and-white halftone reproductions of a manuscript atlas of the world according to Ptolemy, drawn about 1482 in 27 plates by a copyist and geographer, Donnus Nicolaus Germanus. He dedicated the work to his "Most Illustrious Prince and Lord," the Duke of Modena, "Ornament of our Italian nobility." The earliest printed world maps owe much to these manuscript maps.

The reprint, and this brief notice, arises out of the commemoration of that transoceanic project of 1492. The book is part of the learned evidence on which adventuresome Columbus rested his royal proposal. It is a work we have all heard about but never seen. A close look explains much; it is in fact more or less an unreadable book. For it is mainly a gazetteer, the long list of place names and locations that acts as index to any big atlas. It includes about 8,000 entries for Europe, Africa, Asia and the big islands, the whole of the classical world from Iceland to Ceylon, west to the fortunate Canaries and east to the bend of the Yellow River. Ptolemy speaks of an atlas in detail ("we will make ten maps for Europe"), but none of his maps survives. This was a text for the hardworking, an invitation to mapmakers, and it still repays that kind of attention.

There is some readable matter here, comments on map projections, on mountains, rivers, mines and naval stations, and a few juicy bits on women covered with hair, men with skins like rhinos, magnetic islands, and cannibals. But mainly the book is a long, orderly list, ancient names of settlements and of their peoples in region after region, each with latitudes and longitudes given to five minutes of arc or better, of course with frequent error.

Ptolemy calculated from "the extreme eastern region of the world known to us... the metropolis of Sinae... [to the] western limit... twelve equatorial hours," just 180 degrees of longitude. Ptolemy's knowledge goes no farther east, staying short of the China Sea. But the Europeans of the 15th century knew the narrative of the Venetian Marco Polo, who told of recent naval expeditions launched unsuccessfully by the Great Khan against the island of Japan. Even Polo's generous estimate of the distance from China's capital to Japan would hardly stretch the arc of the inhabited world beyond 210 degrees.

A prudent estimate sets the westward voyage from the Canaries to Japan at about 150 degrees. Hopeful Columbus made landfall at what he took to be offshore Japan after a voyage that was about the length he had anticipated, only 60 degrees of arc. That imprudent, gifted and above all lucky mariner thus stitched the Old World tightly to the New, perhaps for the first time since the glaciers dwindled.

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ESSAY by Anne Eisenberg

Metaphor in the Language of Science

Those of you who keep up with proteins may have read about chaperones. No, they are not adults dispatched to oversee teenagers at a sock hop. Chaperones are the molecules that stabilize and protect young polypeptides, helping them fold into three-dimensional conformations. Without the guidance of their chaperones, the newborns would not fold perfectly, and without perfect folds, they would fail as proteins.

Chaperones used in this way is a metaphor, a device that, as Aristotle once said, "consists in giving the thing a name that belongs to something else."

Once metaphors were the stuff of poetry not proteins—but no more. You are just as likely these days to run across them in a scientific review as in a sonnet. Despite the 300-year effort by Hobbes, Locke and a legion of logical positivists to confine them to the English classroom, metaphors are suddenly inescapable in technical prose. From chemical scissors and solvent cage to optical molasses and squeezed light, from DNA fingerprints to read-only-memory, metaphor is out of the scientific closet.

Hobbes would not be pleased. "When [men] use words metaphorically; that is, in other sense than that they are ordained for, [they] thereby deceive others," he said in *Leviathan.* "Such [inconstant] names can never be true grounds of any ratiocination."

Locke didn't care for metaphors either. "Figurative application of words... are for nothing else but to insinuate wrong ideas, move the passions, and thereby mislead the judgment, and so indeed are perfect cheats," he said in *Essay concerning Human Understanding.* "They are certainly, in all discourses that pretend to inform or instruct, wholly to be avoided."

But avoiding them in scientific prose was, it turned out, virtually impossible. Even the scientists most eager to follow Locke's advice could not escape metaphor and its cousins simile, personification and analogy. The figurative lurked behind every word: the simplest units of technical vocabulary, from muscle (little mouse) to bacteria (little staffs) to broadcasting (throwing seeds widely), turned out to be metaphorical. True, many of the metaphors were, if not dead, at least dormant—people were no longer conscious of the literal equivalents—but many a scientist who picked a seemingly innocuous term watched in dismay as it suddenly detonated.

This happened to Darwin when he chose the term "natural selection." Darwin's contemporaries heard the expression as a personification. They thought he was saying, "Nature selects," and they reasoned that Nature choosing was the same as God creating—either way, the Lord was still in charge.

"In the literal sense of the word," Darwin responded in *The Origin of Species,* "natural selection is a false term; but who ever objected to chemists speaking of the elective affinities of the various elements?—and yet an acid cannot strictly be said to elect the base with which it in preference combines. It has been said that I speak of natural selection as an active power or Deity; but who objects to an author speaking of the attraction of gravity as ruling the movement of the planets? Every one knows what is meant and is implied by such metaphorical expressions." Despite Darwin's patient explanations, his contemporaries continued to resist the term. Darwin was sandbagged by his own metaphor.

Even when scientists escaped the trickiness of metaphors that lived within single words, they had to cope with the latent treacheries of extended metaphors or analogies. In his 1690 publication *Traité de la Lumière,* Christiaan Huygens proposed a brilliant analogy that explained complex aspects of light such as diffraction and interference. "[Light] spreads," he wrote, "as Sound does, by spherical surfaces and waves: for I call them waves from their resemblance to those which are seen to be formed in water when a stone is thrown into it." But even an analogy this insightful had a slight problem. Waves have a medium—water—but light, as Huygens well knew, travels through a vacuum. He decided that the propagation of light was caused by "particles of the ether... a substance... approaching to perfect hardness and possessing a springiness... in which the movement of Light is successively communicated." It was more than 200 years before Einstein put an end to the idea of ether.

If Huygens followed his analogy a bit far, Percival Lowell, astronomer and author of *Mars and Its Canals* (1906), should have stopped before taking the first step. Lowell was a fearless drawer of analogies. He likened "the theory of the existence of intelligent life on Mars" to "the atomic theory in chemistry" on the basis that both had elements "too small for us to see." Lowell's voyage into the figurative led him to propose a planet-wide Martian irrigation system fed by melting polar ice caps and tended by intelligent beings.

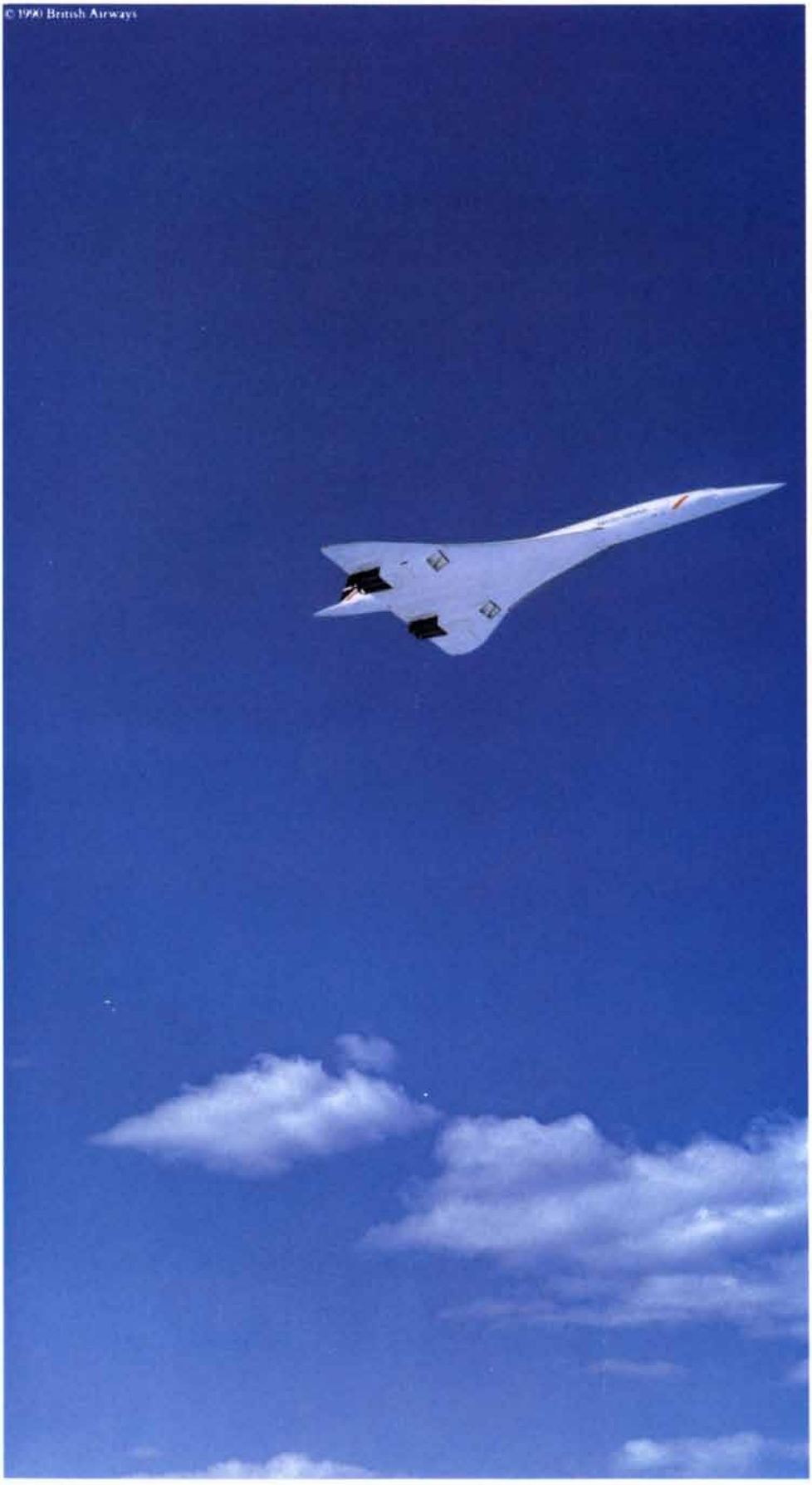
Metaphors survived Lowell, as well as Hobbes and Locke, if for no other reason than scientists, like the rest of the world, think in them. A thing is or is like something else: the modes of a laser cavity are like the standing waves made by the strings of a musical instrument; enzyme and substrate are like lock and key; the spectrum of light is like a musical scale with notes higher and lower than those we perceive.

Metaphors are helpful even when their correspondences are imperfect—as in the model of electron spin, in which the electron is certainly not spinning in the normal sense of, say, the earth's spinning on its axis. Still, the metaphor explains the angular momentum and magnetic field of an electron; it's the best we can do right now. As one wit said of metaphor, although it may mislead, it is the least misleading thing we have.

In the past decade, metaphors in technical text have proliferated, but they seem to evoke as many critics as ever. Computer terminology is a special target; people take issue with memory, language, read, intelligence and other terms that personify computers. Some metaphors are better than others, they argue; this particular set undermines human identity. Use data storage device instead of memory, they advise, machine codes instead of language.

Given the enduring power of metaphors, though, memory, not data storage device, is sure to win out. But we'll have to wait and see—scientists will need to process the idea for a while.

ANNE EISENBERG is a professor in the department of humanities at Polytechnic University in Brooklyn.



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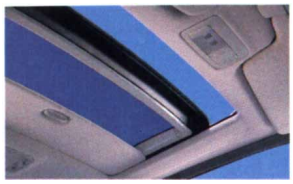

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