SCIENTIFIC AMERICAN

MAY 1990
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DNA fingerprinting: when untried technology takes the stand.

Will mutant neutrinos confirm grand unification theory?

Turning the immune system against tumors.

Trends in transportation: *from the microchip to the greenhouse effect, powerful forces are changing the shape of cars to come.*

"GO FO

Marc Rankin
Marketing Representative

Callie Mitchell
Senior Supply Representative

Ron Richards
Manager, Environment Affairs

The six people on this page aren't professional models or actors. They're part of the new Texaco. Their charge is this: if there's a better way to discover it, recover it, produce it, ship it or sell it... "go for it." For our part, we're eliminating the procedures and obstacles that can get in their way. The results have been rather incredible.

"There's a tremendous team dynamic in the company now that we hadn't had before. You can actually feel the energy around here." Ron

"Exactly. We don't have two or three years to get a project rolling anymore. These days, we *attack* projects. We get the necessary people together in one room, and we don't come out until the problem is solved. Now we're off the drawing board in three to four days." Kelly

"Our customers are being involved in the process, too. It's almost like we flip-flopped the corporate ladder. Instead of the CEO sitting on the top, the customer has

OR IT."

Bill Studzinski
Chemist

Carol Triebel
Superintendent, Planning and Shipping

Kelly Mayo
Systems Analyst

become the most important person. I think they're still a little amazed that we even *ask* for their input." Marc

"It's really paid off in our natural gas liquids business. We've quadrupled our customer base, and now we're a worldwide leader." Callie

"We're heading that way in fuels, too. Our new System³ gasoline has a lot of our competitors taking a second look." Bill

As you can see, there's a new energy at Texaco. We're aggressively searching for new oil. Getting more from our existing fields. Developing products for today that are designed to serve into tomorrow. And pioneering the clean energy sources that must guide us into the future.

"I'm glad to see Texaco taking a leadership role. I'm really proud that I'm a part of it, too." Carol

So are we, Carol. So are we.

Star of the American Road

TEXACO–WE'VE GOT THE ENERGY.

SCIENTIFIC AMERICAN

May 1990 Volume 262 Number 5

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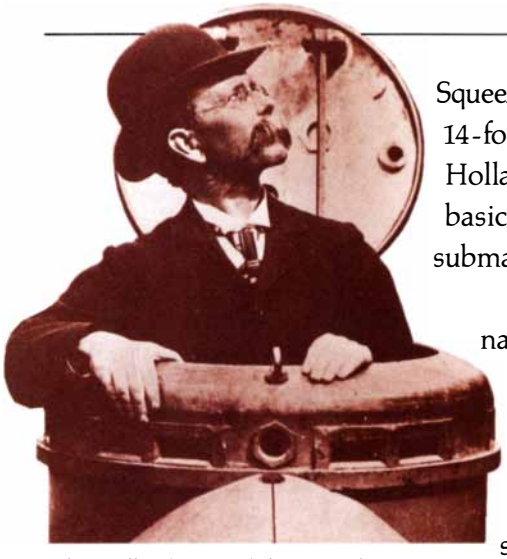
DEPARTMENTS

OUR FIRST SUBMARINE DID ONLY ONE REMARKABLE THING. IT CAME BACK UP.



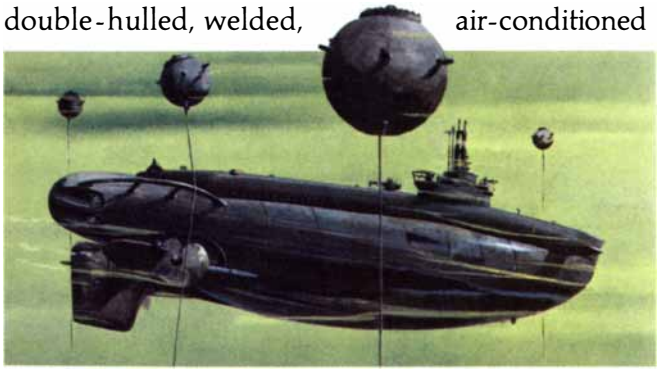
John Holland invented the first submarine accepted by the U.S. Navy. Amazed reports said, "She goes like a fish and dives better than one."

Squeezed into a crude, 14-foot craft, John P. Holland proved the basic principles of submarines in 1878. His poetically named "Boat No. 1" was hauled to the Passaic River by 16 stallions for testing. It stuck in the mud, it leaked, but it came back up.

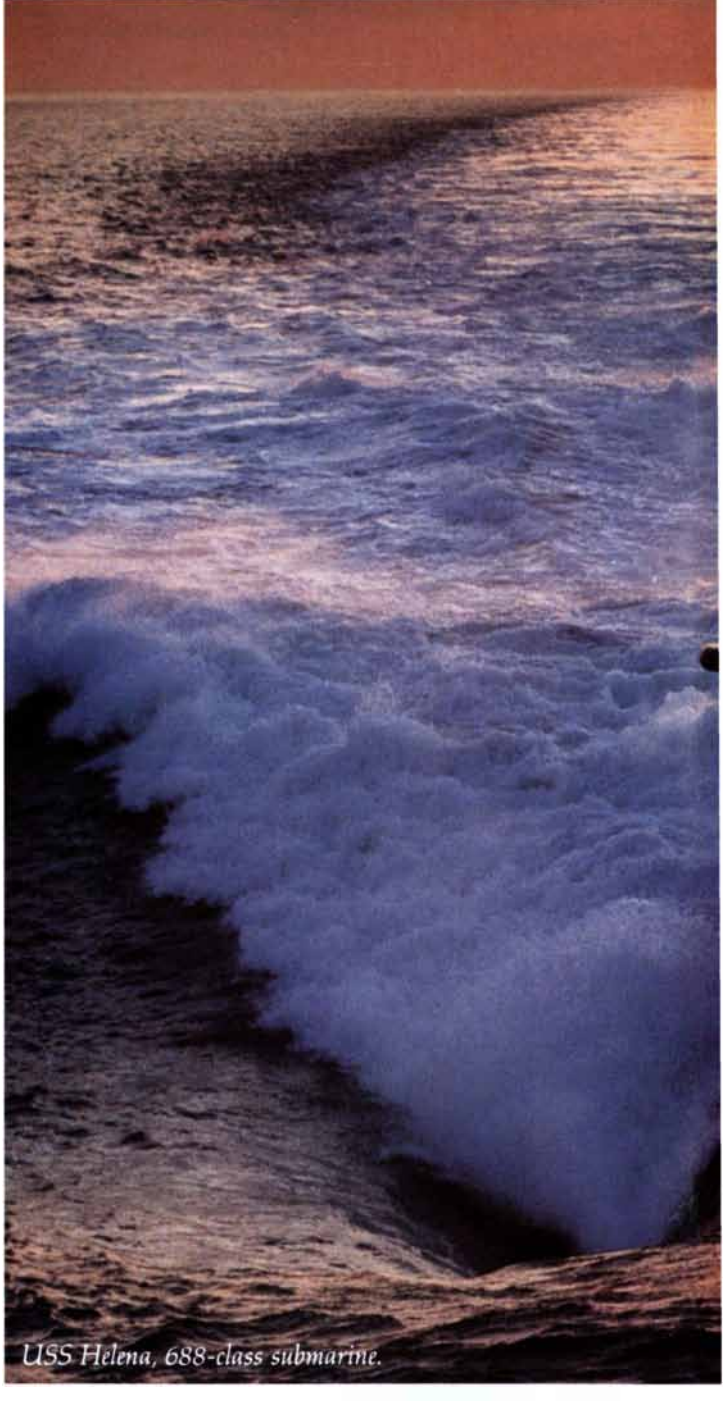
To us, the only thing more remarkable than the submarine itself was the courage of the submariner. Something that's still true today.

Holland got his Electric Boat Company, our earliest ancestor, off to a strong start in 1900, when the 74-ton submersible Holland became the U.S. Navy's first submarine. Showing his confidence in this new type vessel, President Theodore Roosevelt alarmed Secret Service bodyguards by taking an unscheduled dive aboard an A-class Plunger, August 25, 1905.

Running silent as well as deep became possible in 1933, when Electric Boat launched Cuttlefish, the first double-hulled, welded, air-conditioned submarine. She was the prototype for all World War II Navy fleet submarines.



All WWII fleet submarines were based on Cuttlefish, the first submarine to be welded, rather than riveted, and a technical milestone.



USS Helena, 688-class submarine.

But it was on January 17, 1955, that we introduced the most dramatic improvement in submarines since John Holland and Boat No. 1. It was Nautilus, the world's first atom-powered vessel. And in an astonishing adventure, she became the first submarine to sail under the North Pole.

Today, our Tridents, the world's most advanced submarines, routinely patrol for 70 days without surfacing. Longer than the Washington Monument is tall, they are so carefully made that they cruise in virtual silence.

USS Nautilus was the first vessel to radio, "Underway on nuclear power." She then became the first to sail under the North Pole.

Yet innovations continue. Seawolf, a new class of submarine now under construction in our yards, will advance submarine science into the next century.

Seawolf re-proves two principles first proved by John Holland and Boat No. 1. That under deep water is found man's highest technology. And his highest courage.

Dedication to both has kept us improving American submarines for 90 years.

GENERAL DYNAMICS

A Strong Company For A Strong Country

THE COVER painting depicts an automobile dashboard that is just around the corner for motorists. The video screen helps the driver to locate the car on a map. Want to make a phone call? Press the button and a keypad appears. Find a motel? It'll show you where to look, give you the rates and dial so you can make a reservation. It's even a personal computer. Such electronic systems promise to make driving more satisfying—and also safer (see "Trends in Transportation," by Karen Wright, page 92).

THE ILLUSTRATIONS

Cover painting by Ted Lodigensky

Page	Source
47	Stephen Ferry, Gamma-Liaison
48	Neil O. Hardy
50–51	Peter J. Neufeld
52	Johnny Johnson
55	Soviet-American Gallium Experiment
56–60	Andrew Christie
61	Edward Bell
63	Richard Knazek, Cellco Advanced Bioreactors Company, Rockville, Md.
64	Carol Donner
65	Steven A. Rosenberg
66	Johnny Johnson
67	Carol Donner (*top*), Steven A. Rosenberg (*bottom*)
68	Carol Donner
71	Peter Wellnhofer
72	Patricia J. Wynne
73–75	Peter Wellnhofer
76	Patricia J. Wynne
77	Renate Liebreich, Bavarian State Collection for Paleontology and Historical Geology
92–93	Ford Motor Company, Nissan Motor Company, Ltd., and Renault USA, Inc.
94–101	George Retseck and Edward Bell (*top*)
94–95	Edward Bell and Cadillac Motor Car Division, Buick Motor Division, Volkswagen of America, Inc., Chevrolet Motor Division and Chrysler Corporation
96	General Motors Corporation (*middle*), Stephen C. Bates, GM Research Laboratories (*bottom*)
98	George Retseck (*bottom*)
99	Frederick S. Myers and Edward Bell (*bottom*)
100–101	© Detroit Institute of Arts, Founders Society Purchase, Edsel B. Ford Fund and Gift of Edsel B. Ford (*bottom*)
103	Steven Homer/First Light
104–105	Steven Homer/First Light (*top*), Tom Prentiss (*bottom*)
106	Tom Prentiss
107	Edward Bell
109	Sandia National Laboratories
110–111	Hank Iken
114	Sandia National Laboratories
116	Hank Iken
119	Bernard Pierre Wolfe, Photo Researchers, Inc.
120	Johnny Johnson
121–122	Patricia J. Wynne
124	Johnny Johnson
126	Declan Haun (*left*), Michael F. Barnsley and L. Reuter (*right*)
127	Russell Ruthen
128	Andrew Christie
129	Edward Bell (*left*), Michael F. Barnsley and L. Reuter (*right*)

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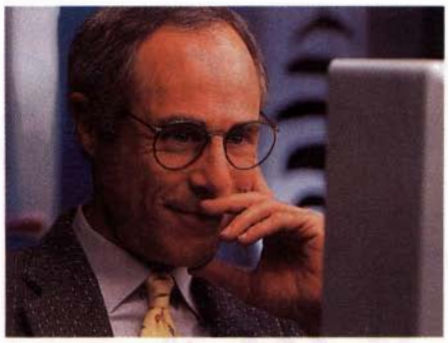
There are two kinds of innovations in the computer business. The ones you just talk about. And the ones you actually use.

Introducing I



The new Macintosh IIfx: 53 innovations, one powerful idea: to give you more power to do more things more easily than ever before.

Hardly a week goes by that you don't read a dramatic announcement touting one personal computer innovation or another.

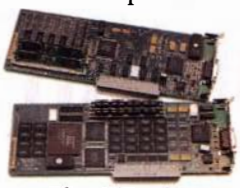
It all sounds impressive.

Until you actually sit down at a keyboard and try to convert all that hype into something practical.

This is what the remarkable new Macintosh® IIfx is all about.

It is, by any measure, one of the most powerful personal computers ever built. Incorporating 53 major innovations, too many to list here. But a few merit special mention:

It is the first personal computer to offer a Motorola 68030 microprocessor running at 40 megahertz. In information processing terms, this is akin to a red Ferrari screaming down the autobahn with *Ride of the Valkyries* cranked all the way up on the stereo.



A pair of new video cards turns 18 new ideas from Apple labs into 16,776,960 more colors you can actually see. But only on a Macintosh.

It's also the first personal computer to have two additional processors to manage the flow of information inside. So that that screaming 68030 chip isn't slowed down by the more mundane tasks of computer housekeeping. And so that you aren't slowed down. Ever.

New A/UX 2.0 lets you run UNIX, X Window System and Macintosh personal productivity programs at the same time. 32 innovations for Apple, hundreds more choices for you.

It comes standard with 4 megabytes of memory and up to 160 megabytes o storage capacity. Plus six NuBus™ slots to let you expand its capabilities even more.

But what makes the IIfx truly powerful is that you can apply all of its 53 innovations to solving the problems you have today.

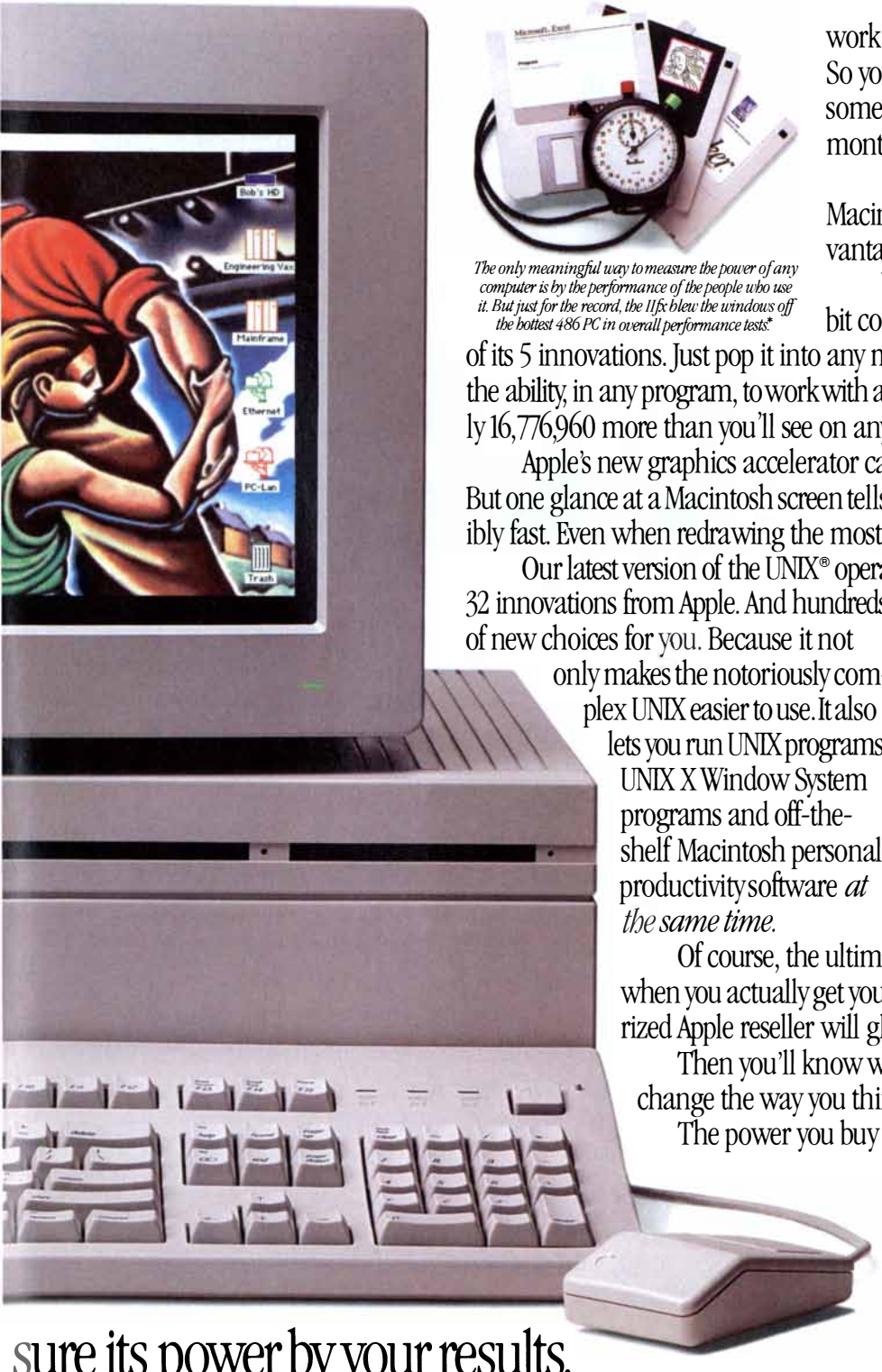
Because it is, above all else, a Macintosh.

It runs thousands of Macintosh programs that all

The new Macintosh IIfx.Mea

National Software Testing Laboratories ran benchmarks comparing the Macintosh IIfx with the IBM Model 70/486 running Microsoft Excel, Aldus Pagemaker and Adobe Illustrator. NSTL found the IIfx things you normally do in business. In the same tests, the IIfx was also faster than the Compaq 386/33. The full NSTL test reports are available on request. Apple, the Apple logo, A/UX and Macintosh are registered trademarks, and "The power to be your best" is a

03 of the latter.



*The only meaningful way to measure the power of any computer is by the performance of the people who use it. But just for the record, the IIfx blew the windows off the hottest 486 PC in overall performance tests.**

work in the same consistent, intuitive way. So you don't have to wait years for someone to write software for it. Or waste months figuring out how it works.

Still, the beauty of owning *any* Macintosh is how easily you can take advantage of the latest Apple ideas.

You can appreciate the new Apple® 24-bit color card without knowing anything of its 5 innovations. Just pop it into any modular Macintosh and you'll have the ability, in any program, to work with as many as 16.8 million colors (roughly 16,776,960 more than you'll see on any other personal computer).

Apple's new graphics accelerator card features a total of 13 innovations. But one glance at a Macintosh screen tells you all you need to know. It's incredibly fast. Even when redrawing the most complex CAD graphics.

Our latest version of the UNIX® operating system—A/UX® 2.0—represents 32 innovations from Apple. And hundreds of new choices for you. Because it not only makes the notoriously complex UNIX easier to use. It also lets you run UNIX programs, UNIX X Window System programs and off-the-shelf Macintosh personal productivity software *at the same time.*

The IIfx runs thousands of Macintosh business and education programs. So you can apply all its power to solving the problems you have today.

Of course, the ultimate test of any innovation comes when you actually get your hands on it. Something your authorized Apple reseller will gladly arrange.

Then you'll know why Macintosh has the power to change the way you think about computers.

The power you buy a computer for in the first place.

The power to be your best.™

sure its power by your results.

The power to be your best, no matter what you do best.

From the most affordable Macintosh Plus to the awesome new Macintosh IIfx, Macintosh gives you more power to do more things more easily than any other personal computer system in the world. The only question is, how much power do you want?

What a wonderful time to be a human being.

First, they tear down the Berlin Wall.

Then, Macintosh® becomes one of the most powerful personal computer systems in the whole world.

What a great way to start a decade. Humanity is in vogue. *Glasnost* is in the papers. And the computer for the rest of us has become the computer for all of us.

Scientists, engineers, teachers and students. CFOs, CEOs and CPAs. The sales force and the secretarial pool.

Anywhere you find people who prefer actually getting things done instead of figuring out rigid, intimidating computers. Which is to say, almost everywhere.

Why, even other personal computer companies are finally starting to see things our way.

But just as you can't expect the KGB to start picking up Nobel Peace Prizes, you can't expect any other computer to work like a Macintosh.

Only a Macintosh lets you learn the basics of thousands of different programs simply by learning one. So you spend a lot more time actually using your computer. And a lot less time figuring it out.

Only a Macintosh offers a whole family of computers that all run the same software with the same point-and-click simplicity. So you can buy any Macintosh today, and you won't have to buy new software if you want to move up to a more powerful Macintosh tomorrow.

Only a Macintosh gives you so much power to do so many things so quickly and so easily.

Of course, just as different economic systems can work together to the benefit of both, so too can Macintosh work with the computer systems you have now: IBM mainframes, Digital VAX computers, token-ring networks, other personal computers, you name it.

And with any Macintosh equipped with an Apple® SuperDrive™ disk drive, you can even move information between a Macintosh and an MS-DOS, OS/2 or Apple II computer on a standard 3½-inch floppy disk.

Of course, the best way to understand the power of Macintosh is to sit down and use one.

Then you'll know why Macintosh has the power to change the way you think about computers.

The power everyone in the world can appreciate.

The power to be your best.™

LETTERS

To the Editors:

"Strategies for Manufacturing," by Robert A. Frosch and Nicholas E. Gallopoulos, in your special issue on "Managing Planet Earth" [SCIENTIFIC AMERICAN, September, 1989] was generally well done. Unfortunately, the authors did not probe deeply enough before arriving at their conclusions about polyvinyl chloride (PVC, or vinyl).

The first problem, they say, is that incinerators must have scrubbers to prevent emissions of hydrochloric acid if vinyl is burned. This is true, but it is not an issue. The application of acid-gas scrubbing to municipal solid-waste incinerators is now a proved air pollution concept. Dry and semidry lime scrubbing systems are required on all new municipal incinerators; moreover, lime injection will probably be required for retrofitting of existing combustors when the Environmental Protection Agency proposes new air requirements.

The second problem cited by the authors is that improperly designed and operated incinerators may emit significant quantities of both hydrochloric acid and dioxins. It is alleged that vinyl waste is the source of these emissions. In fact, research has shown otherwise. Recent tests by the New York State Energy Research and Development Authority demonstrated that the addition of PVC to predominantly wood and paper garbage burned in a municipal incinerator had no statistically significant effect on the emission levels of dioxins. This should not be surprising, considering that 50 to 70 percent of the chlorine found in the waste stream can be traced to sources other than vinyl, including paper, table salt, wood and vegetable matter. Given the virtual impossibility of separating out these chlorine sources, our environmental focus will have to be on improving incinerator operations.

It is an exaggeration to call vinyl a "worst-case example of the problems plastics pose." The truth is that most of the problems attributed to vinyl are not valid. Progress is being made on a number of fronts, including source separation and recycling of plastics and the manufacture of products made from commingled plastics. Giving support to suggestions that society should ban or restrict a useful, recyclable material like vinyl because some uninformed people are "not convinced" of its safety can hardly be the best way to achieve an industrial ecosystem.

CHARLES N. BUSH

Vice President,
Research and Development
The BFGoodrich Company
Geon Vinyl Division
Cleveland, Ohio

To the Editors:

Robert Frosch and Nicholas Gallopoulos claim that plastic containers are safer than the glass containers they replace. This may be true in a few cases, but it is definitely not true when the plastic is PVC. All containers made of PVC contain plasticizers and other additives that are toxic or carcinogenic, or both, and that have an unpleasant tendency to leach into the contents of the container. The health hazards posed by this were completely ignored in the article.

The plasticizer most commonly used in West Germany, di(2-ethylhexyl)phthalate (DEHP), is suspected of causing cancer, gastritis, changes in blood count, menstrual difficulties and an increased probability of miscarriage. As early as 1976 the *Journal of Laboratory and Clinical Medicine* reported that patients on dialysis took up as much as 150 milligrams of DEHP during a five-hour treatment with an artificial kidney that used PVC tubing. The U.S. Food and Drug Administration has been somewhat negligent in not investigating this possibility and taking appropriate action. Under the circumstances, I prefer to buy all of my food and cooking products in nontoxic glass containers.

EDITH BORIE

Institut für Technische Physik
Karlsruhe, West Germany

The authors respond:

The letters by Dr. Bush and by Dr. Borie perfectly frame the dilemma faced by those working in or writing about the environment and pollution. Bush complains that we were too harsh on PVC, and Borie chides us for being too lenient. If opinions and attitudes in environmental matters were not of such great importance, we could be flippant and claim that these two polarized views prove we struck the perfect middle course. Such a facile response, however, would not serve the cause of solving environmental problems rationally.

Bush discusses the use of scrubbers, and he concludes that PVC incineration poses no problems. We do not disagree; indeed, we stated the same facts in our article. We mentioned that regulators and environmentalists are not convinced that this is the case, but in reporting their opinion, we neither endorsed nor disapproved of it. Bush also takes us to task for calling PVC a "worst-case example." We see nothing in his argument to cause us to change this label for PVC. The chlorine in PVC makes the plastic more difficult to cope with than others such as polyethylene or polypropylene. We do not believe, however, PVC should be singled out for banishment or any such drastic measures. Indeed, by illustrating that PVC problems can yield to technological solutions, we had hoped to make it apparent that plastics in general have gotten a bad rap.

We agree with Borie that, for completeness, we should have discussed the risks posed by plasticizers in PVC. Nevertheless, we believe any regulation of the additive content of PVC containers should be based on sound scientific evidence of the health effects of these materials and on a proper evaluation of both the magnitude of the exposure and the relative risks associated with that exposure.

The exclusive use of glass for beverage and other product containers should be based not solely on whether glass is nontoxic but on an examination of the health and environmental effects stemming from all aspects of container manufacture and use. Making containers from glass consumes 20 times as much raw material, twice as much energy and 3.5 times as much water as making them from PVC. It also produces 18 times as much solid waste and twice the quantity of atmospheric emissions. The societal costs of lacerations and other serious injuries caused by broken glass containers should also be included in the accounting. In short, the ecosystems approach we advocate should be applied to make decisions that truly and comprehensively protect human health and the environment.

ROBERT A. FROSCH

NICHOLAS E. GALLOPOULOS

General Motors Research Laboratories
Warren, Mich.

We and our authors thank you for sharing your thoughts with us—and for your forbearance. The sheer number of letters that we receive makes it impossible for us to answer more than a fraction of them.

Everything You Need to Know About Scotch, in 30 Seconds

If all you can spare is half a minute, here's all you need to know about Scotch. You have to acquire a taste for the smooth, smoky, peaty flavor. To do so, there's no better way than to acquaint yourself with a bottle of Ballantine's Finest.

That ought to do it.

Ballantine's

THE TRUE TASTE OF SCOTCH.

Ballantine's Blended Scotch Whisky 43% Alc./Vol. (86 proof). © 1989 Maidstone Wine & Spirits Inc., Los Angeles, CA

Everything You Need to Know About Scotch, in 15 Minutes

Should you have a bit more time on your hands, taste a Scotch worth savoring. Ballantine's Finest. First, pour yourself a glass. Then relax.

Settle into that easy chair. After all, it takes time to appreciate a good Scotch. Let the ice cubes melt a little. That will easily take five minutes.

While you're waiting, consider that Ballantine's is a smooth blend of not four, not twenty, but 42 of the finest single malt Scotch whiskies. Each chosen for its unique contribution to the overall flavor. A clue, perhaps, to Ballantine's number one rank in Europe. Okay. Take a sip.

Taste the Highland smoke? Taste the flowery heather? Taste the earthy peat? Taste the salty sea air? Mmmmmmmmm. That's what you should taste in fine Scotch.

Thank you for such generous use of your time.

Ballantine's

THE TRUE TASTE OF SCOTCH.

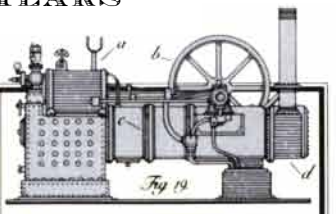
Everything You Need to Know About Scotch, in 17 Years

It rains a lot in Scotland. Always has. How much? Let's just say you'll never hit a sprinkler head on a Scottish golf course. The Highlands alone get more than twice the rainfall of Seattle. Even more than the Amazon River territory.

Faced with such unaccustomed natural abundance the Scots came up with lots of things to do with water. They developed hydro power long before the industrial revolution. They boiled it to power steam engines. And they used it for transportation, building canals as early as 1761.

But, chiefly, the Scots dedicate their water to a more noble purpose. They use it to make Scotch whisky.

Of course it also takes peat, barley and yeast to complete the recipe, but Scotch is, after all, a liquid, and the water makes a big difference. Especially in a complex blend like Ballantine's Finest. Some water runs from granite highlands down through peaty bogs, into small lakes, or *lochans*. Some runs through the peat over the granite, into streams, or *burns*. It makes a difference, too, because Scotch made with one water has a flavor very distinct from Scotch made with another. Which is why Ballantine's has always blended different Scotches together.



Was the man who invented the steam engine inspired by a whisky still?

For smooth, mellow, yet full-bodied flavor every time, we blend mature single malts from each of the Scottish whisky regions. Some are created by our eight affiliated distilleries. Others are famous names, purchased directly from the source. (However, we bow to their desire to remain anonymous.)

In all, we use forty-two single malts to create our Finest and 12 year old blends. In the case of our noble 12 year old, none is younger than 12 years, although some are much older. And our rare 17 year old marries an exclusive selection of more mature spirits into a sophisticated, heady blend for the discriminating Scotch drinker. For special occasions, try Ballantine's legendary 30 year old. Only 200 cases a year find their way to the United States. That's even fewer than the number of Rolls Royces imported each year. *We welcome all correspondence.*

Balblair. A noble contributor to the blend.

MATURED 17 IN OAK

Now you may well think that waiting 12 or 17 years for a Scotch is a bit excessive. And 30 years may indeed be daft. But time is on our side. We've nothing better to do. Besides, it's raining outside.

Ballantine's

THE TRUE TASTE OF SCOTCH

Write to: Ballantine's P.O. Box 8925 Universal City, CA 91608.

50 AND 100 YEARS AGO

MAY, 1940: "Just about a year ago, two German physicists who had been gunning at the metal uranium with neutron bullets suddenly found that they had caused the biggest explosion in atomic history. The new phenomenon was called 'nuclear fission.' Besides the two main fragments, a few spare neutrons were thrown off from the original nucleus. Early last summer a chilly sensation began tingling up and down the spines of the experimenters. Wasn't there a dangerous possibility that the uranium would at last become explosive? Now, a year after the original discovery, word comes from Paris that we don't have to worry—at least, probably not. Scientists there have found that, instead of building up to a grand climax, the uranium-fission chain reaction runs down and stops like an unwound clock."

"The discovery of a royal ship burial at Sutton Hoo is an event overshadowing in romantic interest all other discoveries in that part of England. When Roman power began to wane, enemy raiders started to invade Britain. The Anglo-Saxons were followed by the Vikings, who burned and raped and pillaged to their hearts' content up and down the whole length of Britain's Eastern seaboard. All these people were sea-rovers, and when their great men died they were buried in the ships which had carried them on their voyages in this world. At Sutton Hoo was a massive gold buckle, nothing less than a masterpiece of Anglo-Saxon interlacing design. In addition, the grave contained many silver objects for use in the celestial feasts: a great Byzantine dish, made in Constantinople in the time of the Emperor Anastasius, and nine nested silver bowls, with the same number of drinking horns mounted in silver. Thus, the dead King was to be enabled to entertain in the world of the shadows."

"Illness is industry's biggest bill! In the heavy industries, employing some 15 million persons, the average male worker loses about eight days a year because of sickness. Weary workmen are easy marks for illness and accidental injuries. One Pennsylvania manufacturer instituted two 15-minute rest periods, one in the morning and one in the afternoon. Although this shortened the work day by half an hour, production jumped by 20 percent."

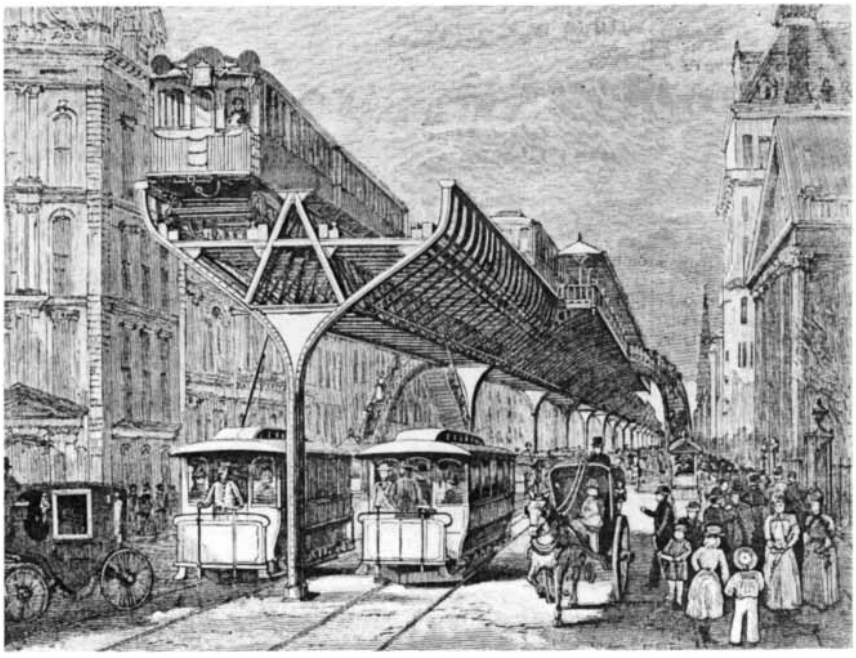
SCIENTIFIC AMERICAN

MAY, 1890: "A new and very simple method of synthesizing indigo has been discovered by Dr. Flimm, of Darmstadt. In studying the action of caustic alkalies upon the monobromine derivative of acetanilid, a solid melting at 131.5°, it was found that when this substance was fused with caustic potash, a product was obtained which at once gave an indigo blue color on the addition of water, and quite a considerable quantity of a blue solid resembling indigo separated out. That this blue substance was really common indigo was proved by the fact that it yielded several of the most characteristic reactions of indigotin, such as solubility in aniline, paraffin, and chloroform; its sublimation; and the formation of sulphonic acids, which gave similar changes of color with nitric acid to those of indigotin."

"A loan association in this city recently invited a number of persons to hear a speech by the celebrated English statesman Mr. Gladstone. A phonographic cylinder was produced, stated to have been just received from London, and when the cylinder was put through the phonograph machine a voice was heard, said to be Mr. Gladstone's. The message was short and rather dry. It related to self-help and thrift, both of which are very desirable qualities, according to Mr. Gladstone."

"In all city streets where there are two surface railway tracks there is a space between them of little use except for direct crossing. To utilize this space is the object of the elevated railway illustrated here. Taken in combination with street tracks below, it practically solves the question of rapid transit. The upper cars move at high speed, make few stops, and carry passengers quickly to long distances. The lower cars move more slowly, stop often, and take local travel chiefly. Single columns, placed between the surface tracks at distances of about 80 feet apart, carry triangular girders, to whose sides are riveted brackets, carrying the tracks, which are made purposely without cross ties and very open, so as to obstruct light and air as little as possible."

"The use of coke, coke dust, or graphite from gas retorts in the manufacture of refractory bricks for lining iron furnaces seems like a contradiction of nature; but an industry in the manufacture of such bricks is actually established, and is growing. Hitherto nothing has been found capable of withstanding the corrosive action of blast furnace slag, which is alternately acidic and basic, and carries away the lining of the hearths of the furnaces as though it possessed no resistance."



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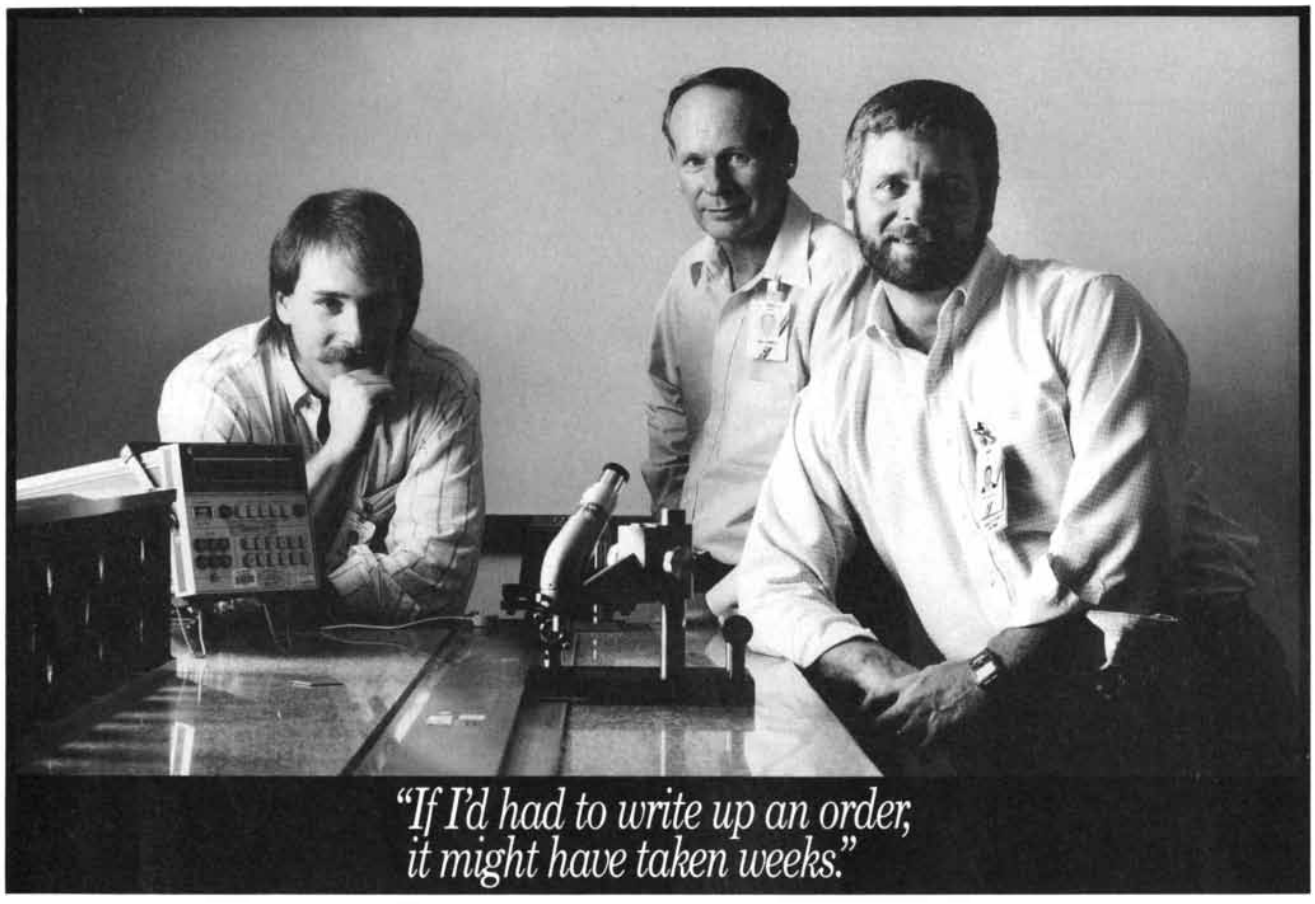

"The job in metrology is testing the accuracy of the instruments and precision tools used throughout the plant. And I had a measuring tool—a laser and microscope—that wasn't lining up right. It rode on an aluminum surface which was wearing and not as stable as I'd like.

"We were working together so I just naturally talked about this to Ted and he said he could cure it. He designed an aluminum holding device that didn't rock, and even added a few new design characteristics, like a window to see the measuring scale.

"If I'd had to write up an order and send it out, it might have taken weeks. This way we saved time and money.

"We have so many talents and capabilities here. Working as a team we can utilize them." *—Roy Enmen, (center) Transport Aircraft Technician and Kevin Machnics, (left) Quality Engineer, Metrology Laboratory; Ted Whitney, (right) Programmer, Numerical Control Programming Department (formerly Tool and Cutter Grinder).*

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SCIENCE AND THE CITIZEN

Second Opinion

The heat is on Gallo—again

Like Lady Macbeth's damned spot, the controversy surrounding the discovery of the AIDS virus refuses to fade. Three years ago the principals in the dispute, Robert C. Gallo of the National Cancer Institute and Luc Montagnier of the Pasteur Institute, seemed to have settled their differences. Now the National Institutes of Health—barely a step ahead of Congressman John D. Dingell—has decided to investigate the role of Gallo's laboratory in the identification of the AIDS virus and the development of a blood test based on it. The clamor has strained the reconciliation between Gallo and Montagnier.

The NIH describes the inquiry as a fact-finding exercise to determine whether there is evidence of misconduct in Gallo's laboratory sufficient to justify a full investigation. The inquiry will be overseen by an independent panel, chosen from a list of names suggested by the National Academy of Sciences and the Institute of Medicine.

What made the wheels of a government investigation creak into action now, when the affair appeared to have been consigned to the history books? It is almost five years since the French government sued the U.S. for breach of contract, accusing it of having used a sample of the AIDS virus supplied by Montagnier to make the U.S. blood test. And it is more than three years since President Ronald Reagan and French Prime Minister Jacques-René Chirac announced that the U.S. and France were dropping their legal disputes, agreeing that both sides had played an equal role in the discovery of the AIDS virus. Gallo and Montagnier then published a joint chronology of their AIDS work, as well as an article in the pages of this magazine [see "AIDS in 1988," by Robert C. Gallo and Luc Montagnier; SCIENTIFIC AMERICAN, October, 1988]. Their public reconciliation was seen by many as guaranteeing for both an invitation to some future Nobel ceremony in Stockholm.

The proximate cause of the NIH's decision to probe the affair is a 50,000-word story in the *Chicago Tribune* by John Crewdson, a national correspondent for the paper. Since the piece appeared last November, Crewdson has followed up with two more stories. He bases his reportage on interviews with sources close to the controversy as well as on 5,000 pages of government documents obtained under the Freedom of Information Act.

Crewdson begins with the established facts. In May, 1983, Montagnier and his colleagues published the first paper describing the AIDS virus, which they named LAV. In April, 1984, Gallo announced that he had both identified a virus that causes AIDS and developed a blood test to detect it. Gallo, who called his virus HTLV-III, published a brace of papers in *Science* the following month that backed up his claim.

Between Montagnier's 1983 paper and Gallo's 1984 announcement—specifically, in September of 1983—Montagnier sent Gallo a viable sample of LAV. Analysis now shows that LAV and HTLV-IIIb, the virus Gallo used in the U.S. blood test, are surprisingly alike for such a variable virus. Crewdson's article suggests Gallo did not characterize the AIDS virus until after he received Montagnier's LAV sample. Crewdson concludes there is "compelling" evidence that what happened in Gallo's laboratory "was either an accident or theft." Montagnier has publicly urged Gallo to acknowledge that contamination by LAV was the source of HTLV-IIIb.

Crewdson's account quickly came to the attention of Dingell, chairman of a House oversight and investigations subcommittee. In December he wrote to William J. Raub, acting director of the NIH, asking what he knew of Crewdson's charges. Raub replied that an inquiry was under way and that inaccuracies or misleading statements had been found in Crewdson's article. Dingell demanded a more specific reply, so Raub outlined 14 areas into which the NIH will inquire.

The NIH inquiry may also reflect a desire to keep its affairs out of Dingell's hands. Dingell wields powerful influence over the NIH budget, and his subcommittee is looking into alleged purchasing irregularities by a member of Gallo's staff. Scientists and NIH officials regard with alarm the prospect that Dingell may breach their walls as he did last year, when he investigated charges that the NIH whitewashed allegations of misconduct by Nobel laureate David Baltimore. The prospect of Gallo on the witness stand may have spurred a preemptive strike. The expert panel seems intended to avoid any future allegations of a whitewash.

Among the matters the NIH inquiry will address are:

- The number of AIDS-virus isolates that were made in Gallo's laboratory, and when. Gallo has detailed four isolates of the AIDS virus that predate his receipt of the LAV sample in September, 1983. But Crewdson's November article alleges inconsistencies between Gallo's laboratory notebooks and his published identification of patients used as sources of the virus.
- The cell line that Gallo used to produce HTLV-IIIb. Crewdson's account suggests one precursor cell line had been used earlier to grow LAV.
- The origin of the pool of virus sources that led to HTLV-IIIb. Crewdson says it originated in a pool created in November, 1983, a month after Gallo was growing the LAV sample from Montagnier.
- Comparison of talks given by Gallo and the published papers derived from them. According to Crewdson, in September, 1983, and February, 1984, Gallo attended meetings at which Montagnier and his colleagues reported dramatic progress in their work with LAV. Gallo spoke but did not mention HTLV-III. Yet in the proceedings of each meeting, Gallo described his isolation of HTLV-III.
- Work in Gallo's laboratory with LAV. Crewdson describes laboratory records that suggest a colleague of Gallo's did various experiments with cultures derived from the French virus. In an article published two months ago, Crewdson writes that in September, 1985, Peter J. Fischinger, then associate director of the cancer institute, questioned Gallo and his associates about their work with LAV. But according to Crewdson, Fischinger's report failed to disclose that LAV

and HTLV-III were known to share similar variant forms—strong evidence of shared origin.

• The deletion from a letter (released by the U.S. to lawyers representing the Pasteur Institute) of references to electron micrographs of LAV taken by Gallo's associates.

• Electron micrographs. Crewdson thinks that he has cast new light on Gallo's admission that micrographs of the AIDS virus he published in his 1984 papers in *Science* were actually photographs of Montagnier's LAV. Gallo ascribes the slip to a technician's error, but Crewdson charges that Gallo had no other picture he could use.

Gallo stoutly defends his honesty. He says he himself asked for an independent panel to oversee the NIH inquiry. Moreover, he maintains that Crewdson distorts the facts. Gallo insists that he had 20 identifications of the AIDS virus by September, 1983. By the following April, he says, he had more than 10 isolates in continuous cell culture.

Gallo dismisses the discrepancies between talks he gave and the published papers, saying he always extemporizes and that updating reports is normal. He says he used HTLV-IIIb for his AIDS test because it produced more virus than did other strains he had isolated. And he explains that many of his laboratory records that refer to LAV were made by a scientist who used the designation to include viruses that had similarities to LAV.

Could Gallo's HTLV-IIIb possibly represent some contamination of an experiment by Montagnier's LAV? Gallo acknowledges that as "a significant possibility." Montagnier offers a wry rejoinder: "Well, in that case we almost agree." Such convergence may foreshadow the NIH's findings, but it is not likely to shorten the road to Stockholm. —*Tim Beardsley*

Open Skies

An old proposal for legal spying gains new life

Back in 1955 President Dwight D. Eisenhower offered to let Soviet spy planes fly freely over the U.S.—if the Soviets would reciprocate. This "Open Skies" policy, Eisenhower argued, would help allay suspicions about military intentions and thereby promote the security of both nations. The U.S.S.R. spurned the offer, claiming the Americans only wanted to find and exploit its soft spots.

Times, obviously, have changed. When President Bush resurrected the Open Skies proposal a year ago, Soviet President Mikhail S. Gorbachev publicly welcomed it. In February representatives of the North Atlantic Treaty Organization (NATO) and the Warsaw Pact met in Ottawa for formal negotiations. In the final communiqué, they stated their commitment to achieving a pact at a follow-up meeting to be held in Budapest in late April.

But some fears die hard: the Soviet military is still resisting a treaty on U.S. terms. "There will be a treaty," says Michael Krepon of the Henry L. Stimson Center in Washington, D.C. "The only question is how serious, or transparent, it will be."

The U.S. favors the most unrestricted approach. It maintains that each country should operate and supply its own planes and that all sensors except those capable of eavesdropping on electronic communications be permitted. In addition to high-resolution optical cameras, sensors would include infrared cameras, which can see at night, synthetic-aperture radar, which can peer through clouds, and air-sampling devices, which can monitor environmental agreements as well as pacts related to chemical, biological and nuclear weapons.

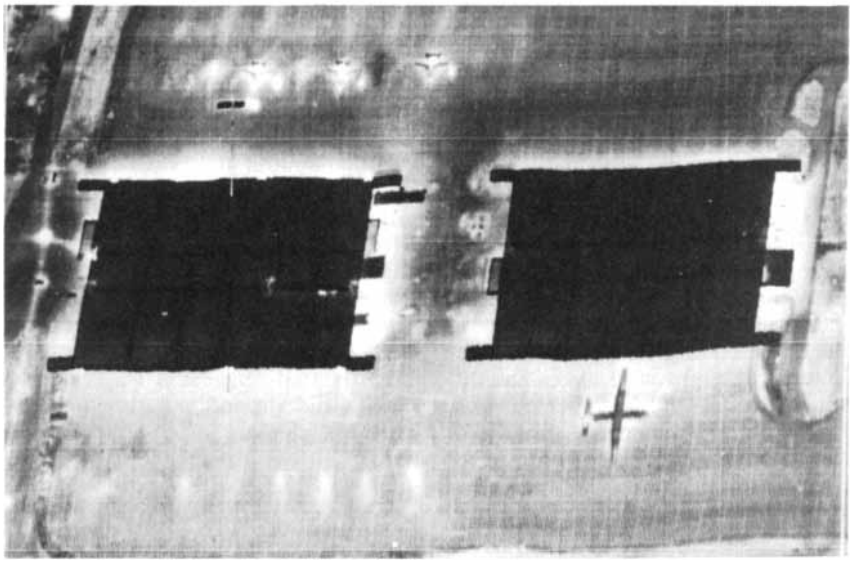
The U.S. says it would submit to one overflight a week by Warsaw Pact planes and argues that the U.S.S.R., because it is much larger, should accept roughly twice as many overflights by NATO. Flights over military bases and other "sensitive" areas would be restricted only for reasons of safety (for example, during a missile test). "Our position is that the more everyone knows, the more comfortable everyone will feel," notes Jonathan B. Tucker of the U.S. Department of State.

Some Soviet officials, though, still think *glasnost* has its limits. At the Ottawa conference, they accused the U.S. of trying to take advantage of its superiority in sensing technology. They proposed that overflights be performed by planes drawn from a common fleet and equipped with only visible-light sensors. All data would feed into a common pool to which all parties to the treaty would have access, so that each country would know what every other country knew.

The Soviets also advocated limiting the number of flights over the Warsaw Pact nations to 30 a year, with a separate limit of 15 flights over the U.S.S.R. itself. They argued that flights over chemical or nuclear plants should be done at altitudes of 10,000 meters or greater and that some military installations be permanently off-limits.

Noting that the other Warsaw Pact countries seemed to favor fewer restrictions, John E. Barrett, an analyst in Canada's Department of External Affairs and International Trade, expressed hope that the U.S.S.R. would

The Soviets want only visible-light sensors allowed on overflights—but the U.S. disagrees



AIRFIELD in Canada was photographed at night with an infrared camera. The image (by Intera Kenting Ltd.) reveals a buried steam line **(far left)** ***and spots where planes warmed the tarmac before being moved*** **(top and bottom left).**

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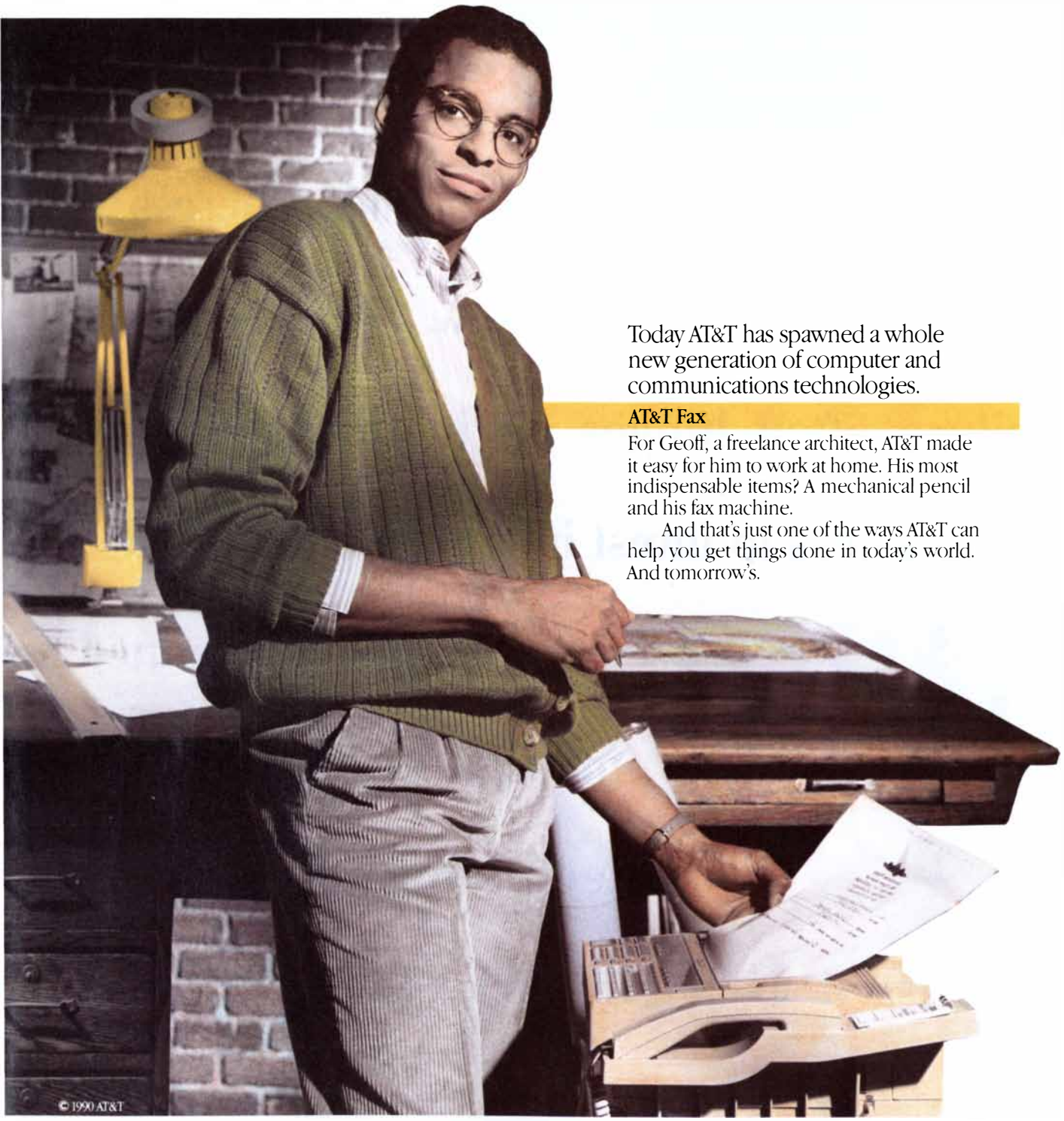

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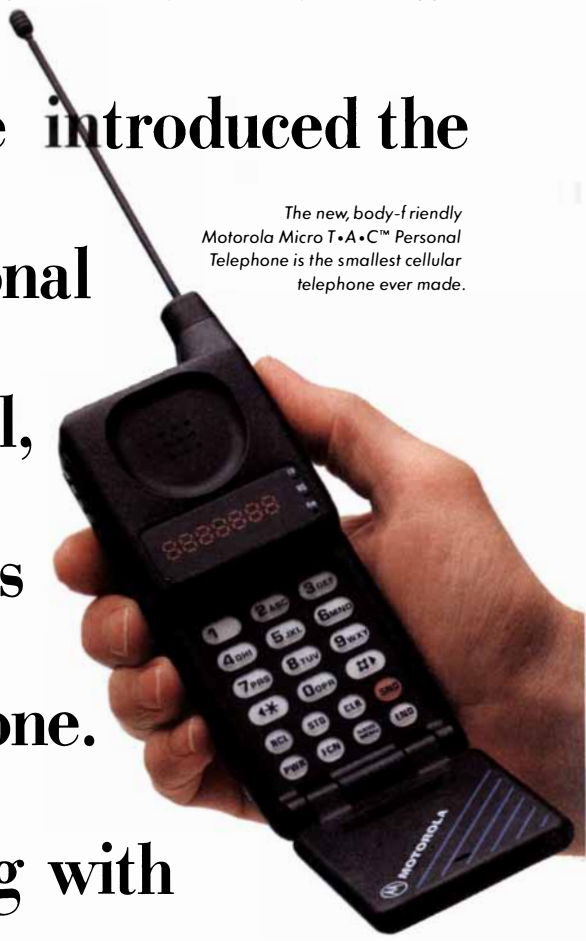

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soften its stance at the April meeting in Budapest. The Soviet statements at Ottawa, he says, seemed to reflect the attitudes of the military bureaucracy, which has not fully accepted the more liberal views of the civilian leaders. "It's like an ocean liner," he says. "It takes time to turn."

The U.S. might also compromise a bit, according to some Canadian officials, both by limiting the capability of its sensors and by allowing Warsaw Pact nations to buy more sophisticated Western-made sensing equipment. Other NATO members favor relaxing restrictions on exports to the Eastern bloc, but the U.S. has not yet committed itself to such a step.

Some other questions will remain unresolved for now. Will Greece and Turkey, which are both NATO members but also age-old enemies, ever agree to mutual overflights? As the Warsaw Pact continues to disintegrate, will its members want to overfly each other? And who will overfly a reunited Germany? (Probably everyone will want to, according to one official.)

Krepon hopes the initial Open Skies agreement will expand to accommodate all these possibilities—and more. "It's very hard to demonize a country when you can roam its airspace," he says. The great advantage of the Open Skies concept, he notes, is that any country that can afford a plane and cameras can participate. "This represents a way that a lot of people can get involved in arms-control verification, not just the big boys." —*John Horgan*

PHYSICAL SCIENCES

Can't Get There from Here

Quantum physics puts a new twist on Zeno's paradox

Two thousand years ago the Greek philosopher Zeno noted that an object moving from one place to another must first reach a halfway point, and before that a point half of the way to the halfway point, and so on. Any movement involves an infinite number of intermediate points, and so any motion must require an infinite amount of time. Motion, Zeno concluded, is logically impossible.

In fact, things do move. Zeno did not consider that an endless series could have a finite sum. But in the counterintuitive realm of quantum physics, something akin to Zeno's paradox can occur: atoms can be paralyzed if they are closely scrutinized. The act of observing prevents the atom from passing a halfway point between two energy levels.

In 1977 E. C. George Sudarshan and Baidyanath Misra of the University of Texas at Austin realized that an unstable object, such as a radioactive atom, would never decay if it were observed continuously. They called this surprising phenomenon the quantum Zeno effect. Now Wayne M. Itano and his colleagues at the National Institute of Standards and Technology (NIST) have observed a variant of this effect in the real world. Their work will appear in *Physical Review A*.

The reason for the Zeno effect lies at the heart of quantum physics, which states that the energy of an atom moving between two energy states is somewhat uncertain and that (for short intervals) the uncertainty grows over time. For an atom to shift from one state to the other, the uncertainty must be large enough to bridge the two. A measurement that determines the atom's energy "collapses" the atom to the measured state. Afterward the uncertainty grows again, but it should be possible to "freeze" an atom in one energy state by taking measurements so frequently that its energy never becomes uncertain enough to let it jump to another state.

To observe the Zeno effect, the NIST team confined 5,000 beryllium ions in an electromagnetic trap and exposed them for 256 milliseconds to a radio frequency that bumps beryllium ions to a higher, excited energy state. During the test they fired short, 2.4-millisecond laser pulses at the ions to determine their energy state. Ions in the bottom state scattered the light pulse back; those in the excited state did not. Each measurement pulse returned a scatter proportional to the number of ions still in the bottom energy state.

When a single measurement pulse was sent at the end of the test, nearly all the ions were found to be in the higher state, as one might expect. More frequent laser pulses caused the number of ions in the higher energy state to decrease. When 64 pulses—the largest number used—were sent, essentially none of the atoms was able to jump to the higher level. The measurement pulses occurred so often that there was no time for each ion's uncertainty to become large enough to permit it to reach the upper level.

The NIST experiment sheds some interesting light on the question of the role of the observer in a system like this. The scattered laser light, used to

determine the energy states of the atoms, was observed after the end of the 256-millisecond test period. The energy states of the ions, however, collapsed when hit by the pulses during the test period, before the return scatters were actually observed.

Despite the apparent link between the viewer and the behavior of the ions, it was the act of measurement—not the act of observing the measurement—that immobilized the ions. Even so, the experiment may strengthen the conviction of those who believe the old adage: "A watched pot never boils." —*Corey S. Powell*

Murky Water

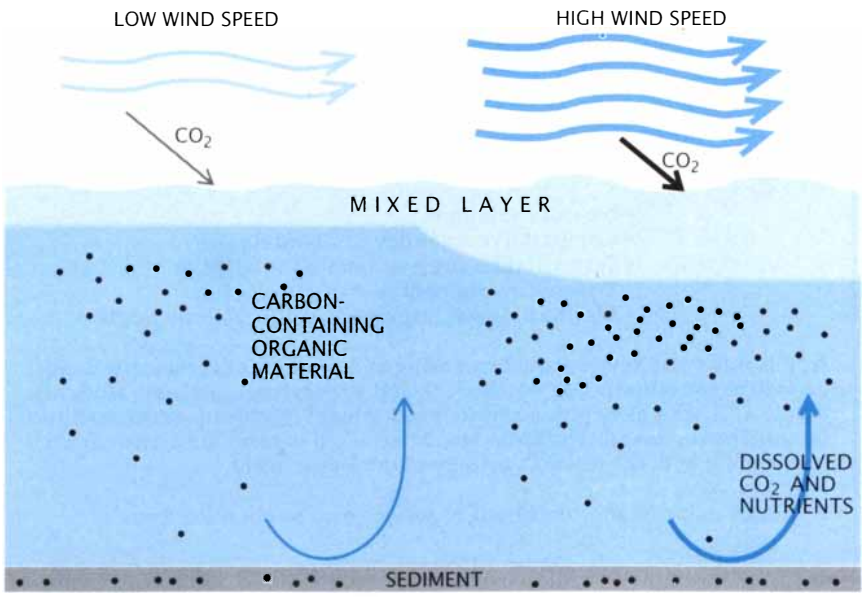
Just what role do oceans play in absorbing greenhouse gases?

Power plants, cars and burning forests emit carbon dioxide; oceans absorb it. The long-accepted wisdom on global warming is that the boundless depths covering nearly three quarters of the world's surface buffer the greenhouse effect. Climatic shifts and sea-level changes will occur—but slowly.

This picture is probably wrong. New data have led investigators to conclude that the oceans consume far less CO_2 than previously thought and thus that land-bound sinks must be consuming more. Furthermore, the ocean's capacity to absorb CO_2 and sequester it from the atmosphere now appears to depend on near-surface wind patterns, which may change as the world heats up.

Every year human activities pump about seven billion tons of carbon (in the form of carbon dioxide) into the atmosphere. Terrestrial and oceanic sinks pull four billion tons back out, leaving an annual increase of three billion. Until recently modelers believed the oceans took up two or three billion tons and that forests, grasslands and soils accounted for the rest.

Then Pieter Tans of the National Oceanic and Atmospheric Administration, Inez Fung of the National Aeronautics and Space Administration and Taro Takahashi of the Lamont-Doherty Geological Survey set out to determine from first principles just how much carbon could pass from atmosphere to ocean. Using a model of atmospheric circulation and data on the relative concentrations of CO_2 in the atmosphere and oceans, the group calculated how much gas the oceans can absorb. Absorption is greatest where CO_2-laden air meets water that con-



***WIND-DRIVEN MIXING** of ocean layers is a crucial factor in oceanic absorption of carbon dioxide, West German researchers contend. Increased mixing leads to greater plankton growth, and wind-borne particles may cause more microscopic shells and organic matter to sink and become incorporated into sediments.*

tains relatively little carbon dioxide; where CO_2 in water is high, the transfer may even go in reverse.

The results were surprising: the ocean apparently absorbs at most a billion tons of carbon, not two or three. Terrestrial sinks must be taking up significantly more carbon than was once believed, but exactly which sinks are performing such yeoman service is as yet a mystery.

Revised data on how much carbon the oceans absorb are mirrored by confusion about what happens to the carbon once it enters the ocean. In its broadest outlines the story is simple: plankton in the top layers of the ocean take up dissolved CO_2 and incorporate it into their shells or organic matter. This material falls into the deep ocean (much of it in the form of fecal pellets from fish that eat plankton or one another) where some of it is eaten, some is locked into sediments and the bulk is decomposed and dissolved. As the deep water returns to the surface at upwelling zones, it carries the dissolved nutrients and CO_2 with it. The difference between the amount of carbon falling down and the amount welling up determines how much the ocean can absorb from the atmosphere.

The details, however, are much more complicated. Plankton productivity, the downward flux of carbon-containing material, decomposition rates and sediment formation vary widely from ocean to ocean, month to month and year to year. The underlying causes of variation are not fully understood, says Eric T. Sundquist of the U.S. Geological Survey. While fossil-fuel emissions do drive some shifts, others may have little to do with human actions, he says.

One explanation for some of the variations may be the wind. Birgit Haake and Venugopalan Ittekot of the Institute for Biogeochemistry and Ocean Chemistry at the University of Hamburg contend that ocean winds can critically influence both the amount of carbonate and organic material produced by plankton and the amount that eventually ends up locked into sediments. Strong winds, the researchers say, increase the depth of the ocean's uppermost mixed layer, where plankton live, leading to increased plankton growth.

Furthermore, the stronger the wind, the greater the amount of terragenous material, such as dust or river sediment, that is mixed into the ocean. This material may provide extra nutrients, and it can bind carbonaceous matter into clumps that are more likely to reach the ocean bottom without being eaten or dissolved.

The net result: more wind equals more carbon taken out of the atmosphere (and vice versa). A set of plankton traps anchored in the Arabian Sea by a German-Indian collaboration yields supporting data. Wind speed, mixed-layer depth and falling carbonaceous debris fluctuate in step over the course of a year. In addition, it appears that more carbon-containing matter actually reaches the bottom when winds are stronger.

Haake is quick to point out that the results are preliminary and the hypothesis unproved. The theory agrees with what is known of major climatic changes—winds were half again as strong and the atmosphere dustier during the ice ages—but more evidence is needed to test it. For example, she says, analysis of sediments worldwide might show a link between dust and plankton.

Or it might not. Sundquist, for one, is unimpressed. Terragenous materials may not significantly affect the rates at which carbon-containing materials sink, he says, and current theories hold that most degradation takes place on the ocean floor, not as particles fall through the water.

Even if strong winds bring more carbon to the ocean floor, the effect on atmospheric-carbon concentrations could be negligible in the short run. Oceanic cycling of carbon dioxide takes place over 100 or even 1,000 years, says Tyler Volk of New York University. Emissions of CO_2 from the combustion of fossil fuels and deforestation could double atmospheric concentrations in decades. Oceans could bring those levels back to normal only over thousands of years, and meanwhile the identity of the land-bound sink (or sinks) soaking up much of the atmosphere's excess carbon remains unknown. *—Paul Wallich*

Go with the Grain

Tiny crystal composites produce new metals and ceramics

It takes a fine flour to make a good cake batter. Similarly, the recipe for a good metal or ceramic calls for a powder of tiny crystals. Over the past four years materials scientists in West Germany, Japan and the U.S. have perfected a process for producing crystals, virtually uniform in size, that contain only a few thousand molecules. An immense number of these crystals can be collected, heated and compressed to form a material that has grains only a few billionths of a meter, or nanometers, long. These "nanophase" materials include metals that are remarkably strong, ceramics that are unusually ductile and composites that have extraordinary structural and electrical properties. Such materials could be useful for engines, aerospace applications and electronic devices.

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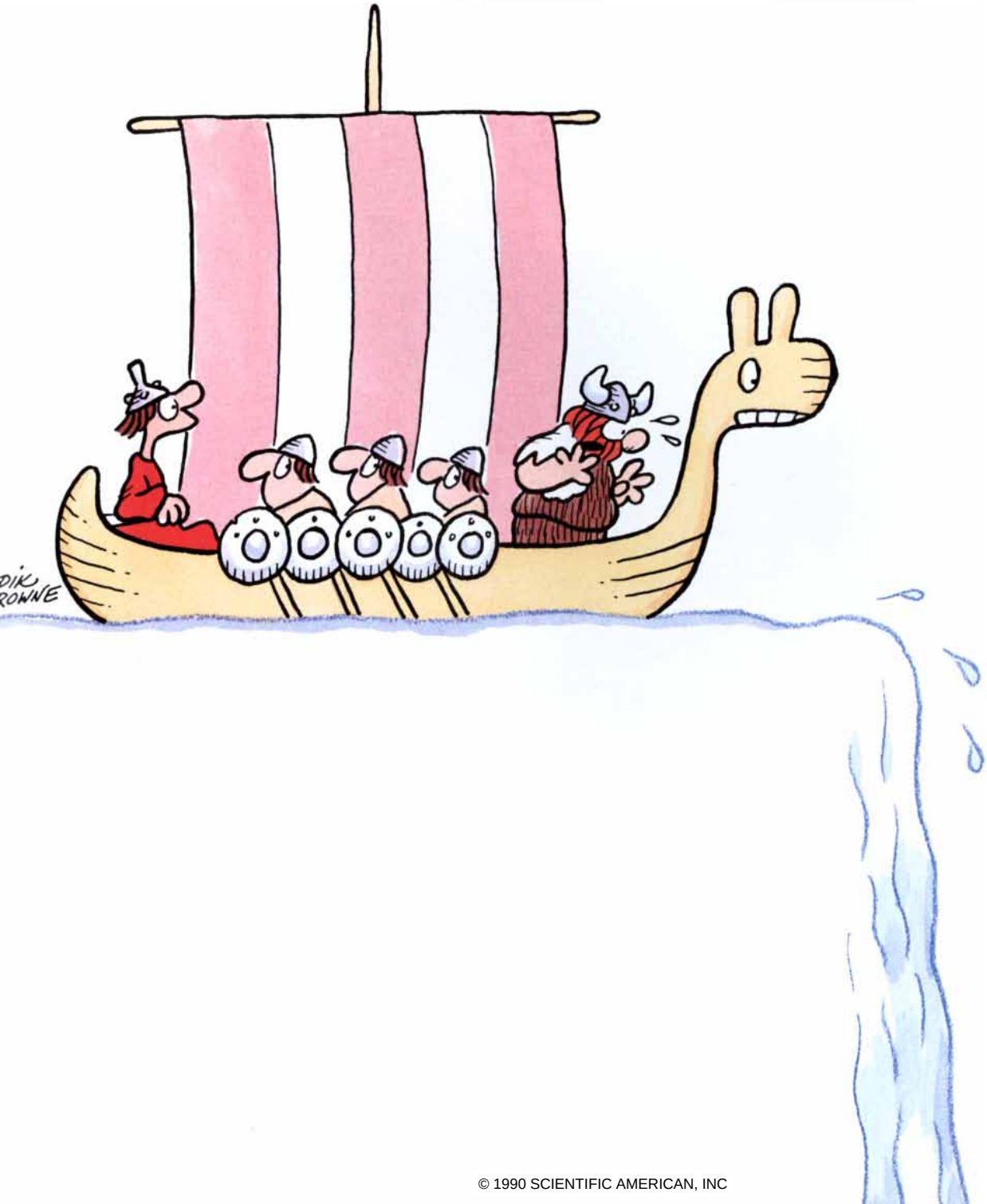

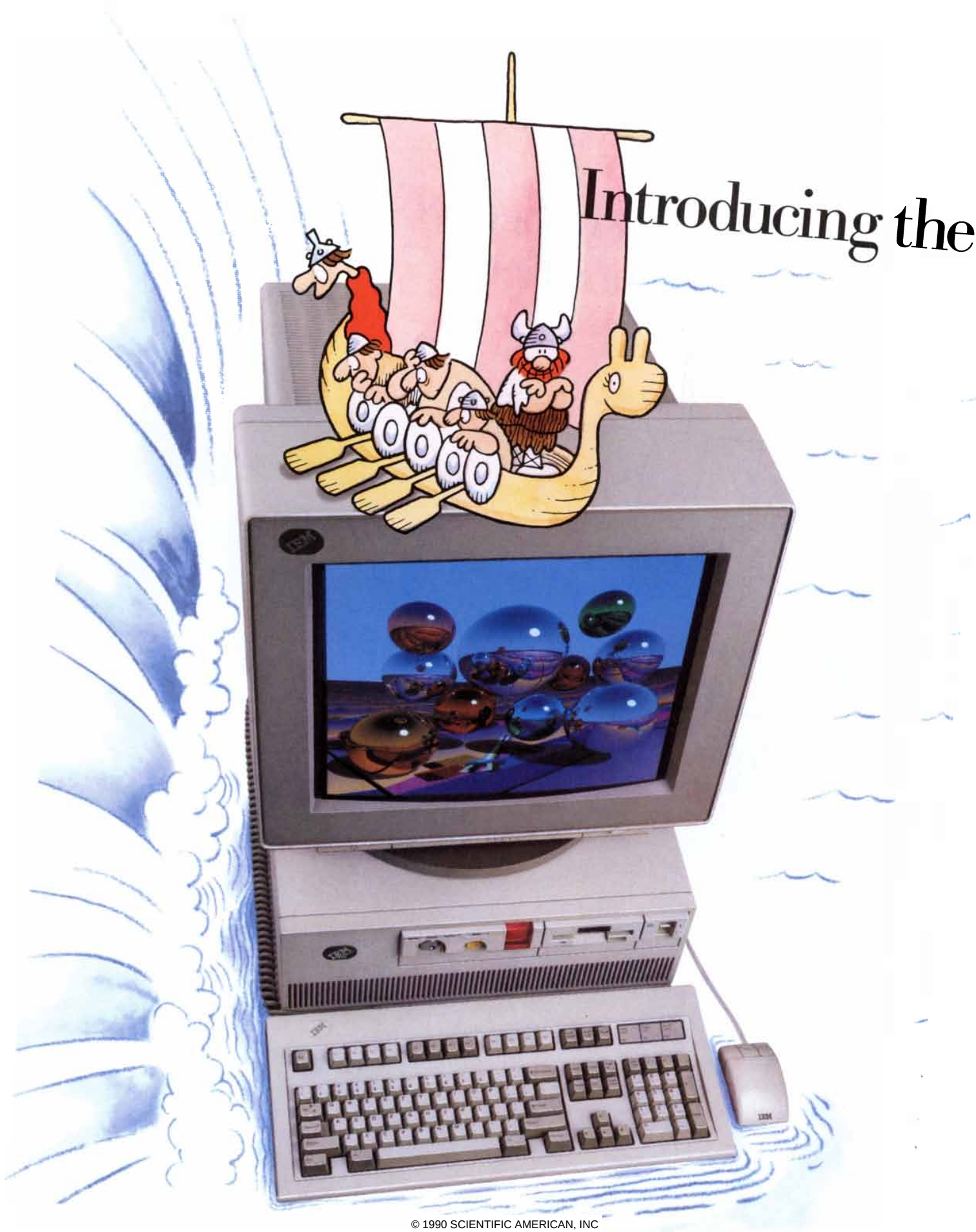

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In 1986 Herbert Gleiter and his colleagues at the University of Saarlandes in Saarbrücken, West Germany, succeeded in producing the first nanophase materials. Adapting the procedure from earlier crystal-growing techniques, they constructed a sealed chamber that contained a heater and a rod cooled by liquid nitrogen. They placed a metal sample on the heater and filled the chamber with an inert gas such as helium. They then heated the sample, which caused the metal atoms to evaporate. The metal atoms cooled in the helium gas and condensed to form a fog of metallic crystals. Convection currents carried the crystals toward the cold rod, to which the particles stuck like a fine soot. The clusters were then scraped off the rod into a container where they were compressed and sintered. To make crystals uniform in size and a few nanometers in diameter, Gleiter and his co-workers developed technologies to control precisely the pressure of the gas and the temperature of the heater.

During the past year investigators have produced crystals of superior quality for a wide range of nanophase materials. Gleiter and Richard W. Siegel of the Argonne National Laboratory have shown that many nanophase metals are three to five times harder than are conventional coarse-grained samples. They have produced nanophase ceramics that, although not as strong as conventional ceramics, are more ductile and more resistant to fractures and corrosion. The workers also hope to fashion a pliable superconducting ceramic.

Gleiter and Siegel are now attempting to exploit other unusual properties of nanophase materials. For instance, gas diffuses through nanophase materials at rates thousands of times faster than those characteristic of coarse-grained samples. Hence, a nanophase material can incorporate virtually any vapor, which, when cooled within the material, can form a new composite. Gleiter and Siegel have combined ceramics with metals, mixed conducting metals with semiconducting materials and formed unusual metallic alloys.

Siegel does not foresee technical difficulties that would prevent the production of nanophase materials on a commercial scale. He predicts that some commercial applications will be made available within a few years. Investigators have not yet determined, however, whether the techniques that produce nanophase materials will be more efficient or less expensive than conventional techniques. The nanophase techniques have at least one advantage over others, Siegel notes; most nanophase powders solidify into materials at temperatures hundreds of kelvins lower than do conventional products.

Materials scientists disagree over why nanophase materials have such extraordinary properties. Some argue that the properties can be explained by general principles of materials science: the finer the grain, the more robust the material. Others propose that the structure of nanophase materials is fundamentally different from coarse-grained materials. They point out that in conventional materials almost all of the molecules are located within a crystal, whereas most of the molecules in a nanophase material touch the boundaries between crystals. If investigators can establish a relation between the properties of nanophase materials and the molecular interactions at the grain boundaries, perhaps they will cook up an even better batter. —*Russell Ruthen*

Cool Breeze

A helium superwind for wind-tunnel experiments

Liquid helium is a fascinating and mysterious substance. The only material that does not solidify at a temperature of absolute zero, it flows with very little viscosity—and, when it is very cold, with almost no viscosity or friction at all. But what good is it?

Until recently its only practical application was as a coolant for such devices as superconducting magnets. Now investigators at the University of Oregon have suggested another use: by moving liquid helium rather than air through a wind tunnel, Russell J. Donnelly and his colleagues say, one could do in an apparatus as small as a single room experiments that now require a facility the size of a city block.

The reduction in size (and hence in cost) results from what is called dynamical similarity. According to this principle, two flow patterns that have the same geometry (such as the flow around a full-size airplane and the flow around a scale model of the plane) will in many cases cause the same relative amount of turbulence—regardless of the difference in size—as long as the flows have the same Reynolds number. This is a dimensionless number equal to the speed of the flow multiplied by some "characteristic length" of the system, multiplied by the density of the flowing fluid and divided by the fluid's viscosity. Because the viscosity of liquid helium is much lower than that of air, the characteristic length of a system under study in a liquid-helium tunnel can be 865 times shorter than the characteristic length of a similar system in an air tunnel.

According to Donnelly's calculations, a fan pushing liquid helium through a tunnel 30 centimeters in diameter could operate at one seventh of a horsepower. The fan of a more conventional cooled-air tunnel operating at similar Reynolds numbers requires 126,000 horsepower. (The cooled-air tunnel does have the advantage of being able to reproduce flows that are faster than the speed of sound; the liquid-helium tunnel could not model such flows, because liquid helium is not as compressible as air.)

In addition to reducing the scale and cost of experiments that can be done in conventional tunnels, the liquid-helium tunnel could open new lines of research by producing flows having higher Reynolds numbers than any yet studied in the laboratory. Many of the turbulent flows in nature (such as the flow of the atmospheric jet stream) have extremely high Reynolds numbers, and even such relatively simple cases as the flow of air past a sphere are poorly understood at high Reynolds numbers.

There is one further possibility. A tunnel might be filled with superfluid liquid helium, the extremely cold form that flows essentially without viscosity or friction. One of the many remarkable properties of such a tunnel would be the method by which the liquid could be pumped through the flow channel. For quantum-mechanical reasons, placing a heat source in a sample of superfluid helium causes extremely fast currents to flow in the liquid. Hence one could conceivably build a tunnel in which the fan is replaced by a simple heating coil—a wind tunnel with no moving parts. —*Ari W. Epstein*

Now You See It...

A remarkable "pulsar" was just a flash in the pan

Early last year a team at the Cerro Tololo Inter-American Observatory in Chile announced they had glimpsed the core of supernova 1987A, the nearest and most spectacular stellar explosion to occur in this century. The object was a pulsar, a whirling neutron star that flashes like

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Some astrophysicists questioned whether a star could spin that fast without flying apart, but others pushed and pulled the laws of physics to accommodate the bizarre object: at last count, about 100 papers on the pulsar had been published.

The skeptics may have been right. The Cerro Tololo team recently admitted it had made a mistake: the pulsar-like signals actually came from a television camera used to transmit images from the telescope to a monitor.

How did the error happen? The 1,968-hertz signal was observed only once, during a seven-hour period in January of 1989. To confirm that the flickering came from the supernova, the team turned the telescope toward another part of the sky. The signal ceased. When the signal also failed to appear in follow-up observations of the supernova, the astronomers concluded that debris had blocked it.

Early this year, however, the flickering signal reappeared, but this time it persisted when the telescope was turned away from the supernova. The workers eventually traced the signal to the television camera, which has a quartz timer that oscillates 1,968 times a second.

Team members recall that after their first apparent sighting, they had turned the camera off before directing the telescope away from the supernova to validate the signal. Moreover, they had left the camera off during later observations.

There is still good reason to believe that a neutron star is hiding within the supernova's envelope of expanding debris. For the past few years the supernova has dimmed as radioactive elements in the envelope decayed into stable forms. But recently its glow has been sustained; astronomers think this remaining radiation almost certainly comes from a neutron star, shining through the envelope like a light bulb in a Japanese lantern.

"We know there is something in there," says Stan Woosley of the University of California at Santa Cruz. The neutron star need not be a pulsar. Matter falling back onto the star could short-circuit the electric field that produces the pulsar's lighthouse beam, Woosley explains. Yet the accretion of the matter would still generate a powerful, distinctive signal.

Sooner or later, as the supernova's envelope dissipates, its inner core should stand revealed. John Middleditch of the Los Alamos National Laboratory, a member of the team that made the erroneous pulsar observation, says he and his colleagues still hope to make the first, true sighting. "If we're lucky, it could be any day," he says. "If we're dismally unlucky, it could take 20 years." —*J.H.*

BIOLOGICAL SCIENCES

Reach Out and Touch...

Stroking plants turns on their genes

Apart from a few oddities such as the Venus flytrap and the mimosa, most plants do not visibly react when you touch them. Don't be deceived. If recent experiments at the Stanford University Medical Center are anything to go by, plants may even respond to physical stimuli at a genetic level. Janet Braam and Ronald W. Davis have found several genes in a common laboratory plant called *Arabidopsis,* a member of the mustard family, that are turned on when the plant's leaves are gently touched. The response starts within 10 minutes after stimulation and lasts more than an hour.

The researchers did not set out to look for effects of touch on gene expression. While studying a plant hormone, they noticed that spraying *Arabidopsis* with a solution of the hormone increased the activity of some genes tenfold to a hundredfold. A control experiment showed, however, that spraying with plain water had the same effect.

The investigators, who describe their work in *Cell,* then found that simply touching the plants increased the activity of at least four genes. The genes' response to touch was detected by an increase in production of their corresponding strands of messenger RNA. Messenger RNA carries the instructions encoded in genes out of the cell nucleus, where they are used to make protein.

One of the touch-sensitive genes seems to carry the genetic code for calmodulin, a protein that binds to calcium ions. Two of the others code for something very much like it. An increase in the concentration of calcium ions in a cell often functions as a chemical signal. Braam speculates that calcium ions may be somehow involved in plants' response to touch. The same genes that were affected by spraying and by touching were also affected by wind and by cutting the plants' leaves.

Researchers have estimated that about 80 percent of plant species alter their development in some way in response to physical stimulation. Still, it is a surprise that gene expression should be so quickly affected by a touch. How a plant responds to stimulation is a "fundamental problem in plant biology," Braam says.

But—fervent gardeners note—exposing *Arabidopsis* to music had no detectable effect. And plants that were touched regularly grew slower than untouched plants. Of course, there is always prayer. —*T.M.B.*

Snail Tale

Growth strategy protects a snail from its predators

In the corporate jungle a classic defense against a takeover is to acquire another company so that the combined entity is too much to buy. The ploy seems to be used in freshwater ecosystems as well. Investigators have discovered that a common pond snail responds to predation by growing too big to be eaten.

The workers, Todd A. Crowl and Alan P. Covich, report in *Science* that they noticed how snails in populations preyed on by a common species of crayfish are bigger than normal. Yet when Crowl and Covich reared such snails in a laboratory at the University of Oklahoma, their descendants were no larger than normal snails.

How large the snails grew depended on the source of the water in which they matured. If the water came from a tank containing only snails or only crayfish—or even snails and crayfish kept apart by a mesh—the snails would stop growing at a length of about four millimeters and turn their energies to reproduction.

If the water came instead from a tank where crayfish had been allowed to eat snails, then snails would keep on growing until they reached a length of about 10 millimeters—which puts them beyond the reach of most crayfish. The strategy does exact an evolutionary cost: in order to keep on growing, the snails must delay reproduction. Snails that continued to grow did not reproduce until they were about 70 days old; normally, they begin to reproduce at 40 days.

Covich has found a similar ability to exchange early reproduction for size in a tropical snail, *Biomphalaria.* It responded most strongly when a trop-

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ical shrimp was the predator, whereas the temperate pond snail responded most strongly to the crayfish, its own natural enemy. The response would appear to be an evolved adaptation.

How do snails know when crayfish are preying on their kith? They do not grow large or delay reproduction in the presence of crushed snails, so they are not simply responding to molluscan carnage. Crowl suspects the snails are detecting the product of a chemical reaction between a constituent of crayfish and something in the snails. So far, no one has noticed an adaptive response on the part of the snails to the consumption of *escargots avec beurre noir.* —*T.M.B.*

Tainted Feed, Mad Cows

Could a British cattle disease infect U.S. herds?

Since 1986, 11,000 cattle in the U.K. have come down with a mysterious, fatal condition known as mad cow disease. The early symptoms are anxiety and increased reaction to sound and touch. Later the animals adopt a characteristic swaying or high-stepping gait and become unmanageable. Infected cattle must be destroyed.

The disease, bovine spongiform encephalopathy (BSE), is characterized by a degeneration of the brain similar to that caused by scrapie, which attacks sheep and goats. BSE resembles an encephalopathy found in Rocky Mountain elk and transmissible mink encephalopathy (TME), a disease that plagues U.S. mink farms. BSE also has disturbing similarities to human afflictions, including Creutzfeldt-Jakob disease and kuru, a disease found in New Guinea tribespeople who practiced cannibalism.

Although no cases of BSE have been reported in the U.S., researchers and some agricultural officials are worried that the disease could already have been introduced to livestock through animal products imported from Great Britain and used in cattle feed. Nobody has ever isolated a pathogen that causes BSE and related diseases, but experiments have shown that a virus-like infectious agent is almost certainly to blame. Mice fed brain tissue of cattle with BSE develop a neurodegenerative disease, and cattle inoculated with tissue of BSE-infected cows develop the disease themselves. The incubation period is always more than 2.5 years and may reach eight years.

One researcher who is concerned about the transmission of scrapielike diseases through feed is Richard F. Marsh, a veterinary scientist from the University of Wisconsin at Madison. Marsh had transmitted scrapie to mink by inoculating them with scrapie-infected tissue. Because mink are sometimes fed sheep offal, Marsh thought he had found an important clue in 1985 when he was asked to investigate a suspected outbreak of TME on a farm near Stetsonville, Wis.

But those mink had never been fed sheep offal. Instead they were fed raw cattle carcasses. So Marsh inoculated cattle with brain tissue of the diseased mink from the Stetsonville farm. Those cattle developed an infection that "looked very like BSE pathologically," he says. Moreover, the disease—which Marsh calls bovine mink encephalopathy—could be transmitted orally back to mink. This finding suggests it is distinct from scrapie.

Bovine mink encephalopathy is clearly not the same as BSE: the former can be transmitted to hamsters but not mice, whereas the opposite is true of BSE. Still, the way BSE is transmitted is unsettling. A study conducted last year for the British health and agricultural departments concluded that BSE spread undetected in the early 1980's through feed supplements containing rendered animal protein. (BSE seems not to be transmitted directly from one animal to another.) One likely cause for the emergence of the disease, the report suggested, was increased use of sheep offal in animal feeds, including sheep infected with scrapie.

Alarmed by the outbreak of BSE in the U.K. and an increase of scrapie in the U.S., the Animal Protein Producer Industry, an association of U.S. rendering industries, recommended last December that its members stop processing sheep for use in feed for ruminants. But the renderers may not have gone far enough: the use of cattle protein in animal rations has increased dramatically over the past three years. If a BSE-like agent has already infected some U.S. cattle—which the Stetsonville episode suggests is possible—it may spread through animal feeds. "The exact same thing could happen over here as happened in Britain," Marsh says.

The U.S. Department of Agriculture decided last July to stop issuing permits to import meat scraps and bonemeal from the U.K. It also banned the import of live animals. In September the USDA halted the import of bovine calf serum, which is used in medical products (although evidence suggests calves are not infectious). Some experts, such as Mark M. Robinson of Washington State University, think these measures make the spread of BSE in the U.S. unlikely. "If [BSE] appears, we're ready for it," he says. Marsh is less sanguine. He argues that the consequences of an outbreak of BSE in the U.S. would be so dire for the cattle industry that, at the very least, a BSE surveillance program should be instituted immediately. —*T.M.B.*

MEDICINE

Through a Glass, Darkly

Are wearers of tinted glasses more likely to be depressed?

Wearers of rose-colored glasses are cheery, or so the cliché goes. But there may also be a darker side to wearing shades. Many British physicians have long suspected that patients who favor tinted lenses are abnormally prone to depression and hypochondria. So Robert J. W. M. Howard of the Maudsley Hospital in London decided to test this notion. "I thought it was unfair to keep saying this without any real proof," he says.

Howard and a colleague, Roland M. Valori, conducted an experiment with patients admitted to local hospitals for physical complaints, such as heart pain and digestive distress. They gave psychological tests to 20 patients who wore tinted glasses—ranging from lightly tinted to dark—and 20 patients whose age and diagnosis were similar.

The researchers reported their findings in the *Journal of the Royal Society of Medicine*. Their conclusion: tinted-glasses wearers displayed significantly higher levels of depression and psychosomatic illness than the control subjects, as well as more obsessive-compulsiveness, phobic anxiety, paranoia and even psychosis.

What underlies the correlation? Howard and Valori favor a theory set forth by physician Patrick D. Trevor-Roper in his 1984 book *The Eye and Its Disorders*. He speculated that "neurotics" wear tinted glasses in the hope that they will protect or conceal their "frail sensibilities . . . from the light of day." Ironically, the glasses serve instead to "advertise" the wearer's problems, Trevor-Roper noted.

In a letter to be published in the *American Journal of Psychiatry,* Howard asks U.S. psychiatrists whether they have encountered anything like the tinted-glasses phenomenon. He

suspects Americans who wear tinted glasses may have different symptoms. He observes, for example, that the British rarely wear nonprescription sunglasses, whereas many Americans seem to do so "as a kind of macho thing." He is particularly interested in Americans who wear mirrored sunglasses. "I think you would probably find a high incidence of borderline personalities there," he says.

"A lot of people have become very upset" since the article was published, Howard remarks. It didn't help that one London tabloid interpreted the finding to mean that anyone sporting colored eyewear could be a psychotic killer. So far, two tinted-glasses wearers have sent Howard hate mail.

Howard also notes that four of his eight colleagues at the Maudsley Hospital once wore tinted glasses (they stopped after his article appeared). This fact seems to support another bit of folklore: that psychiatrists are often as disturbed as their patients. "That's an obvious extrapolation of our results," says Howard, who is a psychiatrist, "but I don't really feel qualified to comment on that." —*J.H.*

An antidrug message gets its facts wrong

This public-service advertisement has recently appeared in dozens of U.S. medical journals (see, for example, the inside back cover of the February 9 *Journal of the American Medical Association*). It serves a noble purpose: to reduce drug abuse through treatment. Unfortunately, the claim that "last year, 15 million Americans used cocaine—and 5 million of those who survived required medical help" has no basis in fact.

The most recent estimates of cocaine use come from a household survey done in 1988 by the National Institute on Drug Abuse, the main federal agency supporting research on illicit drugs. NIDA estimated that 8.2 million Americans—not 15 million—had used cocaine in the previous year.

That same year, NIDA received reports of 62,141 medical emergencies and 3,308 deaths in which cocaine was implicated, according to Nicholas J. Kozel, chief epidemiologist at NIDA. He adds that not all U.S. hospitals or physicians report to NIDA and that the actual numbers of people treated for cocaine-related ailments are almost certainly higher. But when asked what could be the basis of the claim that "5 million of those who survived required medical help," Kozel replied: "I have no idea."

No one at the Partnership for a Drug-Free America, a consortium of businesses that donate resources to publicize the dangers of illicit drugs, seems to know the source of the ad's statistics either. In response to a query from SCIENTIFIC AMERICAN, Theresa V. Grant, a spokesperson for the Partnership, investigated the ad. She acknowledges that it is "plain wrong" and "should have been pulled."

The ad was designed in 1987 by an advertising agency that is now defunct, according to Grant. (NIDA's estimates of cocaine use were higher then but still fell several million short of the figures cited in the ad.) She speculates that the ad's creators, whom she was unable to contact, "extrapolated from a *Newsweek* article or something" in arriving at their figures.

The Partnership's pro bono nature and prolific output can make fact-checking difficult, Grant notes. Indeed, the cocaine-hotline message is only one of about 200 ads developed by the Partnership since it formed three years ago. One memorable television message compares a drug user's brain to a fried egg. —*J.H.*

Radiation Risks Revisited

A study raises the specter of an effect on offspring

An unexplained excess of childhood leukemia around some nuclear sites in Great Britain has long concerned medical researchers. Now a new study points to an unexpected cause: it suggests that men who have been exposed to radiation may be at increased risk of fathering children who acquire either leukemia or a related disease, non-Hodgkin's lymphoma.

Martin J. Gardner and his colleagues at the British Medical Research Council's environmental epidemiology unit at Southampton focused on a leukemia "cluster" near the Sellafield nuclear fuel–reprocessing plant in Cumbria. Fears that radioactive pollution from Sellafield might be the cause of leukemia in children living in the nearby village of Seascale first prompted a government inquiry in 1984. Yet a connection seemed unlikely, because the children's estimated radiation exposures were too low.

But the Gardner investigation, recently published in the *British Medical Journal,* examines 52 cases of leukemia and 22 cases of non-Hodgkin's lymphoma diagnosed in young people in West Cumbria between 1950 and 1985. The findings do confirm that children born less than five kilometers from Sellafield had a fivefold increased chance of acquiring leukemia.

The surprise came when Gardner's group compared the cases with 1,001 healthy control subjects, some living close to Sellafield and some not. What became apparent was that the best explanation (out of many possible ones examined) was *not* direct exposure to sources of radioactive contam-

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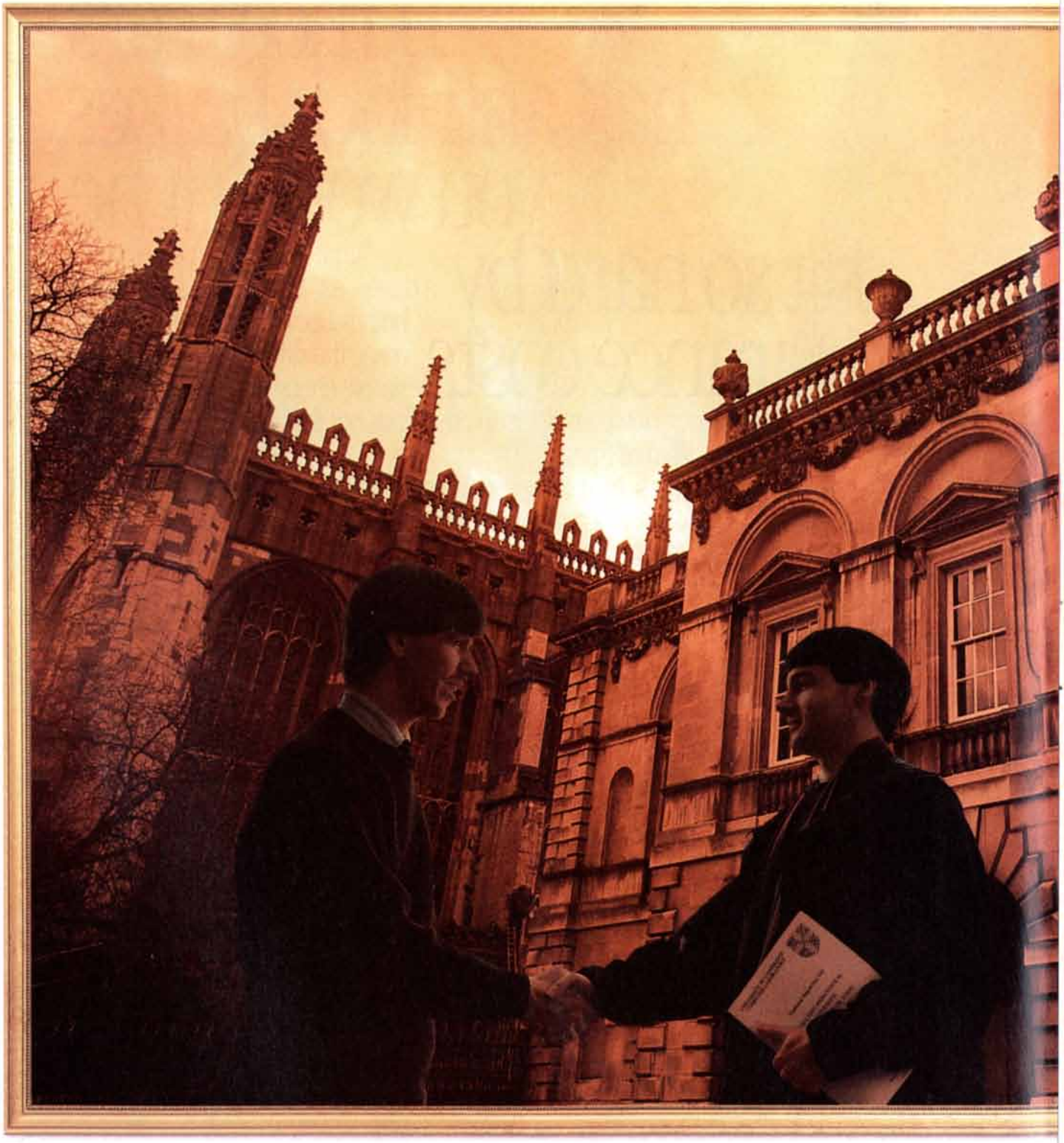

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ination. Rather, it was having a father who worked at Sellafield.

Men who received a lifetime dose of more than 100 millisieverts while employed at Sellafield and men who received a dose of 10 millisieverts in the six months prior to fathering their children ran a fourfold to eightfold increased risk of producing a child with leukemia or non-Hodgkin's lymphoma. Since publication of the Gardner report, the families of three leukemia victims whose fathers worked at the Sellafield plant have sued the plant's operator, British Nuclear Fuels.

Although high doses of radiation in male mice can also engender cancer in offspring, the Gardner finding is worrisome because the radiation doses of the Sellafield workers were low. The U.S. legal dose limit for nuclear-industry workers is higher, at 50 millisieverts per year (although most receive less). If the new risk estimates are correct, dose limits for potential fathers would almost certainly have to be reduced.

Is the study flawed? "One must take it seriously—it's a good paper," says epidemiologist Sir Richard Doll of the University of Oxford, who first established the link between lung cancer and cigarette smoking. "It's epidemiologically sound, and it has the merit of explaining the cluster of cases at Seascale."

But Sir Richard points out that only four leukemia cases in the Gardner study were known to be children of workers exposed to the highest radiation doses. As a result, the estimated risk could be wildly wrong. He also cautions that something other than whole-body radiation—such as a radioactive chemical that the Sellafield workers might have ingested—may be to blame. Arthur C. Upton of the New York University Medical Center, who chaired a panel that recently reassessed radiation effects for the National Research Council, agrees: "It's an interesting and provocative study, but I don't think one can draw any firm conclusions."

Indeed, the Sellafield study raises questions it cannot answer. One mystery is why no excess of leukemia cases has been seen in children of men who survived the Japanese atomic bomb blasts. A possible answer is that the effect of radiation exposure on reproductive cells might be short-lived. Seymour Jablon, expert statistician at the National Cancer Institute, points out that few children were conceived soon after the war. "Although the Japanese evidence doesn't support [the Gardner finding], it does not necessarily contradict it either," he says. "The whole thing is just an enormous puzzle." Jablon is considering mounting a study on children of male uranium miners. In the meantime, ongoing examinations of other leukemia clusters in Great Britain may soon help answer the question. —*T.M.B.*

PROFILE

Free Radical

A word (or two) about linguist Noam Chomsky

Uh-oh. I think I've insulted Noam Chomsky. I just said I found it ironic that his political views are so antiauthoritarian, given that in linguistics he *is* the authority.

"No I'm not," he snaps. His voice—which ordinarily is almost hypnotically calm, even when he is eviscerating someone—suddenly has an edge. "My position in linguistics is a minority position, and it always has been."

Who but Chomsky would bridle at the suggestion that, on at least one topic, a lot of people agree with him? He may dispute it, but his theories about language—which he thinks springs from an innate human faculty—have dominated linguistics for more than 30 years. "There is no major theoretical issue in linguistics today that is debated in terms other than those in which he has chosen to define it," says an entry in the *Encyclopaedia Britannica.*

Yet Chomsky has another career—as a social critic—and in this realm he is relentlessly iconoclastic. He likes to call the U.S. a "terrorist superpower" and the media its "propaganda agent." Repelled by capitalism, he despises the U.S.S.R. as well, declaring that "the Bolshevik revolution basically destroyed socialism."

Indeed, Chomsky seems to apply his worldview—which he sums up as "whatever the establishment is, I'll be against it"—to everything, even himself. "I'm not a professional linguist," he says. "I'm almost totally incapable of learning languages, for one thing because I find it so boring." The Massachusetts Institute of Technology, he insists, has employed him for 35 years only because it doesn't care about the humanities. Chomsky keeps his poker face when he says such things, but I think I detect a sly delight.

I recently spent a day with Chomsky in Cambridge. At 61, he is wiry, with the slight hunch of a chronic reader

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and writer. He wears steel-rimmed glasses, sneakers, chinos and an open-necked shirt. But for the lines in his face and the gray in his longish hair, he could pass for a college student—albeit one who prefers Kant to fraternity parties.

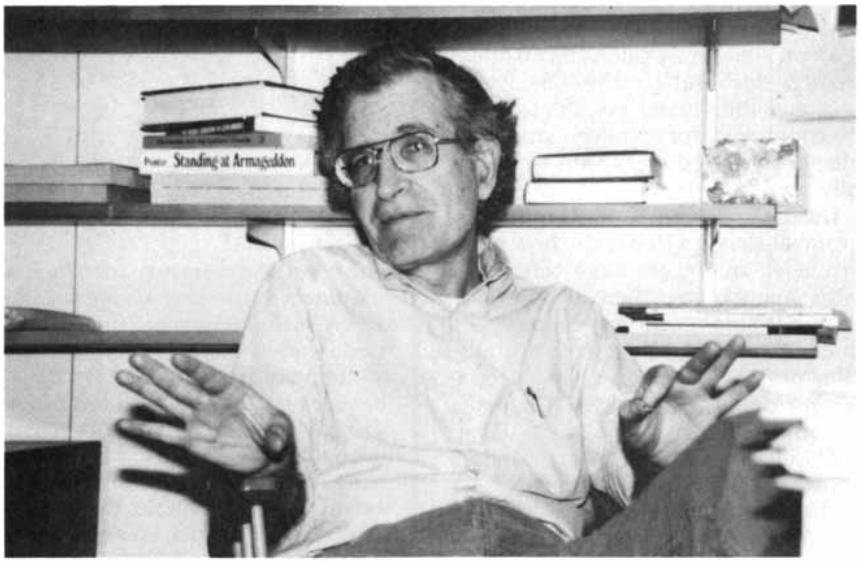
During my visit I watched him tell a group at Harvard University how modern labor unions are more concerned with maintaining their own power than with representing workers. His audience? Union organizers, naturally. "I'm not interested in giving people A's for doing things right," Chomsky informs me later.

Chomsky's intellectual leanings showed up early. Born in Philadelphia in 1928, he was raised as a "practicing Jewish atheist," he says, adding, "that's not as much of a contradiction as it sounds." At 10, he wrote his first political article—a polemic against the Fascist takeover of Spain—for the newspaper of his progressive school. A year or two later he was studying the grammar of medieval Hebrew with his father, a Hebrew scholar; as a teenager he taught at a Hebrew school (not bad for someone with no aptitude for learning languages).

A "semi-college dropout" in the late 1940's, Chomsky nonetheless fell under the influence of Zellig S. Harris, a linguist at the University of Pennsylvania. At the time, linguistics—indeed, all the social sciences—were dominated by behaviorism, which held that science should consider only what can be observed and that mental states are beyond its purview.

Behaviorists also hewed to the notion—elucidated by the British philosopher John Locke in the 17th century—that the mind begins as a "blank slate" that is inscribed on by experience. The structure of language, then, should also be shaped by circumstances rather than innate predilections and so should be essentially arbitrary. As a result of these tenets, most linguists focused on cataloguing the fauna and flora of human languages in all their bewildering variety rather than trying to find underlying principles.

Prodded by Harris, a maverick himself, Chomsky challenged the behaviorist approach. Just as the readings on a physicist's meter are significant only to the extent that they illuminate the structure of matter, Chomsky argued, language is interesting only insofar as it reveals the structure of the mind. He advocated shifting the focus of linguistics from the epiphenomena of language to an epistemological question: What does the mind know



NOAM CHOMSKY thinks language springs from an innate human faculty.

when it knows a language, and how does it know it?

To penetrate this question, Chomsky began devising a system of rules that could generate grammatical sentences. Other linguists, including Harris, had devised such systems, but Chomsky borrowed from mathematics and logic to create a so-called generative grammar more rigorous and comprehensive than any predecessor.

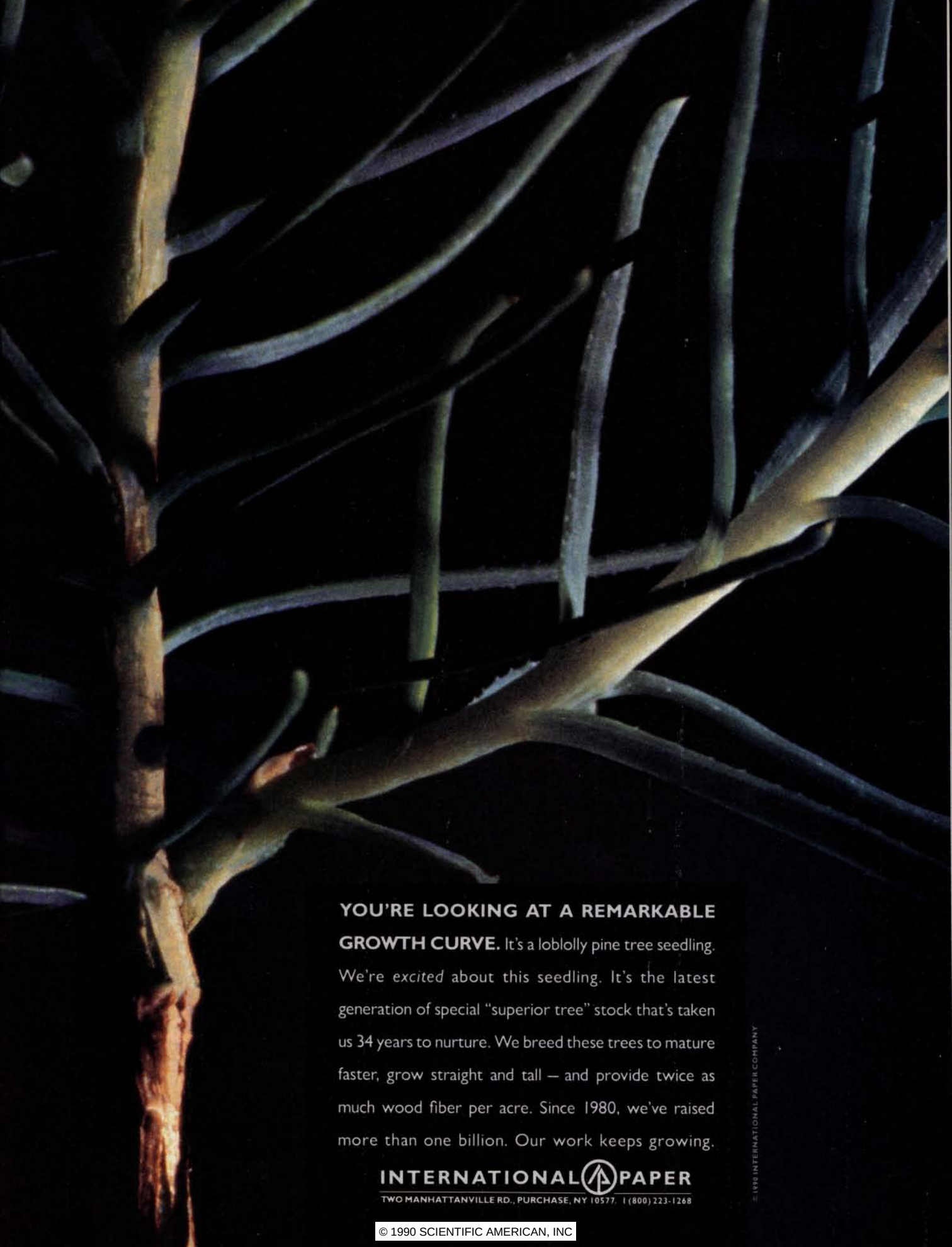
Working with this tool, Chomsky showed that language is far more complex than anyone had suspected—too complex to be entirely learned, he contended. For example, to turn the sentence "The man is here" into a yes or no question, one merely puts the verb before the subject: "Is the man here?" But how does one turn the slightly more complex sentence, "The man who is tall is here," into a question? One might expect a child who has just mastered the simpler example to place the first "is" in front of the sentence and say, "Is the man who tall is here?" But children never make this mistake, according to Chomsky. They always move the *main* verb, not the first verb, to the front of the sentence.

Chomsky points out that this rule is quite subtle, and in fact it is difficult to express either in formal linguistic terms or in a computer program. Yet children apply it without ever being explicitly taught to do so.

This example and countless others like it, Chomsky maintains, show that we do not learn all the rules of grammar solely through induction or trial and error, as behaviorists believed; some fundamental principles of language must already be imbedded in our brains. Indeed, Chomsky insists that the word "learn" should not be applied to language—as it is, say, to driving a car. He equates the ability to converse with the physiological changes that come with puberty; with minimal environmental nourishment, humans simply acquire both as part of growing up.

Chomsky's theories, first set forth in "Syntactic Structures" in 1957, triggered a reaction against behaviorism and toward cognitivism—in which mental states are central—that continues to this day. Counterattacks have been mounted. Perhaps the most famous occurred in the 1970's, when a group at Columbia University taught a chimpanzee—named Nim Chimpsky—to communicate through sign language. The investigators claimed their work supported the behaviorist model rather than Chomsky's. Chomsky, who thinks language is a uniquely human trait, dismisses this challenge. Saying apes can acquire language because they can learn some simple signs, he argues, is like saying humans can fly because they can jump.

Chomsky's ideas continue to evolve. About 10 years ago, he says, a "major paradigm shift" occurred in linguistics. He and other workers proposed that the innate language faculty be viewed as a collection of switches imbedded in a network. All humans are born with essentially the same network, but the switches flip over into different positions—corresponding to different rules of grammar—depending on whether a child learns Swahili or Chinese or English. The job of linguists, Chomsky says, should be to see beyond these superficial rules, or settings, to the underlying network, in



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which is embodied the "deep structure" of language.

While he was revolutionizing the field of linguistics, Chomsky never abandoned his political activism. He was one of the first prominent American intellectuals to oppose the Vietnam War, and he became something of a hero to the Left when he was indicted for encouraging students to resist the draft (the case was never brought to trial).

But since the Vietnam War ended, Chomsky has made enemies left and right. In 1979 he signed a petition defending the right to free speech of Robert Faurisson, a French historian who has argued that most accounts of the Holocaust are exaggerated. This incident, together with Chomsky's criticism of Israel and support for Palestinian rights, has led many intellectuals to denounce him.

Chomsky's claim that the U.S. media serve corporate-state interests rather than the truth also tends to annoy journalists. He is particularly hard on liberals (Anthony Lewis and Tom Wicker, columnists for the *New York Times*, for example), whom he accuses of creating the illusion of dissent when in fact they support the status quo in all but trivial matters.

Not surprisingly, then, it is hard to find any mention of Chomsky in a national publication—let alone on television. Chomsky is hardly repentant. "If they started reviewing my books in the *New York Times*," he says, "my first question would be, 'What am I doing wrong?'"

Chomsky does not lack other avenues of discourse. He teaches two linguistics classes a week at M.I.T. and spends 20 or so hours consulting with students. He writes a lot of letters (more than 2,000 last year, according to his secretary, some of them 15 pages long and single-spaced) and gives scores of lectures a year all across the world. And of course, people can always buy his books (over 25 at last count, roughly divided between linguistics and politics).

Chomsky can be powerfully persuasive. By the end of the meeting I observed at Harvard, he had the labor leaders nodding in agreement with him—even as he accused them of selling out to business. But Chomsky says his goal is to make people think rather than to convert them to his viewpoint. "People typically ask me, 'Who should I believe?' and my typical answer is, 'If you ask that question, you're in trouble, because there's nobody you should believe, including me.'" —*John Horgan*

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When Science Takes the Witness Stand

In courts of law, forensic testimony often goes unchallenged by a scientifically naive legal community. Forensic methods must be screened with greater care if justice is to be served

by Peter J. Neufeld and Neville Colman

In the early evening of November 21, 1974, powerful bombs ripped through two pubs in the industrial city of Birmingham, England, leaving 21 dead and 162 injured. The government immediately blamed the Irish Republican Army for the attacks and mounted a massive search for the perpetrators. After a railroad clerk reported that six Irishmen had boarded a train in Birmingham minutes before the first bomb blast, police intercepted the men as they disembarked at the port of Heysham. The six men were taken to the police station, and there, their hands were swabbed with chemicals that would reveal the presence of any nitrites, which would be consistent with the recent handling of explosives. The forensic scientist who performed this procedure, known as the Greiss test, reported positive findings on the right hands of two of the six suspects. That evidence became the linchpin of the government's successful prosecution of the "Birmingham Six."

Now, 16 years later, the six men may be released. The Greiss test, on which their convictions had been largely based, has proved unreliable. It turns out that a variety of common substances such as old playing cards, cigarette packages, lacquer and aerosol spray will, along with explosives, yield a positive result. As it happened, the six men had spent most of their train ride to Heysham playing cards and smoking cigarettes.

The Birmingham case raises troubling issues about the application of forensic technology to criminal investigations. Since the discovery of fingerprinting at the turn of this century, science has assumed an increasingly powerful role in the execution of justice. Indeed, scientific testimony is often the deciding factor for the judicial resolution of civil and criminal cases. The scientific analysis of fingerprints, blood, semen, shreds of clothing, hair, weapons, tire treads and other physical evidence left at the scene of a crime can seem more compelling to a jury than the testimony of eyewitnesses. As one juror put it after a recent trial in Queens, N.Y., "You can't argue with science."

Scientists generally welcome this trend. Because the scientific community polices scientific research, subjecting new theories and findings to peer review and independent verification, it is often assumed the same standards prevail when science is applied to the fact-finding process in a judicial trial. But in reality such controls are absent in a court of law. Instead nonscientists—lawyers, judges and jurors—are called on to evaluate critically the competence of a scientific witness. Frequently lawyers are oblivious of potential flaws in a scientific method or argument and so fail to challenge it. At other times, the adversaries in a case will present opposing expert opinions, leaving it up to a jury of laypersons to decide the merits of the scientific arguments.

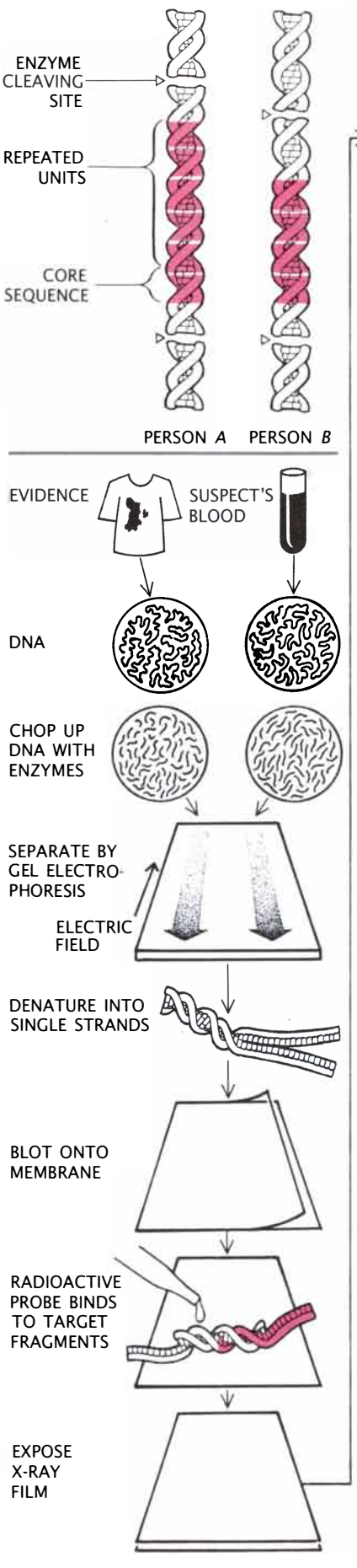
The disjunction between scientific and judicial standards of evidence has allowed novel forensic methods to be used in criminal trials prematurely or without verification. The problem has become painfully apparent in the case of forensic DNA profiling, a recent technique that in theory can identify an individual from his or her DNA with a high degree of certainty. Although

PETER J. NEUFELD and NEVILLE COLMAN have collaborated for several years on the problem of admitting new scientific techniques into criminal cases and have lectured on the subject to both defense attorneys and prosecutors. Neufeld, an attorney specializing in criminal defense and civil-rights litigation, was co-counsel in *People v. Castro,* in which DNA evidence was first successfully challenged. He is a member of the New York State governor's panel on forensic DNA analysis. Neufeld received his J.D. in 1975 from the New York University School of Law and is adjunct associate professor at the Fordham University School of Law. Colman is director of the Center for Clinical Laboratories at Mount Sinai Medical Center in New York City. He received his M.D. in 1969 and his Ph.D. in 1974 from the University of the Witwatersrand, Johannesburg. He has advised counsel and testified in legal proceedings involving the admissibility of scientific evidence.

many aspects of forensic DNA identification have not been adequately examined by the scientific community, police and prosecutors have carried out DNA analysis in more than 1,000 criminal investigations in the U.S. since 1987. Few of these cases reached trial. In most instances, defendants pleaded guilty on advice of counsel after a presumably infallible DNA test declared a match.

Several recent cases have raised serious reservations about the claims made for DNA evidence. Last spring, during a pretrial hearing in *People v. Castro* in New York City, Michael L. Baird of Lifecodes Corporation in Valhalla, N.Y., one of the two major commercial forensic DNA laboratories in the U.S., reported the odds of a random match between a bloodstain and

EXPERT WITNESS Lorraine Flaherty, a molecular geneticist at the New York State Department of Health, testifies on DNA analysis during last year's pretrial hearing of *People v. Castro*. Bronx County Supreme Court Justice Gerald Sheindlin later ruled against admitting key DNA evidence into the double-murder trial. The case was the first to examine thoroughly—and challenge successfully—DNA tests, which had already been used to obtain convictions in hundreds of earlier trials.



DNA IDENTIFICATION currently hinges on the existence of certain regions in DNA, called restriction fragment length polymorphisms (RFLP's), which contain "core" sequences (*color*) that are repeated in tandem a variable number of times from person to person. Each RFLP can be identified by a special probe that recognizes and binds to any fragment containing the core sequence. Special enzymes snip RFLP's out of DNA. Forensic casework involves taking DNA extracted from evidence and from, for example, a suspect's blood, breaking it up into RFLP's and separating them by gel electrophoresis. A radioactive probe binds to the RFLP's, whose positions are then recorded as dark bands on X-ray film. If the striped patterns from the evidence and from the suspect appear to match, one then calculates the probability of such a match occurring by chance.

the suspect at one in 100 million. Eric S. Lander of Harvard University and the Massachusetts Institute of Technology examined the same data and arrived at odds of one in 24. Ultimately, several proponents of DNA testing denounced Lifecodes' data in the case as scientifically unreliable. Some of Lifecodes' key methods were repudiated, casting doubt on the integrity of hundreds of earlier criminal convictions. The ongoing debate over DNA testing underscores the need to deal more effectively with the difficulties that arise whenever complex scientific technology is introduced as evidence in a court of law.

A trial is ideally a search for truth. To help juries in their quest, the law allows qualified experts to testify and express opinions on matters in which they are professionally trained. Yet the esoteric nature of an expert's opinions, together with the jargon and the expert's scholarly credentials, may cast an aura of infallibility over his or her testimony. Hence, to prevent juries from being influenced by questionable evidence or expert testimony, U.S. courts usually review the material in a pretrial hearing or outside the presence of the jury.

To be admitted as evidence, a forensic test should, as a matter of common sense, satisfy three criteria: the underlying scientific theory must be considered valid by the scientific community; the technique itself must be known to be reliable; and the technique must be shown to have been properly applied in the particular case.

The expression of common sense in a court of law, however, is at times elusive. A majority of U.S. courts decide on the admissibility of scientific evidence based on guidelines established in 1923 by *Frye v. U.S.,* in which the Court of Appeals for the District of Columbia affirmed a lower court's decision to exclude evidence derived from a precursor of the polygraph. "Just when a scientific principle or discovery crosses the line between the experimental and demonstrable stages is difficult to define," the court declared in *Frye.* "Somewhere in this twilight zone the evidential force of the principle must be recognized, and while courts will go a long way in admitting expert testimony deduced from a well-recognized scientific principle or discovery, the thing from which the deduction is made must be sufficiently established to have gained general acceptance in the particular field in which it belongs."

Judges, scientists, lawyers and legal

scholars have all criticized the *Frye* standard. Some say it is too vague. Some argue that it is unduly restrictive. Still others complain that it is not restrictive enough. Should "general acceptance," for example, require a consensus or a simple majority of scientists? Also, what is it that must be generally accepted? In the case of DNA profiling, is it the theory that no two individuals, except for identical twins, have the same DNA? Is it the various techniques employed in the test, such as Southern blotting and gel electrophoresis? Or is it the specific application of DNA profiling to dried blood and semen samples recovered from the scene of a crime?

Furthermore, what is the appropriate "particular field" in which a technique must be accepted? Does a test for DNA profiling have to be accepted only by forensic serologists, or must it also be recognized by the broader community of human geneticists, hematologists and biochemists? In a recent California case, DNA evidence analyzed by means of the polymerase chain reaction (PCR) was excluded because that method was not generally accepted by forensic scientists. Yet several months earlier a Texas court that was evaluating the identical PCR method looked more broadly to the opinions of molecular biologists and human geneticists and reached the opposite conclusion.

For many applications of science to forensics, the underlying theory is well established, and legal debate rages mainly over whether one must prove only that a technique is generally accepted for scientific research or, more strictly, that the technique is reliable when applied to forensics.

Why the distinction between nonforensic and forensic applications? Scientists commonly accept that when any technology is tried in a different application, such as forensics, it must be tested thoroughly to ensure an empirical understanding of the technique's usefulness and limitations. Indeed, many a technique that has proved reliable for research—polygraphy, for example—has turned out to be of questionable reliability when applied to forensic casework.

Clearly, in order for the courts to evaluate forensic evidence, judges and lawyers must be able to appreciate the scientific issues at hand. Regrettably, lawyers rarely do more than review the qualifications of the expert (typically based on perfunctory queries about institutional affiliation and publications) and verify the facts on which the expert's conclusions are based. The reason for this limited inquiry is simple: most lawyers and judges lack the adequate scientific background to argue or decide the admissibility of expert testimony. Often judges think—mistakenly, in our opinion—that justice is best served by admitting expert testimony into evidence and deferring to the jury for the determination of its weight.

The problem of scientific illiteracy is compounded by the tendency of judges to refuse to reconsider the validity of a particular kind of scientific evidence once it has been accepted by another judge in an earlier case. This practice is founded on the well-recognized need to respect precedent in order to ensure the uniform administration of justice. But in the case of forensic tests, the frequent failure of courts to take a fresh look at the underlying science has been responsible for many a miscarriage of justice.

Perhaps the most notorious example of the problem is the so-called paraffin test (a cousin of the Greiss test employed in the Birmingham Six investigation), which was used by crime laboratories throughout the U.S. to detect nitrite and nitrate residues, presumably from gunpowder, on suspects' hands to show that they had recently fired a gun. The test was first admitted as scientific evidence in a 1936 trial in Pennsylvania. Other states then simply adopted that decision without independently scrutinizing the research.

For the next 25 years innumerable people were convicted with the help of this test. It was not until the mid-1960's that a comprehensive scientific study revealed damning flaws in the paraffin test. In particular, the test gave an unacceptably high number of false positives: substances other than gunpowder that gave a positive reading included urine, tobacco, tobacco ash, fertilizer and colored fingernail polish. In this instance the legal process failed, allowing people accused of crimes to be convicted on evidence that later proved to be worthless.

More recently the debate over scientific courtroom evidence has centered on two applications of biotechnology: protein-marker analysis and DNA identification. Both techniques employ gel electrophoresis to reveal genetic differences, called polymorphisms, in blood proteins and DNA. These two techniques can potentially match blood, semen or other such evidence found at a crime scene to a suspect or victim.

In the late 1960's crime laboratories became interested in protein polymorphisms in populations. The techniques for studying protein polymorphisms were originally developed as tools for population geneticists and were experimentally tested, published in refereed journals and independently verified. The techniques were then modified by and for law-enforcement personnel in order to cope with problems unique to forensic samples, such as their often limited quantity, their unknown age and the presence of unidentified contaminants. These modifications were rarely published in the scientific literature or validated by independent workers.

For example, molecular geneticists study polymorphic proteins in red blood cells and serum by using fresh, liquid blood and analyzing it under controlled laboratory conditions, all subject to scientific peer review. These techniques were then adapted for use on forensic samples of dried blood by the introduction of various modifications, few of which were subjected to comparable scientific scrutiny. No one ever adequately explored the effects of environmental insults to samples, such as heat, humidity, temperature and light. Neither did anyone verify the claim that forensic samples would not be affected significantly by microbes and unknown substances typically found on streets or in carpets.

One of the major modifications made by forensic laboratories was the "multisystem" test. In the original version of this test, three different polymorphic proteins were identified in a single procedure; the purpose was to derive as much information as possible from a small sample. The three-marker multisystem test was further modified by the addition of a fourth protein marker in 1980 by the New York City Medical Examiner's serology laboratory.

By 1987 evidence derived from the "four-in-one" multisystem had been introduced in several hundred criminal prosecutions in New York State. In that year, however, during a pretrial hearing in *People v. Seda,* the director of the New York City laboratory admitted under cross-examination that only one article had been published about that system—and that the article had recommended the test be used only to screen out obvious mismatches because of a flaw that tended to obscure the results.

In *People v. Seda,* the judge ruled that the four-in-one multisystem did not satisfy the *Frye* standard of general acceptance by the scientific commu-

nity and so could not be introduced into evidence. Unfortunately, *Seda* was the first case involving the test in which the defense went to the effort of calling witnesses to challenge the technology. Consequently, the integrity of hundreds of earlier convictions stands in doubt.

In the past two years DNA profiling has all but eclipsed protein markers in forensic identification. The technique is based on a method originally developed to study the inheritance of diseases, both to identify the disease-causing genes in families known to harbor an inherited disease and to predict individual susceptibility when the gene is known.

Crime investigators have embraced the new technique because it offers two significant advantages over conventional protein markers. First, DNA typing can be conducted on much smaller and older samples. And second, DNA typing was reported to offer from three to 10 orders of magnitude greater certainty of a match. Promotional literature distributed by Lifecodes asserts that its test "has the power to identify one individual in the world's population." Not to be outdone, Cellmark Diagnostics in Germantown, Md.—Lifecodes' main competitor—claims that with its method, "the chance that any two people will have the same DNA print is one in 30 billion." Yet, as testimony in the *Castro* case showed, such claims can be dubious.

The hype over DNA typing spreads the impression that a DNA profile identifies the "genetic code" unique to an individual and indeed is as unique as a fingerprint. Actually, because 99 percent of the three billion base pairs in human DNA are identical among all individuals, forensic scientists look for ways to isolate the relatively few variable regions. These regions can be cut out of DNA by restriction enzymes and are called restriction fragment length polymorphisms (RFLP's).

For DNA identification, one wants RFLP's that are highly polymorphic—that is, those that have the greatest number of variants, or alleles, in the population. It turns out that certain regions of human DNA contain "core" sequences that are repeated in tandem, like freight cars of a train. The number of these repeated sequences tends to vary considerably from person to person; one person might have 13 repeated units at that locus, whereas another might have 29. Special restriction enzymes cut DNA into millions of pieces, including fragments that contain the repeated segments. Because the number of repeated segments varies among individuals, so too does the overall length of these fragments vary.

How can these variable fragments be picked out of the haystack of irrelevant DNA segments? The answer lies in "probes" that bind only to fragments containing the core sequence. If the core sequence occurs at only one DNA locus, the probe is called a single-locus probe. If the core sequence occurs at many different loci, the probe is called a multilocus probe. Forensic laboratories currently make use of three different methods of DNA typing: single-locus RFLP, multilocus RFLP and the polymerase chain reaction. Because the single-locus system is the one most widely employed in forensic DNA identification, we will describe it in some detail.

For forensic DNA identification by single-locus RFLP analysis, DNA from various sources is digested with restriction enzymes, placed in separate lanes on an electrophoretic gel and subjected to an electric field. The field pulls fragments down the lane, with smaller fragments traveling faster than larger ones. The fragments, now sorted by size, are denatured into single strands and transferred from the gel onto a nitrocellulose or nylon membrane, which fixes the fragments in place. (Incidentally, anyone who handles nitrocellulose might test positive on the Greiss test!)

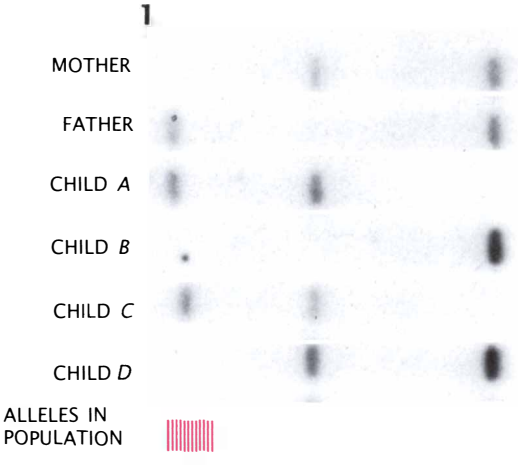
At this point, a radioactive probe is applied, which hybridizes, or binds, to the polymorphic fragments. The mesh is then laid on a sheet of X-ray film to produce an autoradiograph. The radioactively labeled fragments are thereby revealed as a series of bands resembling a railroad track with irregularly spaced ties; the position of the bands is a measure of the size of the polymorphic fragments. The probe can be rinsed away, and a new probe can be applied to identify a different set of alleles.

The autoradiograph resulting from a single-locus probe will ordinarily show alleles of two distinct sizes, one inherited from each parent; such a pattern indicates that the person is heterozygous for that locus. If the probe reveals only one distinct allele, it is assumed that the person inherited the same-size allele from both parents and that the person is homozygous for the locus. Forensic DNA-testing laboratories typically employ several single-locus probes, each of which binds to a different site.

To determine whether two samples of DNA come from a single source, one examines the bands identified by a particular probe on the autoradiograph and decides whether they match. One then refers to data from population-genetics studies to find out how often that particular allele size occurs. A typical allele might be found in 10 percent of the population, making it not all that unlikely that two random people will carry the same allele. But if one looks at alleles at three or four different sites, it becomes increasingly unlikely that two individuals will have the same alleles for all the sites. It is this hypothesis that gives DNA profiling its persuasive power.

How well does forensic DNA profiling stand up under the *Frye* standard? Certainly the underlying theory—that no two people, except for identical twins, have the identical DNA—is unquestioned, and so DNA identification is possible in theory. But is that theory being applied to give a reliable forensic test? And if so, is that test being carried out properly?

In scientific and medical research, DNA typing is most often employed to trace the inheritance of disease-causing alleles within a family. In this diagnostic application, however, one can assume that one allele was inherited from the mother and the other from the father. Because each parent has only two alleles for that gene, barring a mutation, the pattern observed in the child is limited at most to four possible combinations. In addition, if the results are ambiguous, one can rerun the experiment with fresh blood sam-



FORENSIC DNA TYPING is fraught with uncertainty. If the autoradiographs in group 1 are assumed to be from one family, then the alleles of the children must be derived from the parents, even though one of the bands for child *C* is visibly

ples or refer to the alleles of other family members.

In forensic DNA typing, however, it is much more difficult to determine whether an allele from one sample is identical to an allele from another. In the RFLP systems employed in forensics, the number of alleles can run into the hundreds—in contrast to the four from which one must choose when identifying the alleles of a child whose parents are known. Indeed, forensic RFLP systems produce so many different alleles that they virtually form a continuum. In some RFLP's the most common alleles can be crowded into a quarter-inch span on a 13-inch lane. Gel electrophoresis can resolve only a limited number of alleles, however—perhaps between 30 and 100 depending on the particular RFLP—and so alleles that are similar, but not the same, in size may be declared identical. Hence, it can become difficult indeed to declare with confidence that one band matches another. What is worse, forensic samples are often limited in amount and so cannot be retested if ambiguities arise.

These inherent difficulties are further complicated by a problem called band shifting. This phenomenon occurs when DNA fragments migrate at different speeds through separate lanes on a single gel. It has been attributed to a number of factors, involving variables such as the preparation of gels, the concentrations of sample DNA, the amount of salt in the DNA solution and contamination. Band shifting can occur even if the various lanes contain DNA from the same person. Because allele sizes in forensic RFLP systems are closely spaced, it is difficult to know whether the relative positions of bands arise purely from the size of allele fragments or whether band shifting might play a part.

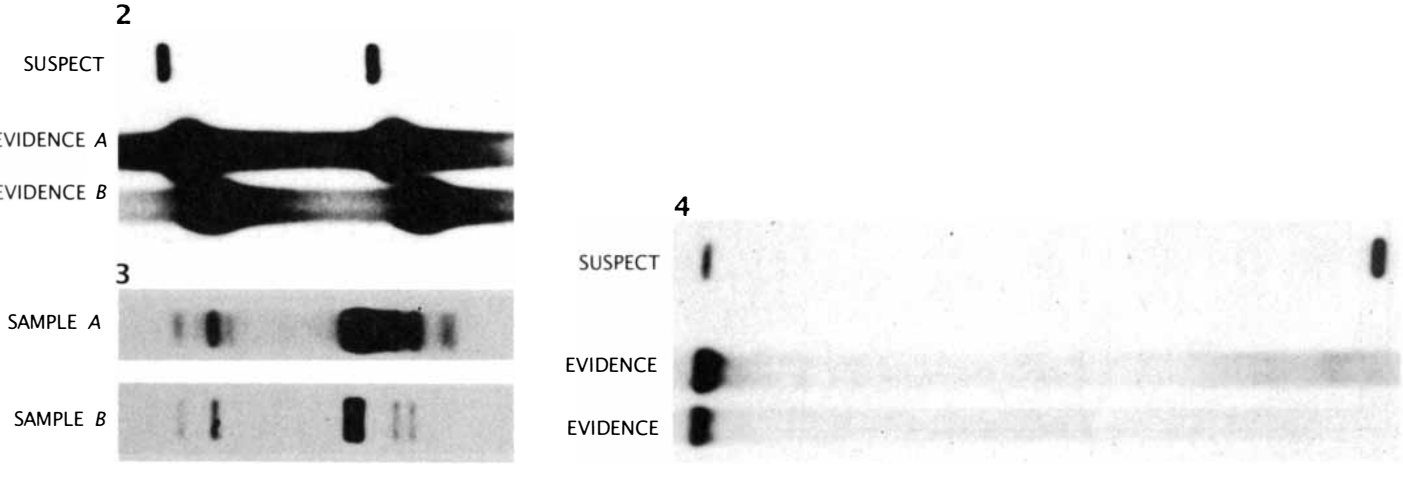
The courts' handling of band shifting is an excellent illustration of the problems that arise when courts, rather than the scientific peer-review process, take on the task of determining whether a method is reliable. Two years ago, when DNA evidence was first introduced in U.S. courtrooms, most forensic DNA scientists rejected the existence of band shifting. But now some experts think band shifting occurs in perhaps 30 percent of forensic DNA tests. There are now many theories about the cause, but as of this writing not one refereed article on the subject has been published.

Forensic DNA laboratories are rushing to develop special probes that bind to monomorphic loci—restriction-enzyme fragments that are the same size in every person—as a possible way to control for band shifting. In theory, if the monomorphic regions are displaced, one would know that band shifting had occurred and could then calculate a correction factor. The difficulty again is that neither this method, nor any other possible solution, has been peer reviewed.

Yet in a rape case tried last December in Maine, *State v. McLeod,* the laboratory director who had supervised the DNA tests for the prosecution testified that a correction factor derived from a monomorphic probe allowed him to declare a match between the suspect's blood and the semen recovered from the victim, even though the bands were visibly shifted. When evidence then came to light that a second monomorphic probe indicated a smaller correction factor, which did not account for the disparity between the bands, he acknowledged that monomorphic probes may yield inconsistent correction factors; nevertheless, he argued that the first correction was appropriate to the bands in question. The prosecutor, though, recognized the folly of defending this argument in the absence of published supporting data and withdrew the DNA evidence. In dozens of other cases, however, judges have been persuaded by the same types of arguments, even though there is no body of research to guide the court. As a matter of common sense, the proper place to first address such issues is in scientific journals, not the courtroom.

Another major problem that arises in forensic DNA typing is contamination. More often than not, crime-scene specimens are contaminated or degraded. The presence of bacteria, organic material or degradation raises the risk of both false positives and false negatives. For example, contamination can degrade DNA so that the larger fragments are destroyed. In such instances a probe that should yield two bands may yield only one (the smaller band).

Research laboratories employ internal controls to avoid the misinterpretation that can result from such artifacts. But such controls may not be suitable for forensic casework. For example, one suggested control for band shifting is to run a mixing experiment: sample *A* is run in lane one, sample *B* in lane two and *A* and *B* in lane three. If



shifted. But if that same lane were of a person whose parentage is unknown, then the band could correspond to one of the other alleles (*color bands*) observed in the population. In group 2, the band patterns from the suspect and from evidence *A* and *B* appear to be displaced relative to one another, which may indicate a band shift. In group 3, sample *A* contains all of the bands from sample *B,* along with extra bands, possibly from contaminants. In group 4, a suspect has two bands, whereas the forensic evidence has only one; the "missing" band may have resulted because degradation of the DNA destroyed the larger fragments. On the other hand, all of these cases could also indicate a real genetic difference.

both samples are from the same person, then ideally lane three would produce one set of bands, whereas if they are from different people, it would show two sets of bands. Unfortunately, in forensic casework there is often not enough material to run a mixing experiment. What is more, recent unpublished studies indicate that certain contaminants, such as dyes, can bind to DNA and alter its mobility in a gel, so that a mixing experiment using samples from the same person can produce two sets of bands.

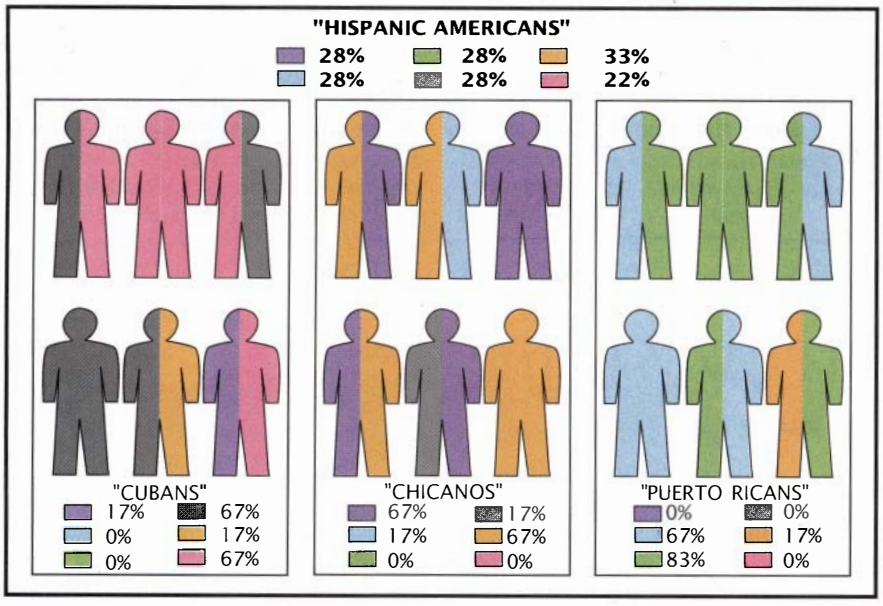
The power of forensic DNA typing arises from its ability not only to demonstrate that two samples exhibit the same pattern but also to suggest that the pattern is extremely rare. The validity of the data and assumptions on which forensic laboratories have been relying to estimate the rarity are currently being debated within the scientific community.

There are two particularly important criticisms. First, because it is difficult to discriminate accurately among the dozens of alleles at a particular locus, the task of calculating the frequency with which each allele appears in the population is inherently compromised. Second, the statistical equations for calculating the frequency of a particular pattern of alleles apply only to a population that has resulted from random mating—a condition that is called Hardy-Weinberg equilibrium.

If a population is in Hardy-Weinberg equilibrium, one can assume allele types are shuffled at random. The occurrence of one allele is then independent of the occurrence of a second allele. One can therefore calculate the frequency of the "genotype," or a particular pair of alleles, for a specific locus by multiplying the frequency of each allele and doubling it (because one has the same probability of inheriting each allele from both parents). The frequency of a genotype for a combination of loci is then obtained simply by multiplying the frequency of the genotype for each individual locus. For example, if the genotypes at loci *A, B, C* and *D* each occur in 10 percent of the population, then the probability that a person would have these genotypes at all four loci is .1 multiplied by itself four times: .0001.

Forensic DNA laboratories carry out these calculations based on data they have assembled themselves. Most of the data have not been published in peer-review journals or independently validated. One problem is that none of the major laboratories employs the same RFLP system. And even if the laboratories decide to adopt uniform probes and enzymes, the results may still differ significantly unless they all also adopt identical protocols. Commercial DNA-testing laboratories are reluctant to do so, however, because each considers its RFLP system to be proprietary, and the probes and enzymes are sold or licensed to crime laboratories around the country.

Another serious issue is that some populations may not be in equilibrium, in which case neither the alleles nor the various loci may be independent. For such a population, there is as yet no consensus on how to calculate the frequency of a genotype (given the limited data bases of the forensic DNA laboratories). As matters stand, population geneticists are debating whether various racial and ethnic communities exhibit significant population substructures so as to preclude the use of current data bases for the highly polymorphic systems employed in forensic DNA identification. For example, do Hispanics in the U.S. constitute a single mixed population? Or is there nonrandom mating, with Cubans more likely to mate with other Cubans and Chicanos more likely to mate with other Chicanos? Should there be a separate data base on allele frequencies within each of these subpopulations? To find out, population geneticists will need to gather more data.



POPULATION DATA may not yet be reliable enough to calculate the frequency of a genotype accurately. In the hypothetical Hispanic-American population depicted here, a particular DNA site has six distinct alleles, each represented by its own color. Heterozygous individuals are shaded with two colors to represent the two alleles inherited from the parents; homozygous individuals, who have inherited the same allele from both parents, are shaded with one color. Allele frequencies for the entire population differ markedly from allele frequencies for the subgroups shown here.

More than 1,000 criminal investigations in the U.S. have now involved DNA evidence, but in only a few dozen cases has DNA evidence been challenged in a pretrial hearing. According to our own study of these hearings, until the *Castro* case in New York, not one of these hearings addressed the problems of forensic DNA typing that distinguish it from diagnostic DNA typing. In all but two of the early hearings, defense attorneys failed to obtain the raw population data on which conclusions about allele frequencies were predicated. In the first four appeals-court decisions on DNA evidence, the defense failed to present any expert witnesses during trial, and cross-examination of the prosecution's expert witnesses was at best perfunctory.

Some of this was not for lack of trying. The defense counsel in one case explained that he had asked dozens of molecular biologists to testify but all had refused. Interviews with some of the scientists revealed that most of them, being familiar with scientific research involving DNA typing, assumed the forensic application of the technique would be equally reliable. Some who were aware of possible problems were reluctant to criticize the technology publicly for fear that this would be misconstrued as a gen-

eral attack on the underlying science.

Another troubling fact is that defense attorneys are often not able to spend the time or funds required to deal with the complexities of the issues. Novel scientific evidence is most often used to solve violent crimes, and defendants in such cases come predominantly from the less affluent sectors of society. Consequently, most of them must rely on court-appointed counsel selected from public-defender offices, legal-aid societies or the financially less successful members of the private bar. Many of these advocates are exceptionally skillful, but they often lack the time and resources to mount a serious challenge to scientific evidence. And frankly, there are also many less-than-adequate attorneys who are simply overwhelmed by the complexity of the subject.

What is more, in most states a court-appointed lawyer may not retain an expert witness without the approval of the trial judge. In recent DNA cases in Oklahoma and Alabama, for example, the defense did not retain any experts, because the presiding judge had refused to authorize funds. In the *Castro* case, a critical factor in the defense's successful challenge was the participation of several leading scientific experts—most of whom agreed to testify without a fee.

Because defendants are seldom able to challenge novel scientific evidence, we feel that independent overseeing of forensic methods is the only way to ensure justice. Specifically, national standards must be set before a scientific technique can be transferred from the research laboratory to the courtroom, and there must be laws to ensure that these standards are enforced.

The regulation of forensic laboratories has an excellent model: the Clinical Laboratories Improvement Act of 1967 (which was amended in 1988). The act established a system of accreditation and proficiency testing for clinical laboratories that service the medical profession. The law was enacted to ensure that such service laboratories, which are not subject to the same peer scrutiny as research laboratories, would nonetheless provide reliable products and services.

In contrast, no private or public crime laboratory today is regulated by any government agency. Nor is there any mandatory accreditation of forensic laboratories or requirement that they submit to independent proficiency testing. It is also troubling that there are no formally enforced, objective criteria for interpreting forensic data. Four fifths of the forensic laboratories in North America are within police or prosecutor agencies, and so there is an enormous potential for bias because technicians may be aware of the facts of the case. In short, there is more regulation of clinical laboratories that determine whether one has mononucleosis than there is of forensic laboratories able to produce DNA test results that can help send a person to the electric chair.

Accreditation and proficiency testing will work only if implemented with care. National standards for forensic testing must serve the interests of justice, not of parties who have vested interests in the technology. This is not an imaginary danger: from 1988 to 1989 a committee of the American Association of Blood Banks set out to develop national standards for forensic DNA typing and brought in two scientists to provide expertise in molecular genetics; these two happened to be the senior scientists at Lifecodes and Cellmark, the two companies that perform virtually all commercial forensic DNA identification in the U.S.

Some observers suggest delegating the task of setting national standards for forensic DNA identification to the Federal Bureau of Investigation. But there is reason to be wary of this approach. Last year the FBI began to perform forensic DNA identification without first publishing its methodology in refereed journals. In the few pretrial hearings that have challenged DNA tests conducted by the FBI, the bureau has been reluctant to supply the raw data on which it based its criteria, citing its "privilege against self-criticism"—a concept that, incidentally, has little precedent in law. The FBI also opposes independent proficiency testing, arguing that no outsider is qualified to evaluate the bureau's performance. In addition, at a recent FBI-sponsored symposium on DNA typing that attracted 300 forensic scientists from around the country, FBI personnel were alone in opposing proposals requiring laboratories to explain in writing the basis for their conclusions and to have their reports signed by the scientists and technicians who conducted the test.

The FBI's stance on these issues flies against norms established elsewhere in the scientific community. For example, if the author of a scientific article refused to divulge his or her raw data to peer review, the article would be rejected. There is also a clear consensus in favor of independent proficiency tests. If a clinical laboratory refused to comply with any reasonable public request to examine the results of proficiency tests, it would risk losing its accreditation. And it would be unthinkable for a diagnostic laboratory to deliver to the obstetrician of a pregnant woman an unsigned report with only the word "abort" appearing on the page.

Independent scientists are finally beginning to awaken to the urgency of these issues. Last fall the New York State Forensic DNA Analysis Panel proposed detailed requirements for certifying, licensing and accrediting forensic DNA laboratories. The Congressional Office of Technology Assessment is expected to issue a report on the regulation of DNA typing by the time this article appears. The National Academy of Sciences has appointed a committee to study appropriate standards for DNA typing and is expected to issue a report early next year.

It is regrettable that these measures were set in motion only after flaws in current DNA typing came to light in the courtroom. We hope the anticipated reforms will enhance the interests of justice in the future, although this may be small solace to defendants who were wrongfully convicted or to crime victims who saw the true culprit set free. It is our hope that, with appropriate national standards and regulation of forensic laboratories, powerful new forensic techniques such as DNA typing will serve an important and beneficial role in criminal justice. When all is said and done, there should be no better test for identifying a criminal—or for exonerating an innocent suspect.

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The Solar-Neutrino Problem

Painstaking observations show that the sun emits fewer of these elusive particles than theories predict. This deficit challenges current understanding of physics and of the process by which the sun shines

by John N. Bahcall

Along with its familiar heat and light, the sun radiates great quantities of elusive subatomic particles called neutrinos. Neutrinos have no electric charge, are virtually massless and move approximately at the speed of light. They are unaffected even by the strong nuclear force that holds the nuclei of atoms together.

Observing such particles presents a formidable challenge, one that is interesting for the same reason it is difficult. Neutrinos interact so weakly with matter that they can emerge freely and provide information from otherwise inaccessible places such as the center of the sun. The message that the solar neutrinos carry is puzzling and provocative: some flaw seems to exist either in the current models of the sun or in our present understanding of the laws of physics. Solving this mystery may reveal new clues as to how the sun shines, how stars evolve and whether the forces of nature are fundamentally related.

The neutrino comes in three known types, or flavors. The one most often seen in terrestrial experiments is the electron neutrino, which interacts with common electrons. The other two flavors—the muon neutrino and the tau neutrino—interact with massive, short-lived cousins of the electron, known as muons and tau particles. Electrons, muons and tau particles, along with their corresponding neutrinos, are thought to be fundamental particles, some of the building blocks out of which the universe is constructed.

Solar neutrinos cannot be collected and studied, because most of them pass right through the earth. Occasionally, however, a neutrino interacts with an atom in an observable manner. From 1968 to 1986, the world's only solar-neutrino detector was a beautiful experiment conducted in the Homestake Gold Mine at Lead, S.D., by Raymond Davis, Jr., who was then at the Brookhaven National Laboratory and is now at the University of Pennsylvania. Davis filled a large tank with perchloroethylene, a cleaning fluid that contains chlorine. A neutrino can interact with chlorine 37 (a stable isotope that makes up one fourth of all chlorine on the earth), converting one of the neutrons in its nucleus into a proton and changing the atom into argon 37 (a radioactive isotope of the inert gas). Every few months Davis flushed the tank, chemically separated the argon atoms and counted them by their radioactive decays to estimate the flux of neutrinos that passed through the tank.

The rate at which neutrinos interact with ordinary matter is so slow that a new unit was defined to express it: the solar-neutrino unit (SNU, pronounced "snew"), equal to one event per second for every 10^{36} target atoms. Standard theories of the nuclear reactions in the sun predict that a chlorine 37 detector should observe a flux of 7.9 ± 2.6 SNU, wherein the errors describe the total theoretical uncertainty.

Almost as soon as the chlorine 37 experiment began running, the observed flux seemed low. At first the discrepancy could plausibly be attributed to theoretical and experimental uncertainties. After 18 years of refining the theoretical calculations and experimental data, the discrepancy stands and is now larger than the uncertainties. Davis and his co-workers find the flux of solar neutrinos to be $2.1 \pm .3$ SNU.

A second experiment, located in Kamioka, Japan, and known as Kamiokande II, has been monitoring solar neutrinos since 1986. This experiment employs a different detection method: it searches for electrons knocked free from water molecules by passing neutrinos. Measurements at Kamiokande II are consistent with Davis's results. The mystery of the missing neutrinos is commonly referred to as the solar-neutrino problem.

The neutrino problem concerns astronomers who are trying to understand the processes that enable the sun and other stars to shine. The outer layers of the sun are disrupted by convection, turbulence, rotation and magnetic fields, which make the processes occurring in these regions complex and difficult to understand. Neutrinos are generated deep in the sun's core, where conditions should be much easier to calculate.

Essentially all solar models postulate that the sun shines by nuclear fusion, whereby hydrogen nuclei (protons) fuse together into helium nuclei, also known as alpha particles (two protons and two neutrons bound together). About 600 million tons of solar hydrogen are consumed by this process every second. This set of reactions is thought to power stable solar-type and less massive stars. It is known as the PP chain because it begins by the fusion of two protons. The net result of the PP

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INTERNATIONAL ASSAULT on the solar-neutrino problem is under way at the Soviet-American Gallium Experiment (SAGE) in the Soviet Union. SAGE will search for neutrinos produced by the most basic nuclear reactions in the solar core. Initial results are expected in June. Visible light reveals information only about the sun's complicated outer regions; neutrinos pass through the interior as if it were transparent. Neutrinos offer a unique view of conditions inside the sun and a test of current theories of physics.

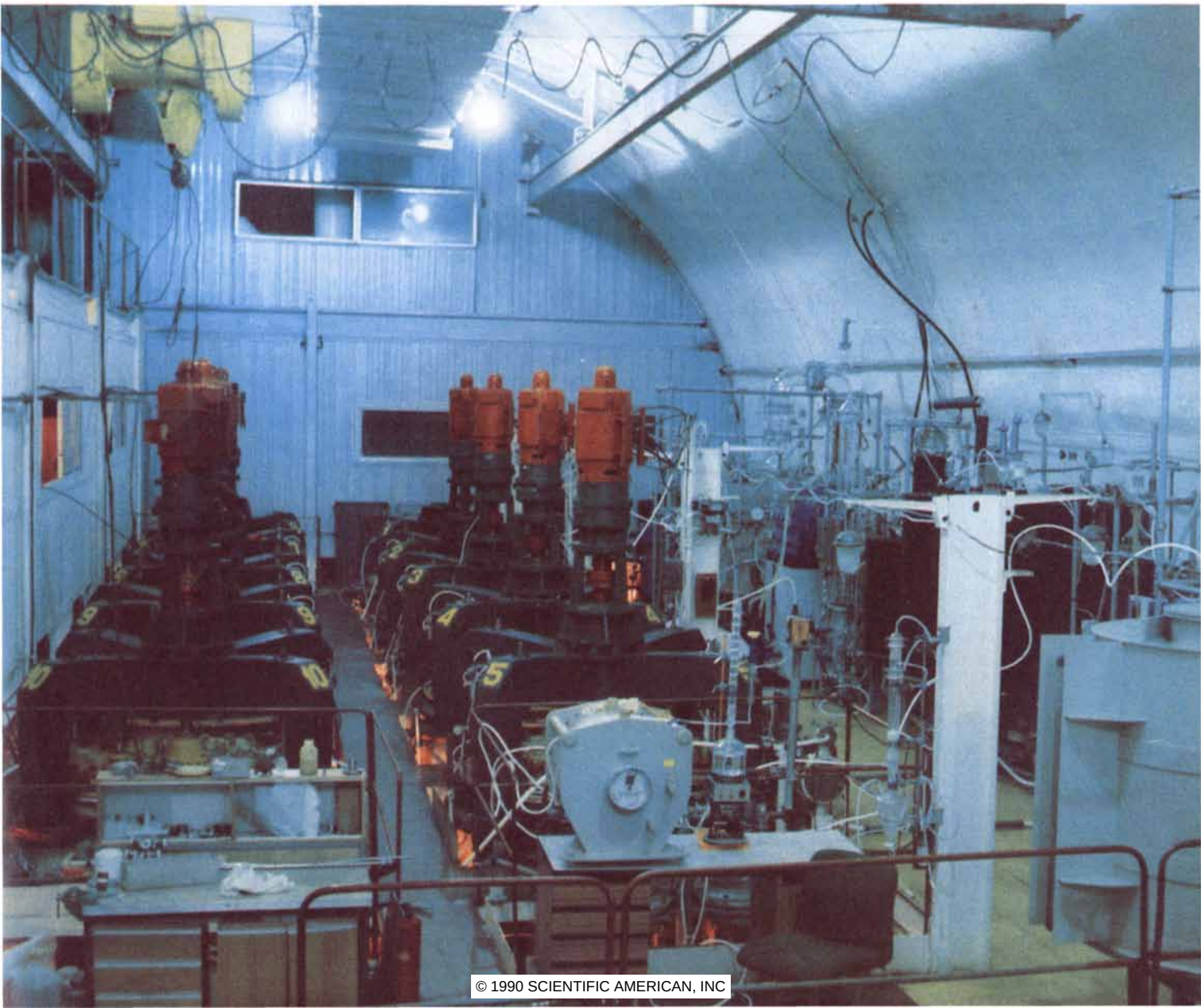
chain is that four protons are converted into an alpha particle, two positrons (the antimatter twins of electrons), two electron neutrinos and about 25 million electron volts of energy. (A photon of visible light has an energy of about two electron volts.)

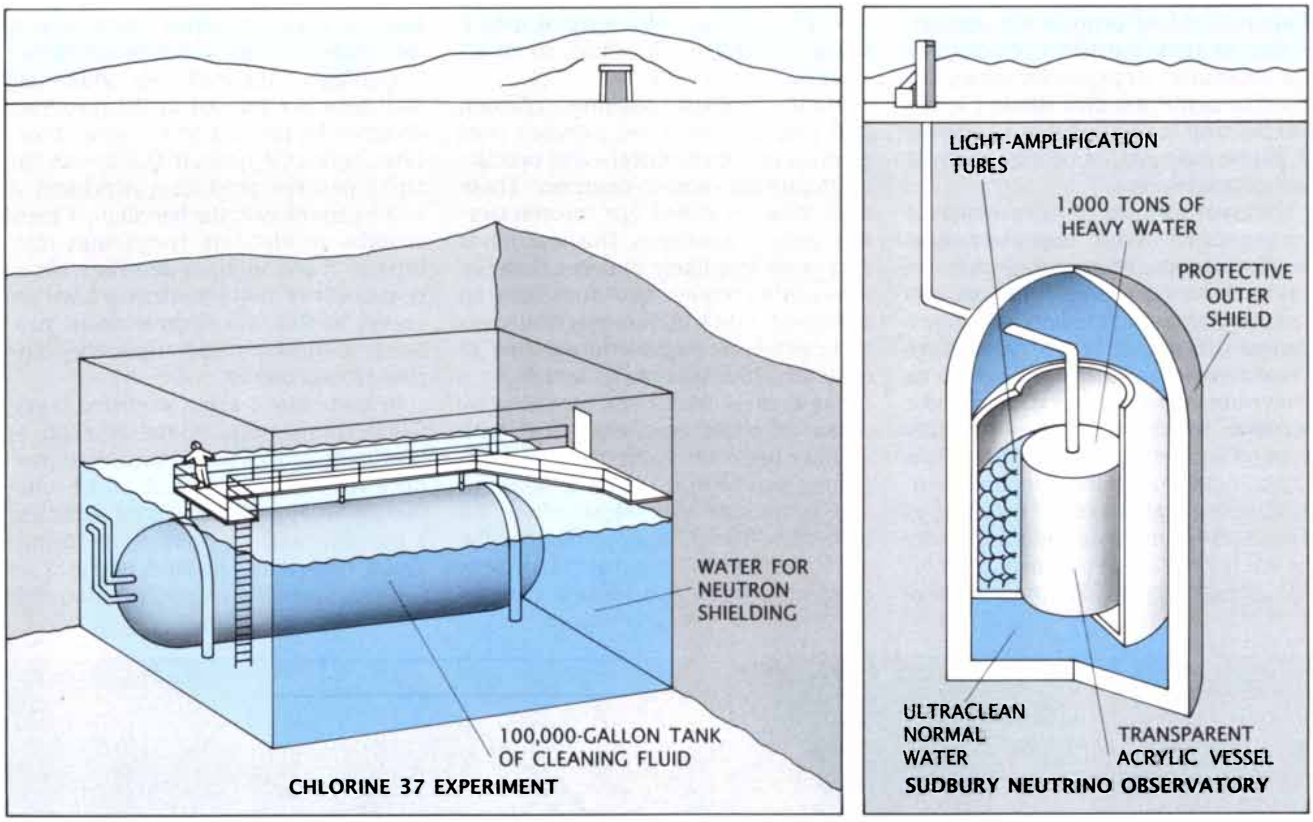
The great majority of solar neutrinos are generated by the first reaction in the PP chain, the PP (proton-proton) reaction, in which a proton decays into a neutron in the immediate vicinity of another proton; the two particles form a heavy variety of hydrogen known as deuterium, along with a positron and a neutrino. Neutrinos produced in this reaction have energies of no more than 420,000 electron volts. The lowest-energy neutrino that can be detected in Davis's experiment is determined by the energy required to transmute chlorine 37 into argon 37, approximately 814,000 electron volts. Kamiokande II has an even higher threshold, about 7.5 million electron volts.

Another neutrino-generating reaction in the sun involves three particles—two protons and an electron—and produces deuterium and a neutrino. These neutrinos are called PEP (proton-electron-proton) neutrinos. This reaction is 230 times less likely to occur than the PP reaction, but PEP neutrinos have an energy of 1.442 million electron volts and can be observed by the chlorine 37 detector, although not efficiently.

The deuterium nucleus produced by either of these reactions fuses with another proton to form helium 3 (containing two protons and one neutron) and a gamma ray. Most often—85 percent of the time, according to the standard models—the reaction cycle is completed when two helium 3 nuclei fuse to form an alpha particle and two spare protons, which return to the beginning of the cycle. No additional neutrinos are formed in this process. Roughly 15 percent of the time, however, helium 3 instead fuses with an alpha particle, producing beryllium 7 and a gamma ray; the beryllium 7 then absorbs an electron, transmutes into lithium 7 and emits a neutrino. Ninety percent of these neutrinos have an energy of 861,000 electron volts, just barely sufficient to show up in the chlorine 37 experiment.

In rare cases—about once for every 5,000 completions of the PP chain—beryllium 7 fuses with a proton to produce radioactive boron 8, which ultimately decays into two alpha particles, a positron and an energetic neutrino. These neutrinos can have energies as great as 15 million electron volts, and





NEUTRINO DETECTORS rely on rare interactions between neutrinos and ordinary matter. The first detector, operating in a mine in Lead, S.D., since 1968, contains 100,000 gallons of chlorine-rich cleaning fluid (*left*). Chlorine atoms occasionally absorb a neutrino, producing an atom of radioactive argon that can be chemically isolated. The new Sudbury Neutrino Observatory in Ontario (*right*) will incorporate 1,000 tons of heavy water (containing deuterium, or hydrogen with one neutron). A neutrino can scatter off an electron in the water, producing a burst of radiation, or off a deuterium nucleus, splitting it into a proton and a neutron. Deuterium can also absorb a neutrino, yielding two protons and a positron (an antielectron).

calculations indicate boron 8 decay is responsible for most of the neutrinos detected.

A helium 3 nucleus in the solar interior can fuse with a spare proton to form an alpha particle, a positron and a neutrino. The resulting HEP (helium-proton) neutrinos have energies of up to 18.77 million electron volts, but this reaction is so rare—1,000 times less likely than the boron 8 reaction—that it does not contribute significantly to the neutrino counts at existing detectors.

The theory used to predict these reactions is well understood and internally self-consistent. Yet the observed neutrino flux from the sun is not consistent with the flux expected from this set of reactions.

Could the solar-neutrino problem be the result of some error in the standard model of the sun? Such a model can in principle be highly precise because astronomers accurately know the sun's mass, luminosity, age and surface chemical composition. The sun is also a calm, middle-aged star that is still in its simplest stage of evolution.

The standard solar model is based on several plausible assumptions that are supported by considerable evidence. The sun is assumed to have evolved without any major departures from equilibrium since its birth. The nuclear reactions described above have the energy to supply the sun's luminosity for five billion years, the age of the solar system. Thermal pressure and the outward flow of radiation must exactly balance the inward pull of the sun's powerful gravity; otherwise the sun would collapse (or expand) in less than one hour. The sun presumably formed having a uniform chemical composition. Over millennia nuclear reactions in the core have consumed hydrogen and produced helium. The outer layers do not seem to mix with the core and so are thought still to approximate the sun's initial composition.

The standard model explains the relation between luminosity, mass and temperature in the sun and in stars differing in luminosity by as much as a factor of 100 million. In recent years acoustic oscillations of the sun's surface have been used to investigate its internal structure; the frequencies of the oscillations calculated from the standard model agree with the thousands of observed values to better than 1 percent. The greatest achievement of the solar model is so overwhelming that it is usually overlooked: astronomers use the theory routinely in interpreting observations of the physical and chemical compositions of stars in all sorts of environments, from the solar neighborhood to distant galaxies, without obvious inconsistencies. Any modifications of the solar model, therefore, would have profound implications for astronomy. The only direct signal of the stellar nuclear reactions predicted by the standard model is the neutrino flux from the sun. The problem is, the prediction seems to be wrong.

One might suppose that it is difficult to calculate the conditions at the center of the sun. Yet, despite the high temperature (approximately 15 million kelvins) and great density (150 grams per cubic centimeter, 13 times the density of lead), the center of the sun is expected to be described by well-known gas laws, modified only by small corrections that do not significantly alter the predicted neutrino fluxes.

A large source of uncertainty in calculating the solar-neutrino flux is the unknown composition of the deep interior, where neutrinos are generated. Several authors have noted that solar-neutrino production is sensitive to the chemical composition of the interior and have proposed models in which the sun was born with an interior composition quite different from that of its visible exterior. None of these models has proved to be consistent with all the observed characteristics of the sun. Moreover, various standard evolutionary models of the sun, developed by independent teams of researchers, predict neutrino fluxes identical to within 10 percent, provided they all use the same input parameters.

Is it possible that the calculated neutrino fluxes are in error? The margin of error in the calculated solar-neutrino flux is estimated on the basis of the total theoretical range, that is, the range of values that appear in plausible published calculations. This procedure provides no guarantee against a fundamental misconception in the theory underlying these calculations, but this method of estimating error has the advantage of simplicity and objectivity. In practice, the true value will lie outside the total theoretical range only if someone who determined an input parameter made a mistake.

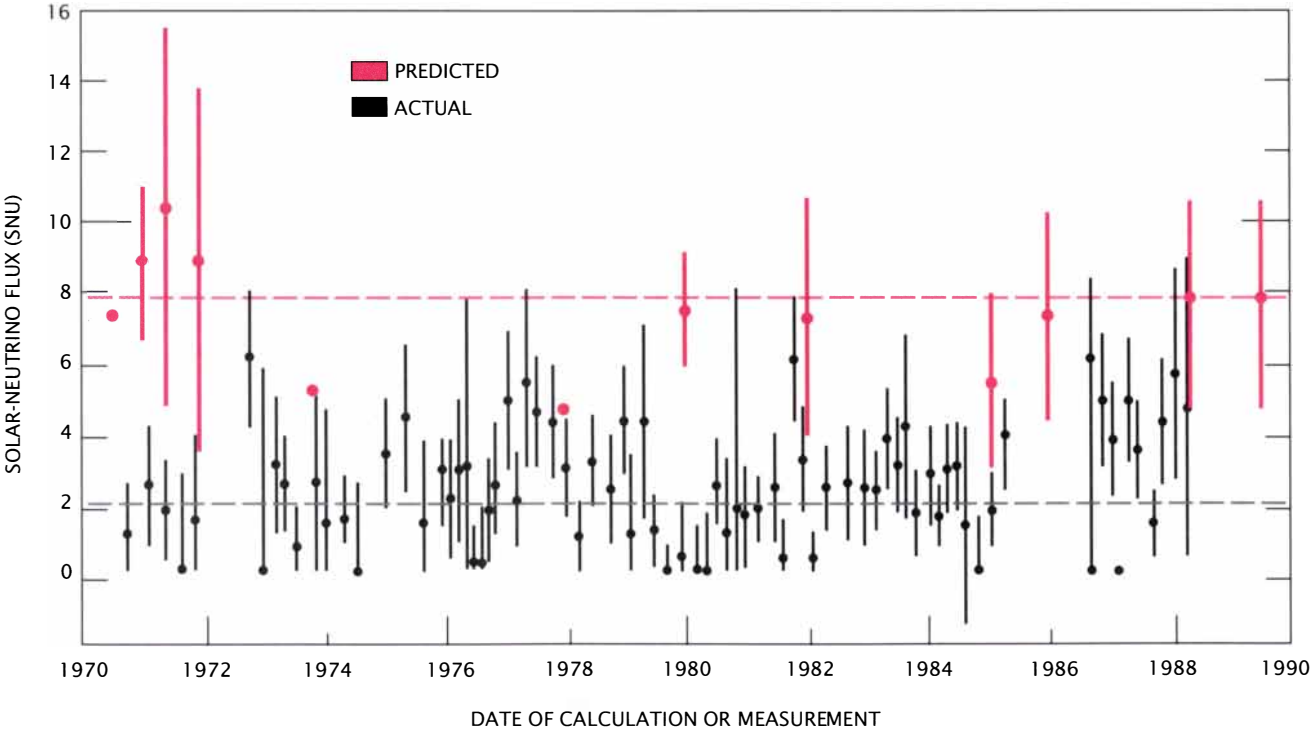
Between 1963 and 1988 my collaborators (most often Roger K. Ulrich of the University of California at Los Angeles) and I published 19 calculations of neutrino-event rates in a chlorine 37 experiment. All 11 of these calculations published since 1970 are consistent with the rate of 7.9 ± 2.6 solar-neutrino units given above.

Could experimental error explain the solar-neutrino problem? The chlorine 37 experiment is located deep underground in order to shield the experiment from the background of cosmic rays that can cause spurious signals. The argon 37 atoms produced in the tank are extracted with more than 90 percent efficiency; they are detected using sensitive electronic counters that can detect the radioactive decay of only one atom per month.

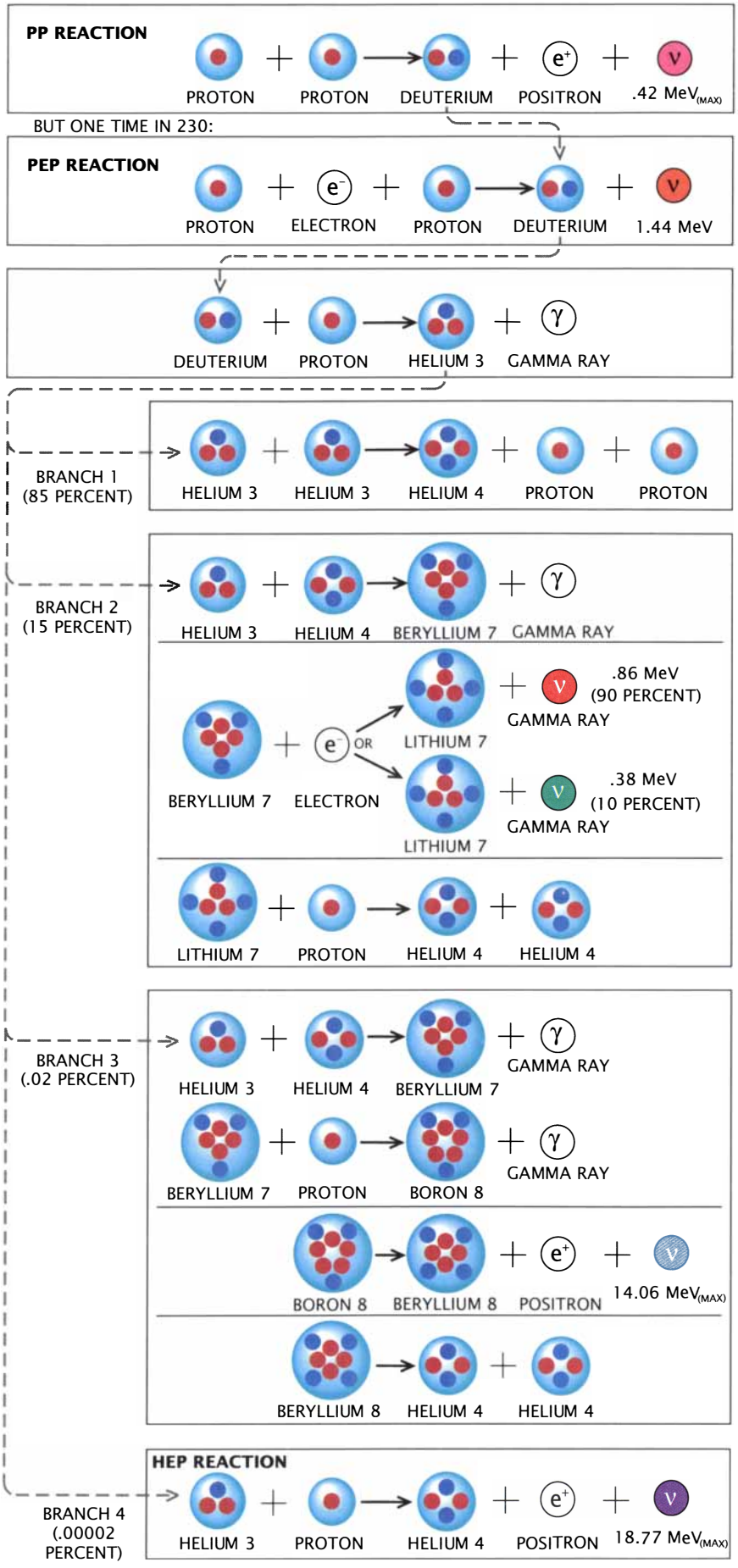
Davis has acquired and analyzed 18 years of neutrino-flux data, which show an average production rate of argon 37 of .46 ± .04 atom per day. The process of subtracting background and allowing for the efficiency with which chlorine 37 interacts with neutrinos leads to the problematic flux of 2.1 ± .3 SNU. The numbers reflect a 68 percent confidence level, meaning there is a 32 percent chance that the true value lies outside the stated range of error. Nine recent experimental runs, made between 1986 and 1988, imply a solar-neutrino flux of 3.2 ± .7 SNU, still well below the predicted flux but possibly indicative of a real increase.

The Kamiokande II experiment detects Cerenkov radiation (essentially an optical "sonic boom") emitted by electrons accelerated to close to the speed of light by interactions with energetic neutrinos. The Kamiokande detector was originally designed to observe the postulated decay of protons. Late in 1984 a team from the University of Pennsylvania (led by Eugene W. Beier and Alfred K. Mann) helped their Japanese colleagues (led by Masatoshi Koshiba and Yoji Totsuka of the University of Tokyo) to upgrade the detector to permit the detection of the less energetic events that are produced by solar neutrinos. By good luck the conversion was completed at the end of 1986, just months before the explosion of the bright supernova in February, 1987. Kamiokande II detected neutrinos from the supernova and found agreement with current theories of the physics occurring in these violent events.

Neutrino-electron interactions scat-



CALCULATED AND MEASURED solar-neutrino fluxes have consistently disagreed over the past two decades. Fluxes are measured in solar-neutrino units (SNU), defined as one neutrino interaction per 10^{36} atoms per second. Measurements from the chlorine neutrino detector (*black lines*) give an overall solar-neutrino flux of 2.1 ± .3 SNU (*black broken line*), although there are hints that the number may vary over time. Theoretical calculations since 1970 (*red lines*) consistently have predicted a flux of 7.9 ± 2.6 SNU (*red broken line*). Even at the extremes of the error ranges, the two values do not overlap. Either some process prevents neutrinos from being detected or the method by which the sun shines differs from that predicted by current theoretical models.



ter the electrons in the forward direction and so give some indication of the direction of the source of the neutrino flux. Kamiokande II has found that electrons are preferentially scattered along the direction of the earth-sun axis, confirming that neutrinos do indeed come from the sun. Preliminary neutrino-flux measurements from the Kamiokande detector are consistent with the chlorine 37 experiment, approximately .39 the number expected from the standard solar model. The two experiments together provide strong evidence that a real deficit of solar neutrinos exists.

One possible explanation for the neutrino deficit is that the sun is undergoing a temporary lull in activity and that over long periods its total neutrino output actually agrees with theory. To test this possibility, George A. Cowan of the Los Alamos National Laboratory and Wick C. Haxton, who is now at the University of Washington, proposed an experiment to measure the time variability of the neutrino flux. Solar neutrinos passing through the earth occasionally react with atoms of the rare element molybdenum, yielding an electron and a radioactive isotope of the element technetium; this isotope gradually decays but is continually replenished by neutrino bombardment. Only energetic solar neutrinos, such as those generated in the boron 8 process, are capable of driving this reaction.

Radioactive technetium has a half-life of 4.2 million years. Its current abundance reflects its overall rate of production during the past several million years and hence the intensity of the solar-neutrino flux in past ages. A research team headed by Kurt Wolfsberg of Los Alamos will measure the

PROTON-PROTON CHAIN of nuclear reactions is thought to provide more than 98 percent of the sun's energy. The initial proton-proton reaction produces the vast majority of solar neutrinos; these neutrinos have too little energy to be observed in the chlorine detector but should show up in the new gallium detectors. Energetic boron 8 neutrinos are thought to dominate the solar neutrinos detected in the chlorine experiment. The even more energetic helium-proton (HEP) neutrinos are so rare that they make only a minor contribution to the measured flux. The relative frequency of these reactions is based on inferences regarding conditions in the solar interior; if the inferences are wrong, the neutrino-flux predictions also could be wrong.

abundance of radioactive technetium in undisturbed rocks from the 1800-meter-deep Henderson molybdenum mine in Clear Creek County, Colo.

The standard solar model predicts that the behavior of the sun does not change over a few million years, and so the time-averaged neutrino flux from the technetium experiment should agree with contemporary flux measurements. If so, then the low flux of neutrinos from the sun is not a temporary phenomenon. If, on the other hand, the historical level matches the higher experimental predictions, the prevailing belief in the extreme constancy of the sun's behavior must be in error. Some uncertainty will linger, because the level of background radiation and the production rate of technetium are somewhat uncertain.

A key piece of information that is still missing is the quantity of low-energy solar neutrinos from the primary PP reaction, which cannot be determined by the chlorine 37 or Kamiokande II experiments. Two new neutrino observatories that use gallium 71 detectors will explore this energy range. When gallium 71 absorbs a neutrino, the result is an electron and an atom of radioactive germanium 71; the germanium atoms can be chemically separated from the gallium, and the amount of germanium 71 determined by counting radioactive decays.

The minimum neutrino energy necessary for the gallium 71 reaction is 233,000 electron volts, well below the maximum energy of neutrinos generated by the important PP reaction. Calculations based on the standard model of the sun and the commonly accepted physics of elementary particles indicate that neutrinos from the PP reaction should account for approximately half of the events detectable in a gallium 71 detector.

Gallium neutrino detectors are being operated in the Soviet Union and in Italy. The Soviet experiment is being conducted in conjunction with U.S. collaborators at Los Alamos, Louisiana State University, the University of Pennsylvania and Princeton University and is therefore sometimes referred to as SAGE (Soviet-American Gallium Experiment). This experiment uses 60 tons of gallium metal and has been constructed beneath a high mountain in the North Caucasus region of the Soviet Union. First results from SAGE are expected to be announced at an international conference in June.

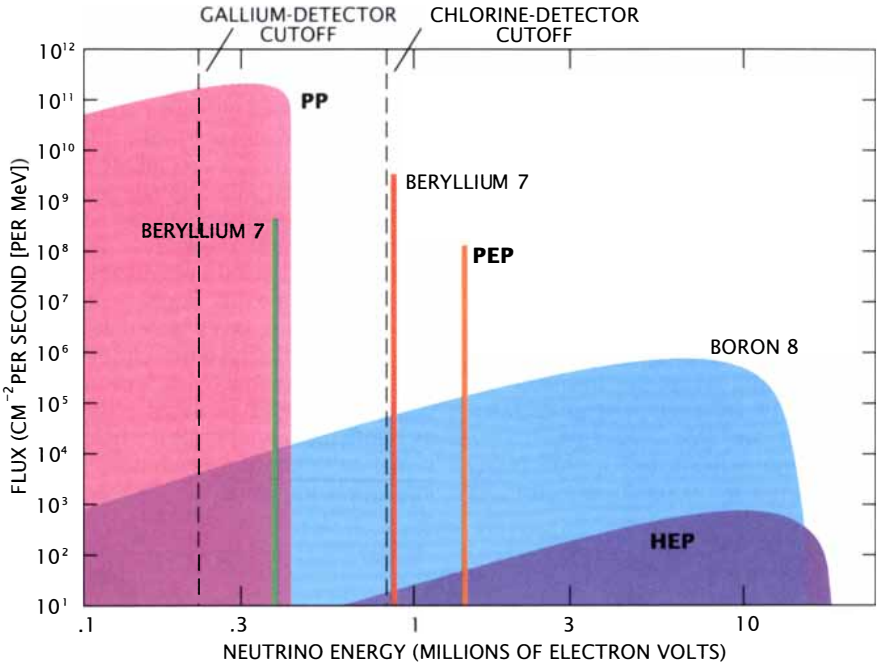
The experiment in Italy is being organized by GALLEX, a collaboration involving research teams from West Germany, France, Italy, Israel and the U.S.; it will employ a detector consisting of 30 tons of gallium in the form of gallium chloride. The experiment will be located in a laboratory built in the Gran Sasso tunnel in central Italy. The GALLEX group hopes to begin measurements this year. The scale of both of these experiments is impressive considering that at the time the experimental techniques were developed, the total world production of gallium was only 10 tons per year.

The SAGE and GALLEX experiments will use different chemical-extraction methods but similar atomic counters; a comparison of their results should reveal any systematic errors. Currently understood laws of neutrino physics imply that the event rate observed in the gallium experiments must be at least 60 percent of that predicted by the standard model in order to keep the sun shining; this is true virtually independent of possible alterations of the solar model. If the laws of physics are modified, however, the event rate could be different, perhaps no more than 10 percent of the standard value.

A powerful new neutrino detector is being developed as a follow-up to the gallium experiments. This past January, the Canadian and U.S. governments approved full funding for a detector consisting of 1,000 tons of heavy water (water containing deuterium in place of ordinary hydrogen) that will be placed in a nickel mine near Sudbury, Ontario. The Sudbury Neutrino Observatory (SNO) is a collaborative effort involving scientists from Canada, the U.S. and the U.K. It will search for electrons produced by neutrinos interacting with deuterium nuclei and will determine the energy and direction of these electrons; it also will monitor Cerenkov radiation from neutrino-electron scattering. The SNO neutrino telescope will be sensitive to boron 8 and HEP neutrinos but will be unable to detect less energetic solar neutrinos.

The SNO will function as a multipurpose detector since it will study both neutrino scattering and neutrino absorption. Absorption can occur only with electron neutrinos; scattering can occur with all three varieties of neutrinos, although muon neutrinos and tau neutrinos are only one seventh as likely to scatter off an electron as are electron neutrinos. Nuclear processes in the sun are thought to create only electron neutrinos, but some theorists have suggested that previously unrecognized physical processes in the sun could transform some of the electron neutrinos into the other two varieties, which would not show up in the chlorine 37 detector. This identity crisis for neutrinos is discussed below.

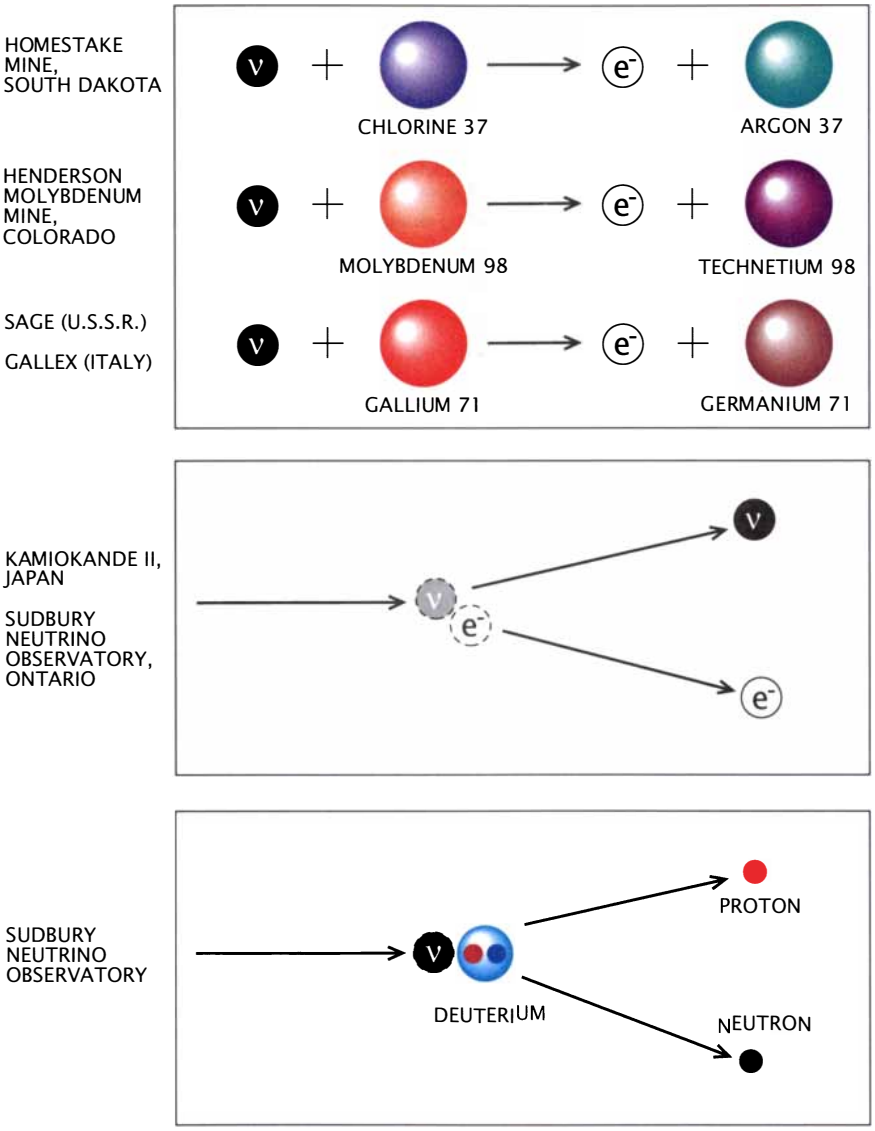
One kind of reaction in a deuterium detector is equally sensitive to all three



ENERGY SPECTRUM of neutrinos produced by nuclear reactions in the sun (*see illustration on opposite page*) derives from standard theories of neutrino physics. Broken lines mark the detection thresholds of gallium and chlorine experiments. The actual energy spectrum may be determined using detectors, such as the Sudbury observatory, that measure individual neutrino absorptions; if the shapes of the curves differ significantly from those shown here, then the standard theories will have to be modified.

varieties of neutrino: the neutral-current mode, in which a neutrino splits a deuterium nucleus into its neutron and proton components. This reaction could form the basis for an "equal opportunity detector" that avoids the biases of neutrino-absorption detectors (sensitive only to electron neutrinos) and scattering detectors (only weakly responsive to tau and muon neutrinos). Comparing the results of an equal-opportunity detector with those produced by more specialized experiments could settle the fundamental question of whether neutrinos transform from one type to another.

Low-temperature devices are being investigated as possible detectors of the low-energy neutrinos produced from the basic PP reaction in the sun. The underlying principle is that a little energy can have a big effect at low temperatures. A group at Stanford University is developing a crystalline silicon detector cooled to extremely low (millikelvin) temperatures to detect low-energy scattered electrons. Neutrino scatters could set up observable excitations in ultracold liquid helium, a possibility being investigated at Brown University. Other groups are developing a detector that uses indium 115, which undergoes neutrino absorption at relatively low energies. An international collaboration headed by Ramaswamys S. Raghavan of AT&T Bell Laboratories plans to study solar neutrinos using boron detectors that will generate flashes of light when neutrinos produce fast-moving electrons.



NEUTRINO INTERACTIONS with normal matter permit the study of solar neutrinos. A neutrino absorbed by an atomic nucleus can transform a neutron into a proton; the atom transmutes into a different element and emits a high-speed electron (*top*). Electrons can scatter off neutrinos; the electron's motion roughly follows the path of the incoming neutrino (*middle*). A deuterium nucleus can absorb a neutrino and split apart with no transfer of electric charge (*bottom*); this neutral-current reaction can be caused by varieties of neutrinos that are not readily detected by other methods.

What possible solutions to the solar-neutrino problem may be revealed by these new detectors? One set of solutions focuses on modifications of the standard solar model. Perhaps—contrary to current belief—the core of the sun is greatly deficient in elements heavier than hydrogen, or perhaps thorough mixing in the sun dilutes heavy elements in the core throughout the mass of the sun. Unstable convection in the sun might cause it to behave differently from what is currently assumed. These modifications all lower the sun's estimated internal temperature and lead to reduced boron 8 neutrino production. None of the modified models is fully consistent with well-established physics, and each involves ad hoc assumptions designed primarily to accommodate the observed neutrino fluxes.

A fascinating solution that attempts to solve both the solar-neutrino problem and the "missing mass" problem in cosmology has been proposed by William H. Press of Harvard University and David N. Spergel of Princeton University and independently by John Faulkner of the University of California at Santa Cruz and Ronald L. Gilliland of the National Center for Atmospheric Research in Boulder, Colo. They hypothesize that an as yet unobserved class of subatomic particles known as weakly interacting massive particles (WIMP's), created in vast quantities in the early universe, account for the large quantities of invisible mass that seems to exist in large cosmic structures. These particles might collect around massive objects such as the sun; if they have the correct properties, WIMP's could redistribute the heat within the sun, reducing the flux of boron 8 neutrinos to the levels detected.

It is also possible that the current models of the sun are correct but that there are deficiencies in the current theories of physics. The theoretically expected neutrino fluxes from the sun are calculated on the basis of the highly successful Standard Model of particle interactions developed by Sheldon L. Glashow of Harvard University, Steven Weinberg of the University of Texas at Austin and Abdus Salam of the International Centre for Theoretical Physics in Trieste, which created a unified description of the electromagnetic and weak nuclear forces. In the simplest version of the Standard Model, all neutrino masses are exactly zero, but

extensions of the model permit a wide range of neutrino masses.

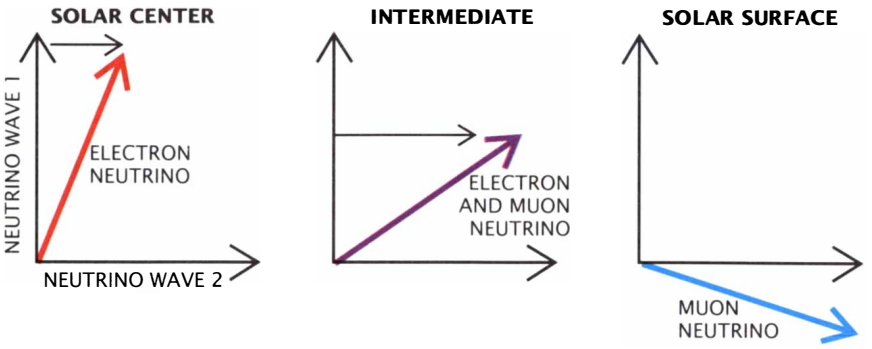
No generally accepted measurement of neutrino masses has yet been made, although cosmological arguments suggest that none of the neutrino flavors has a mass greater than 80 electron volts. The masses predicted by the extensions of the Standard Model are far smaller, in the range of from one electron volt to one millionth of an electron volt.

Measuring such small masses is currently impossible in purely terrestrial experiments, but it may be achieved by examining solar neutrinos. Any neutrino mass would affect the way the particles propagate over long distances, such as between the earth and the sun. Observations of solar neutrinos potentially can reveal a mass as small as one millionth of an electron volt and so offer a method of testing new theoretical models of physics.

A neutrino with a mass could act as a small magnet; it might be possible for the sun's magnetic field to flip the direction of the spin of a neutrino as it emerges from the interior. A neutrino that has a flipped spin would not have been detected. This solution, first proposed many years ago, has recently been revived by Soviet scientists to explain a suggested inverse relation between solar activity and neutrino flux. At times of high solar activity, the level of solar magnetism increases. The solar-neutrino flux appears to have dipped during the peak of the previous cycle (1979–1980) and then to have increased during a time of reduced activity (1986–1988). This solution posits that the neutrino has a magnetic field that is far stronger than standard theories predict and that, according to some calculations, is inconsistent with other astronomical evidence.

Some extensions of current theory, called grand unified theories, or GUT's, seek a common framework for describing all four of the natural forces. In 1985 the physics community was electrified when an elegant solution to the solar-neutrino problem that is consistent with neutrino-mass predictions from GUT's was proposed by Stanislav P. Mikheyev and Alexi Yu. Smirnov of the Soviet Academy of Sciences in Moscow, based on earlier work by Lincoln Wolfenstein of Carnegie-Mellon University. According to this solution, neutrinos can oscillate between the three types, a phenomenon referred to as the Mikheyev-Smirnov-Wolfenstein (MSW) effect.

The MSW effect requires that at least one neutrino have a nonzero mass. As they propagate, neutrinos behave not only as particles but also as waves; a neutrino wave can be considered a combination of two or more states with different masses that move at different speeds. The phase between the two component states could change as the different mass states fall out of step with one another, making an electron neutrino look like a neutrino of a different variety.



MIKHEYEV-SMIRNOV-WOLFENSTEIN (MSW) EFFECT proposes one possible solution to the solar-neutrino problem. Neutrinos may behave as superposed particle waves (shown as two vectors) that move at different speeds. Conditions in the sun could shift the phase of the waves, making a normal electron neutrino (*vertically inclined arrow*) behave like a muon neutrino (*horizontally inclined arrow*), which is difficult to detect.

In the interior of the sun, interactions between electron neutrinos and the densely packed electrons might alter the balance of mass states in the wave; the neutrino would emerge from the sun looking like a heavier tau or muon neutrino, which would not show up in the chlorine 37 detector. Even in a vacuum, the phase of the components of an electron neutrino might change and so alter its characteristics. The neutrino flux might appear to be much less than what is predicted by standard theory, even though neutrinos are created in the center of the sun at the standard rates. For the MSW effect to occur, the mass of the heaviest neutrino need be only from .01 to .001 electron volt.

If the MSW effect is the correct explanation of the solar-neutrino problem, then neutrinos hold important clues to the energies at which the four forces are unified. This energy is thought to be extremely high, perhaps as high as 10^{24} electron volts. Although this energy lies far beyond the range that can be achieved in terrestrial particle accelerators, scientists may be exploring it right now in their observations of neutrinos whose masses are so small as to be unmeasurable. How marvelous and awesome a possibility!

This gutsy explanation of the solar-neutrino problem can be tested directly. Nonstandard and standard solar models alike predict that the shape of the energy spectrum of solar neutrinos follows current calculations, although the total flux generated by each type of nuclear reaction might be different. The MSW explanation predicts that the transformation of electron neutrinos into the other varieties is energy-dependent. The expected energy spectrum therefore would be different from the standard prediction, and so, for example, the flux of PP neutrinos might be far less than current theories allow. The gallium experiments might show a large deficit of neutrinos, indicating the MSW effect at work.

The experiments that will be performed in the coming decade may at last reveal the solution to the solar-neutrino problem. They may point scientists toward a fuller understanding of how stars shine and evolve or perhaps toward a more complete theory of physics and the behavior of the elusive neutrino. If nature is especially cooperative, solar-neutrino experiments may do both.

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Adoptive Immunotherapy for Cancer

Also called cell-transfer therapy, it is one of a new class of approaches being developed to strengthen the innate ability of the immune system to fight cancer

by Steven A. Rosenberg

In 1968, when I was a surgical resident at a Boston hospital, I admitted a 63-year-old man complaining of abdominal pain characteristic of a gallstone attack. I then participated in the surgery to remove his gallbladder. It was a routine case, except for one extraordinary feature.

Twelve years earlier the man had come to the same hospital with abdominal trouble of a different kind. He had undergone surgery for stomach cancer. The tumor in the stomach was excised to ease his discomfort, but as often occurs, the cancer had spread to his liver, where it could not be removed. The man was sent home without treatment, presumably to die within several months. Unexpectedly, when he returned to the hospital for evaluation three months later, he was actually gaining strength. He continued to improve and soon stopped returning. Nothing more was heard from him until we operated on his gallbladder more than a decade later, at which point we found that all evidence of his cancer was gone. The cancer had disappeared.

The spontaneous disappearance of cancer is one of the rarest events in medicine and is often cited as evidence that the immune system—the body's main natural defense against viruses and other "foreign invaders" (including transplanted organs)—can sometimes mount an attack against cancer. Such evidence has spurred many investigators, including myself, to seek immunotherapies for cancer: treatments designed to enhance the native ability of the immune system to eliminate cancer cells. What is characteristic and dangerous about cancer cells is, of course, that they divide uncontrollably and can break off from the original tumor to establish growths (metastases) in other tissues.

During the past 10 years my colleagues and I at the National Cancer Institute have developed experimental immunotherapies for cancer. The treatments have led to the regression of advanced cancer in some patients whose tumors had failed to respond to other regimens.

In my laboratory we concentrate on what is called adoptive immunotherapy, or cell-transfer therapy. We remove cells involved in immune defense from a cancer patient and either "educate" the cells to react against the cancer or else enhance their native ability to kill cancer cells. We then return the immune-system cells to the bloodstream. In combination with the transfer of immune-system cells, or alone, we also administer molecules that are important in the immune response. With these molecules, which can be generated in quantity by recombinant-DNA technology, we attempt to stimulate anticancer activity directly in the body's immune-system cells. Several versions of our treatments are now available at many cancer-treatment centers, and we are intensively studying other versions we hope will be more effective.

Many difficulties remain. Immunotherapy can be complex, costly and associated with potentially severe side effects. Still, cell-transfer therapy and other immunotherapies for cancer are gaining a place beside the three traditional approaches: surgery to remove discrete masses, radiation to shrink or kill localized cancers that are not amenable to surgery and chemotherapy (the systemic injection of drugs to destroy cancerous growths throughout the body).

The need for new treatments is profound. Alone or together, surgery, radiation and chemotherapy cure cancer in almost half of the people in whom it develops. But the incidence of cancer, and thus the number of deaths, remains high. The disease arises in one of every four individuals. One in six people in the U.S. and Europe will die of cancer; in 1988 alone, cancer claimed in excess of 485,000 American lives, more than all who died in World War II and the Vietnam War combined.

Immunotherapy is a particularly appealing addition to the existing treatments in part because, like chemotherapy, it can be delivered systemically to combat metastases. What is more, the immune system is selective: it normally attacks only diseased cells, ignoring healthy ones. Hence, immunotherapies might be devised that are more cancer-specific than chemotherapies, which often kill dividing cells somewhat indiscriminately.

The idea of fighting cancer by unleashing the latent powers of the patient's own immune system is not new. Early in the 20th century some physicians attempted this feat by injecting patients with killed bacteria. Other workers, seeking to activate a cancer-specific response, injected patients with their own cancer cells. These approaches met with little success. Recent developments in immu-

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nology have, however, produced a vastly improved picture of how the immune system functions and, together with progress in genetic engineering, have yielded new leads for therapy.

It is now clear that the immune response involves the integrated action of an army of different cell types, including such white blood cells as monocytes, macrophages, eosinophils, basophils and lymphocytes. The cells of the immune system differ from those of other organs in that they are not in constant contact with one another; instead they circulate throughout the body, moving freely in and out of the circulatory and lymphatic systems.

The cells each have separate functions, but they interact in many ways and can actually regulate one another's activities. The commander and also the predominant foot soldier of this army is the lymphocyte. There are two major subclasses of lymphocyte—*B* cells and *T* cells—and these lymph cells account for the specificity of the immune response.

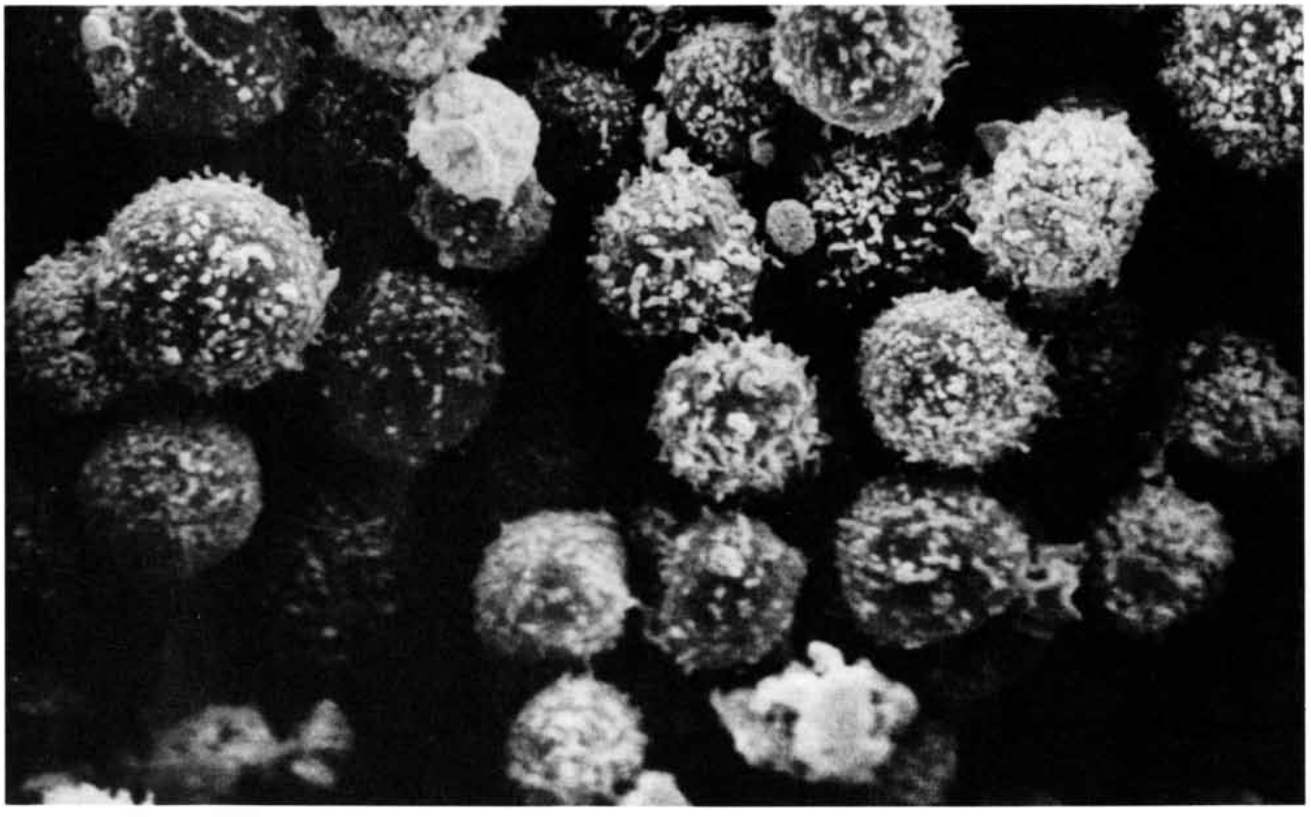
B cells govern the humoral, or antibody-mediated, arm of the immune response, which neutralizes bacteria and other invaders. Each *B* cell is able to recognize only a single antigen: a molecule that identifies a bacterium or other invader as "nonself." Activated *B* cells secrete circulating antibodies that bind to antigens or antigen-bearing targets and mark them for destruction by other components of the immune system.

The *T* cells direct what is called cell-mediated immunity: the destruction by cells of the immune system of foreign tissues or infected cells. There are a variety of *T* cells, including "helper" and "suppressor" cells, which modulate the immune response, and cytotoxic (or "killer") cells, which can kill abnormal cells directly. As is true of *B* cells, each *T* cell bears receptors for only a single antigen. A *T* cell that recognizes and binds a unique antigen displayed on the surface of another cell becomes activated: it can multiply, and if it is a cytotoxic cell, it can kill the bound cell. Cancer cells sometimes display antigens not found on healthy cells, and so they can potentially activate *T* cells carrying receptors for those antigens.

Discoveries made in the 1970's and 1980's further revealed that the cells of the immune system often control one another's activities by secreting small amounts of potent hormones known as cytokines. These newly identified proteins, which include lymphokines (the hormone products of lymphocytes) and monokines (the products of monocytes and macrophages), differ from classic hormones such as insulin in that they normally act locally and do not circulate in the blood.

The new understanding of the immune system led my research group to pursue various lines of investigation into immunotherapy. Hoping to harness the specificity of lymphocytes, we took on the major research challenge of developing adoptive immunotherapy with those cells. We are also studying the effects of delivering one or more cytokines to patients, in an attempt to enhance the cancer-fighting activity of lymphocytes circulating in the body.

The major obstacle to the initial development of the cell-transfer approach for the treatment of human cancer was our inability to isolate from cancer patients, and to ex-



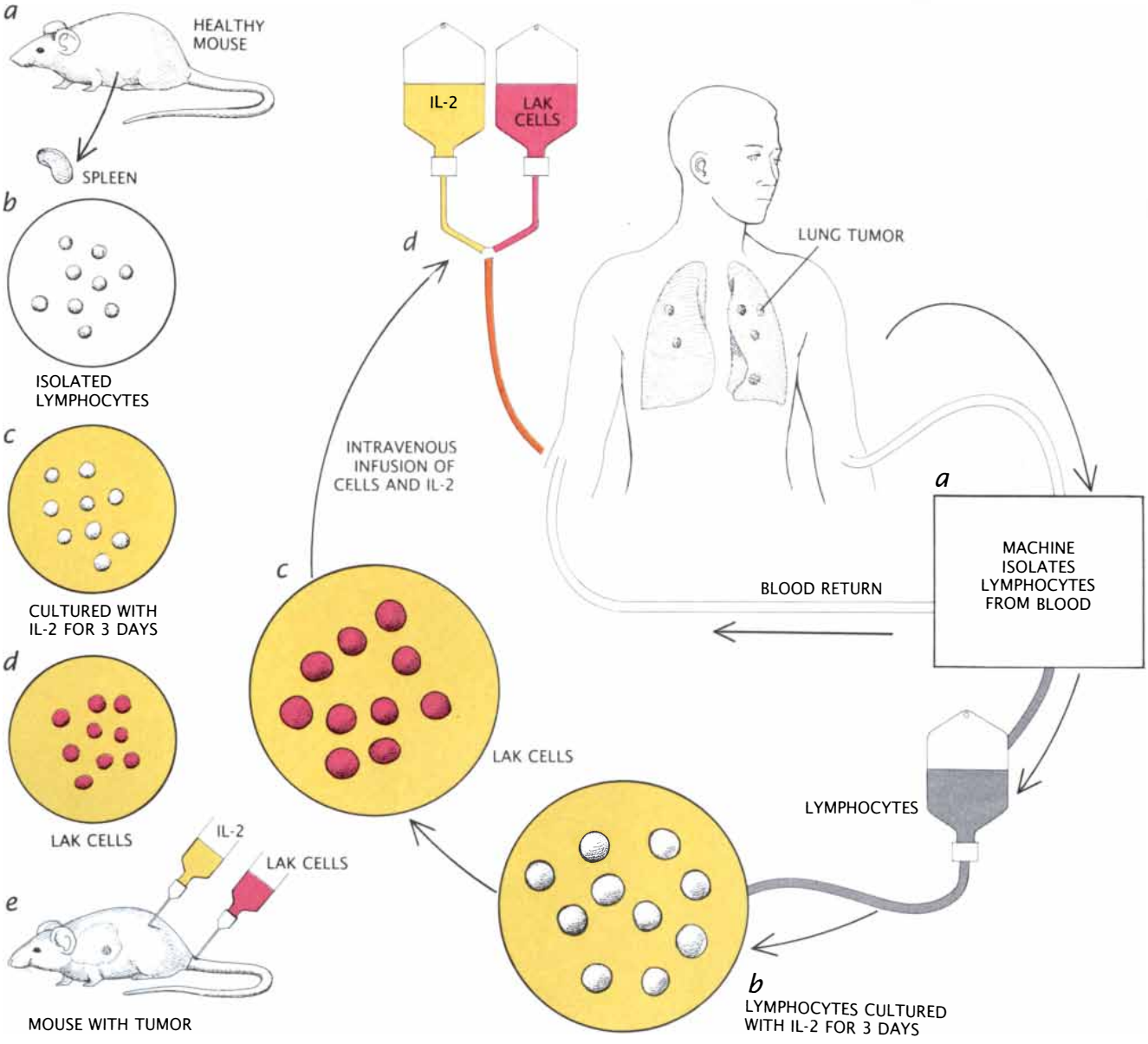
SCANNING ELECTRON MICROGRAPH shows *T* lymphocytes from a patient's cancerous tumor that were cultured in hollow-fiber cartridges. The cultured cells look like any other lymphocytes but are, in actuality, a new experimental weapon against cancer: they are TIL's, tumor-infiltrating lymphocytes, which are able to recognize and attack a particular cancer. Studies suggest that adoptive immunotherapy (the infusion of cancer-fighting cells generated from a patient's own immune-system cells) based on TIL's can help reduce or eliminate advanced cancer in some patients with melanoma (a skin cancer).

pand to large numbers, lymphocytes that have activity against cancer. The potential value of cell-transfer therapy had nonetheless been suggested by studies in animals.

In animals it is possible to raise immune-system cells with reactivity against tumors by repeated immunization of the animals with tumor cells. Indeed, in the late 1960's, Peter Alexander of the Chester Beatty Research Institute in London and Alexander Fefer of the University of Washington showed that the intravenous delivery of lymphocytes from immunized mice into tumor-bearing mice of the same inbred strain could mediate the regression of tumors. (Because the inbred animals are genetically and immunologically identical, the recipient's immune system does not sense that the lymphocytes come from another animal and so does not destroy them.) No feasible way to raise lymphocytes for application in humans had been found, however.

My own first attempts at cell-transfer therapy for humans were born of desperation. In 1968, shortly after encountering the patient whose stomach cancer had disappeared spontaneously, I obtained a unit of blood from him and infused it into another man who also had stomach cancer and was close to death. This transfusion had no effect on the second patient's disease. Similar attempts by other physicians were likewise unsuccessful.

Later I treated a series of cancer patients by delivering lymphocytes derived from pigs immunized against the patients' cancers. The patients were



LAK CELLS (lymphokine-activated killer cells), which were first described in 1980, are another experimental anticancer weapon. For study in mice (*left*), production begins with the removal of the spleen from healthy animals (*a*). The lymphocytes in the spleen are isolated (*b*) and cultured for three days with interleukin-2 (IL-2) (*c*), a hormonelike product of *T* cells. During that time the interleukin-2 causes certain lymphocytes known as null cells to become LAK cells (*d*), which can recognize and attack a variety of cancers. In studies (*e*) the LAK cells, together with interleukin-2, are injected into tumor-bearing mice. For study in humans (*right*), lymphocytes are isolated from the bloodstream (*a*) and cultured with interleukin-2 (*b*) to generate LAK cells (*c*). When patients are treated (*d*), about 50 billion LAK cells are infused intravenously along with interleukin-2.

not harmed by the large numbers of pig lymphocytes, but neither were they helped. Thus, although cancer treatments based on the transfer of lymphocytes remained theoretically attractive, the impossibility of isolating and growing the number of cells needed for successful treatment paralyzed progress.

A discovery made in 1976 offered new encouragement. Robert C. Gallo and his colleagues at the National Cancer Institute described a molecule that was originally called *T* cell growth factor and is now known as interleukin-2 (IL-2). This cytokine is produced by helper *T* cells and causes both those cells and antigen-stimulated cytotoxic *T* cells to replicate [see "Interleukin-2," by Kendall A. Smith; SCIENTIFIC AMERICAN, March].

The discovery of interleukin-2 and the subsequent introduction of methods for growing abundant clones of *T* cells in culture with the cytokine suggested a new option. I thought that if my colleagues and I could isolate from a patient even a small number of *T* cells reactive against the individual's tumor, we might be able to expand the lymphocytes in the laboratory to produce the quantities needed for cell-transfer therapy.

If we were ever to test the ability of such cultured cells to mount an attack against a patient's cancer, we would first have to demonstrate that the injected cells retained their original properties and that they would evoke a strong anticancer response in animals. Therefore, while we sought ways to identify tumor-sensitive *T* cells in humans, we simultaneously conducted several animal studies of cultured lymphocytes.

In 1981 Maury Rosenstein, a postdoctoral fellow working in my laboratory, demonstrated that cultured *T* cells injected into mice did indeed maintain the ability to recognize antigen: they accelerated the specific rejection of skin grafts. Within about a year Timothy J. Eberlein, a surgical resident, and I demonstrated that cultured cells could induce the regression of widespread, metastasized cancer in mice.

In this work we extended an approach that had been exploited successfully by Fefer and his co-workers. Fefer's group had induced a lymphoma to form in the abdominal cavity of mice. They had then achieved regression of the tumor by placing cultured *T* cells from immunized mice in the cavity as well. Eberlein injected cells derived from the same lymphoma into the footpad of mice, waited for the disease to metastasize and then injected cultured *T* cells from immunized mice into a vein.

MELANOMA TUMORS that had spread across a patient's back (*left*) disappeared after LAK cells and interleukin-2 were infused (*right*). Cancer regresses fully in about 10 percent of patients with advanced melanoma or kidney cancer given this treatment.

We found that the treatment could cause complete regression not only of the tumor growing in the footpad but also of cancer that had spread to the blood and lymph nodes. This result was quite important because it meant that the cultured *T* cells did not have to be delivered directly to the cancer; after the *T* cells were injected into the bloodstream, they could find cancer cells on their own.

Later studies by John H. Donohue, another surgical resident in my laboratory, showed that the administration of interleukin-2 simultaneously with the cultured *T* cells enhanced the antitumor effects of the cell-transfer therapy, inducing cancer regression with fewer *T* cells. The cytokine probably helped by causing the transferred cells to multiply in the body.

These successes were heartening, but we continued to be stymied by the problem of isolating *T* cells with antitumor activity from people. Eventually an unexpected finding, made in the course of tackling that problem, led to our first adoptive immunotherapy for human cancer.

The new approach grew out of the discovery in 1980 that interleukin-2 had an unusual activity. Ilana Yron, a postdoctoral fellow, and I reasoned that if the body was mounting an immune response against a cancer, the tumor itself would probably have the highest concentration of tumor-specific lymphocytes. Working with Paul J. Spiess, a biologist in my laboratory, she therefore cultured tumor cells with interleukin-2, aiming to expand and isolate the population of lymphocytes specific for that particular tumor. To their surprise, they found that within three or four days, even before the lymphocytes could multiply, cancer cells next to the white blood cells in the culture appeared to die. It seemed interleukin-2 had an activity not identified before: it could actually stimulate certain lymphocytes to recognize and kill cancer cells.

My colleagues' discovery raised the exciting possibility that we might not need to identify lymphocytes already activated against a patient's cancer; we might be able to induce quiescent cells to attack. Follow-up studies confirmed that we could. When Yron and Spiess exposed lymphocytes from the spleen of healthy mice to interleukin-2, the treated lymphocytes killed tumor cells. Then Michael T. Lotze, a surgical resident, and I extended the work to humans. We showed that exposure to interleukin-2 enabled lymphocytes from the blood of healthy people to kill a variety of human cancer cells in vitro—including those from melanoma (a skin cancer), colon cancer and sarcomas (cancers of connective tissues). The activated cells, which we later named lymphokine-activated killer (LAK) cells, did not harm normal cells.

The pedigree of the cells was another surprise. When Elizabeth A. Grimm joined my laboratory as a postdoctoral fellow and examined the LAK cells in detail, she found that they were not cytotoxic *T* cells or indeed any kind of *T* cell. Nor were they *B* cells. They were derived from the "null" population that constitutes only about 5 percent of all circulating lymphocytes. These cells, ubiquitous in mammals, appear to be part of a primitive immunosurveillance mechanism that can eliminate cancerous or otherwise altered cells nonspecifically, without first hav-

ing to recognize a particular antigen. The ability of the LAK cells to kill a variety of tumor types in vitro suggested that their injection into patients with cancer might be beneficial.

The idea had to be tested in animals before it could be tested in people. In 1984, in my laboratory's first successful immunotherapy experiments with LAK cells, Amitabha Mazumder, a pediatric oncology fellow, injected the cells intravenously into mice whose melanoma had given rise to lung metastases. We found after two weeks that the lungs of the treated animals contained far less cancer than did the lungs of the untreated subjects in a control group. Next James J. Mulé, a postdoctoral fellow, and I quickly showed that administration of interleukin-2 along with the LAK cells enhanced the antitumor activity of the cells, much as it had earlier when the cytokine was delivered with *T* cells derived from immunized animals.

Other investigations revealed that interleukin-2 improved the therapeutic effectiveness of the LAK treatment by stimulating the cells to multiply in the body. Stephen E. Ettinghausen, a surgical resident, and I discovered that infused LAK cells divide in the organs of mice that receive both the cells and interleukin-2 but do not divide when the cells are administered alone. The series of studies suggested that LAK cells could travel in the body to cancers in animals. Under the influence of administered interleukin-2, they also proliferate at tumor sites and destroy cancer cells there.

Given that interleukin-2 improved the effects of LAK treatment, we naturally wondered whether injecting mice with the cytokine by itself could activate the anticancer properties of lymphocytes in the body. If so, large doses would probably be required, because the kidneys rapidly destroy circulating interleukin-2. When the gene for interleukin-2 was cloned and large amounts of the gene product became available, we ran the experiment. Indeed, very high doses of the substance alone did have antitumor effects in mice, although the results were not as impressive as when LAK cells were also administered.

By early in 1984, after doing preliminary clinical trials with killer lymphocytes that were activated by noncytokine immune stimulators, we were ready to undertake phase I trials to establish in humans the safety and the highest tolerated doses of LAK cells and interleukin-2. Because neither LAK cells nor interleukin-2 had ever been administered to patients, we could not begin with the combined therapy; instead we tested each substance separately. Each of the subjects in these and subsequent trials suffered from advanced cancer that had failed to respond to all standard therapies; none were expected to survive more than several months.

We treated six patients with activated LAK cells obtained by isolating the patients' own lymphocytes and then incubating the cells with interleukin-2. Typically we isolate the lymphocytes from circulating blood [*see illustration on page 64*]. Thirty-nine other patients were treated with varying doses of interleukin-2 by itself. None of the patients showed any detectable antitumor response. Later in 1984, after reviewing our data, the Food and Drug Administration gave us permission to test the combination of LAK cells and interleukin-2 as a treatment for patients with advanced cancer.

One of the first patients in the new trial was a 29-year-old nurse from Florida who had melanoma that had spread throughout her body, including to her arms, thighs, back and buttocks. Some tumors had been surgically removed, but others had appeared and had not responded to treatment with the drug interferon. We began her combination therapy with LAK cells and interleukin-2 in November, 1984. During the next three months all of her cancer disappeared. Today, more than five years later, she remains free of the disease.

Her case, which we reported along with 24 others in a 1985 paper in the *New England Journal of Medicine*, was the first demonstration that a therapy aimed at strengthening the activity of a patient's own lymphocytes could induce cancer regression. To date, we have studied more than 150 patients with advanced cancer, the majority of

	TREATMENT WITH LAK CELLS AND IL-2				TREATMENT WITH IL-2 ALONE			
Cancer Diagnosis	Number of Patients	Complete Regression	Partial Regression (At Least 50% of Tumor Mass)	Complete or Partial Regression	Number of Patients	Complete Regression	Partial Regression (At Least 50% of Tumor Mass)	Complete or Partial Regression
KIDNEY	72	8	17	25 (35%)	54	4	8	12 (22%)
MELANOMA	48	4	6	10 (21%)	42	0	10	10 (24%)
COLORECTAL	30	1	4	5 (17%)	12	0	0	0
NON-HODGKIN'S LYMPHOMA	7	1	3	4 (57%)	11	0	0	0
SARCOMA	6	0	0	0	—	—	—	—
LUNG	5	0	0	0	—	—	—	—
BREAST	—	—	—	—	3	0	0	0
OTHER	9	0	0	0	8	0	0	0
TOTAL	177	14	30	44 (25%)	130	4	18	22 (17%)

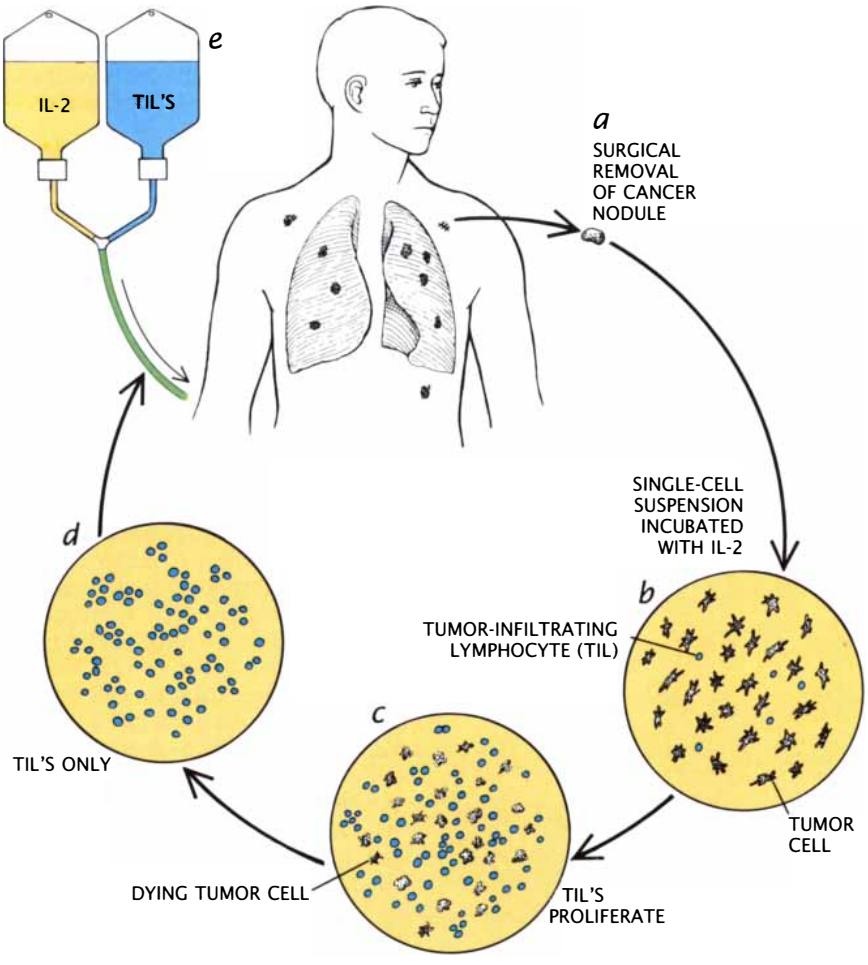
MORE THAN 300 PATIENTS with advanced cancers have been treated either with LAK cells and interleukin-2 or with interleukin-2 alone, which by itself can cause some cancer regression in both mice and humans. In mice the combination therapy is more effective than interleukin-2 alone, but more data are needed before a similar conclusion can be drawn for humans.

whom had melanoma or kidney cancer. (In most patients the original tumor or tumors had been removed, and in all patients the cancer had metastasized.) We have achieved complete tumor regression in about 10 percent of the patients with melanoma and 10 percent of patients with kidney cancer; the tumor mass decreased by at least 50 percent in another 10 percent of those with melanoma and 25 percent with kidney cancer. We have also achieved complete or partial regression of advanced cancer in patients with non-Hodgkin's lymphoma and colon cancer. As for specific tissues, cancers have been reduced or eliminated from the lung, liver, bone, skin and subcutaneous tissue.

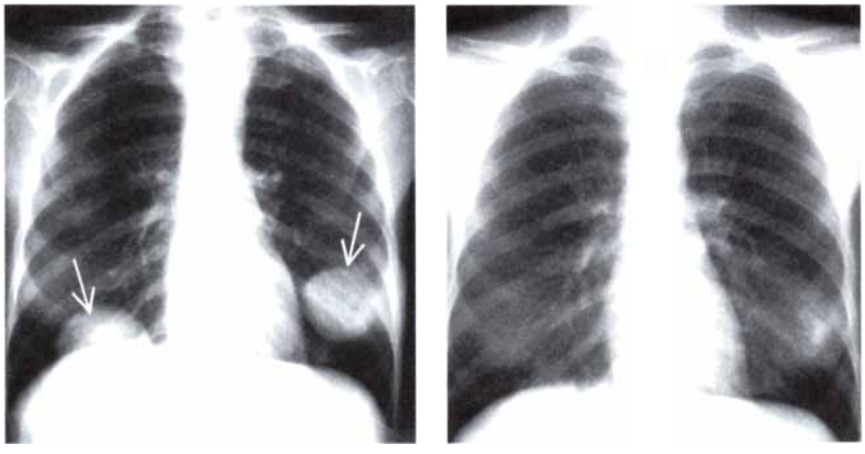
The therapy seems to work in people much as it does in mice. When we removed cancerous nodules from patients receiving the immunotherapy, we found extensive infiltration by lymphocytes along with many dead tumor cells. It appears that LAK cells and other lymphocytes make their way to tumors and, under the influence of the continuous administration of interleukin-2, divide there, causing cancer regression. Other studies have since shown that high doses of interleukin-2 administered alone can also induce cancer regression in some patients. Whether this treatment is as effective as the combined therapy remains to be determined.

Immunotherapy based on the administration of LAK cells plus interleukin-2 or in some cases of interleukin-2 alone is thus a treatment that can help about 20 percent of patients with certain advanced cancers. But its success comes at a price: there can be side effects. The proliferation of lymphocytes in tissues can interfere with the function of vital organs. The administration of high doses of interleukin-2 leads to the leakage of fluid from the blood into tissues, and weight gain from the fluid is common. Less commonly, the accumulating fluid impairs lung function and thereby impedes the delivery of oxygen to tissues. Very occasionally patients die from the effects of the interleukin-2, but the mortality—about 1 percent—is less than that associated with almost any systemic chemotherapy prescribed today for people with advanced cancer. In the remaining 99 percent of our patients, the side effects disappear rapidly once treatment is completed.

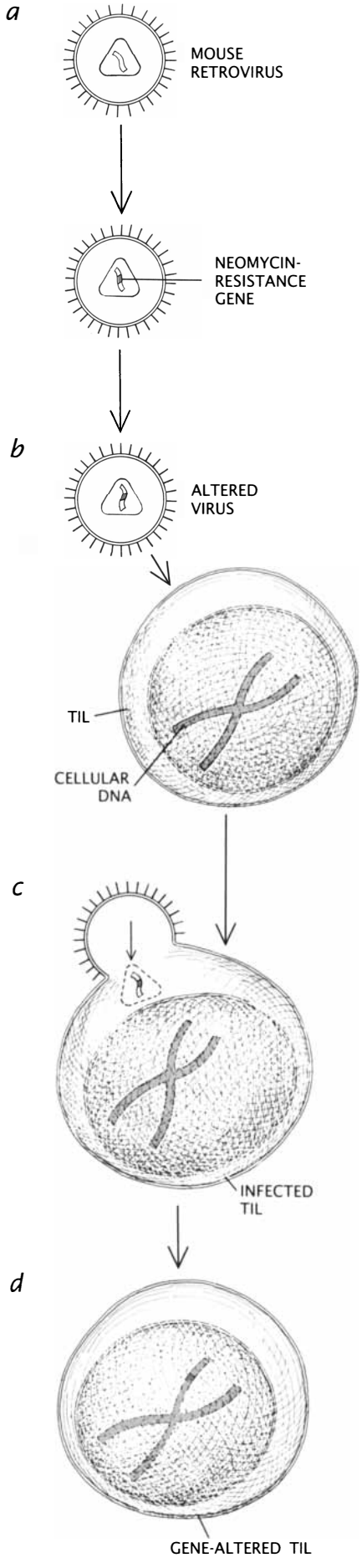
Treatment with LAK cells and interleukin-2 or with interleukin-2 alone is still experimental. In 1987, however, the FDA gave approval for federally designated Comprehensive Cancer



TIL'S, which seem to be more potent than LAK cells, take a month or more to generate for administration to patients. After a nodule of cancerous tissue is removed from a patient (*a*), cells in the nodule are separated from one another by enzymes and then cultured with interleukin-2 (*b*). Under the influence of the interleukin-2, lymphocytes scattered throughout the tumor—the TIL's (*blue*)—begin to proliferate rapidly and to attack the cancer cells (*c*). After a total of 30 to 45 days, the lymphocytes in the culture completely replace the tumor cells (*d*). Two-hundred billion of these replacement TIL's are then infused into the patient along with additional interleukin-2 (*e*).



X-RAY IMAGE made in October, 1987 (*left*), shows that melanoma had spread to a patient's lung (*arrows*). By December, after the patient was treated with TIL's and interleukin-2, most of the cancer had disappeared (*right*). Of 20 patients thus treated for advanced melanoma, 11 had a regression of at least 50 percent of their tumor mass.



Centers and Clinical Cancer Research Centers across the country to administer such therapy to patients with advanced melanoma or kidney cancer.

Our encouraging results with LAK cells led us to search for cells that were even more potent against cancer. We have recently found such cells. We discovered them about four years ago, after resuming our efforts to identify cells already activated against a patient's specific cancer. We again postulated that if the immune system were aroused against a cancer, the tumor site should have the highest concentration of cancer-sensitive lymphocytes. We therefore developed new techniques for isolating lymphocytes from tumors.

In one method we surgically removed a small tumor from an animal, enzymatically digested it to separate the cells and then cultured the cells with interleukin-2 for several weeks. During that time, what we call tumor-infiltrating lymphocytes (TIL's)—lymphocytes in the tumor—multiplied under the influence of the interleukin-2. LAK cells generally stop proliferating after about 10 days, but other lymphocytes capable of killing the tumor continued to grow vigorously and eventually replaced the tumor. We then analyzed these proliferating TIL's and studied their effects in animals.

The TIL's that overran the culture turned out to be classic cytotoxic *T* cells. Unlike LAK cells, they had the specificity we initially sought. On exposure to tumor cells in laboratory dishes, such TIL's often kill only the cells of the tumors from which they are derived and no others. In fact, they represent the best available evidence that at least some humans with cancer do indeed mount a specific immunologic reaction against their tumor.

When we injected our newly isolated cytotoxic TIL's into mice, we found that, on a cell-for-cell basis, they were from 50 to 100 times more effective than LAK cells in causing regression of established tumors—a finding we reported in 1986. That is, if 100 million LAK cells were needed to produce a 50 percent regression in an animal's cancer, only from one million to two million TIL's would be required to achieve the same degree of success. We also found that the TIL's were more effective than LAK cells at eliminating cancer in mice with widespread tumors.

It was not long before we began studying the efficacy of TIL therapy in patients. We obtained the TIL's by surgically removing a tumor nodule approximately the size of a small plum from patients, in most cases under local anesthesia. From the nodule we obtained about 50 million tumor cells; we then cultured them with interleukin-2 until they all died and were replaced by a rich supply of multiplying TIL's. Then approximately 200 billion of these cells were delivered intravenously, along with interleukin-2.

Data on the first 20 patients treated by this approach appeared in the *New England Journal* in December, 1988, almost exactly three years from the report of the first successful trials of LAK cells in humans. All the subjects had melanoma. Fifteen had never before been treated with interleukin-2, and in nine of these the melanoma regressed by at least 50 percent. The same degree of tumor reduction was also seen in two of the five patients who had received high doses of interleukin-2 in the past but to no avail. Thus, 55 percent of our group responded well to the therapy. In fact, the response rate was more than twice that seen when we gave LAK cells and interleukin-2 to patients with melanoma. We do not yet have a good sense of how long cancer regression will persist on average, although thus far cancers have remained in complete or partial remission for from several months to more than a year.

How do the TIL's work? Studies of radioactively labeled cells have shown that some fraction of the cells travel to cancer sites and accumulate there in the days following TIL infusion. Analyses of messenger RNA, the templates for proteins in a cell, suggest that the TIL's destroy tumor cells not only by direct contact but also through production of cytokines capable of mediating tumor-cell killing.

INSERTION of a foreign gene into TIL's is accomplished by a mouse retrovirus, which can splice its own genes into the genetic material of a human cell. In order to make the only genetically altered TIL's administered to patients thus far, workers replace retroviral genes crucial to viral replication with a gene encoding a protein that can render cells resistant to the lethal effects of the antibiotic neomycin (*a*). Next the altered virus is cultured with TIL's (*b*) so that the virus can infect the cells (*c*) and install its genetic material in the cellular DNA (*d*). Thereafter the foreign gene replicates whenever the infected TIL's replicate. Because altered TIL's express the foreign gene, they are uniquely resistant to neomycin and hence are readily distinguishable from all other cells in the body. They can thus serve as tracers to reveal the fate of TIL's inside patients.

Because TIL therapy includes infusions of interleukin-2, it produces much the same set of side effects as does LAK therapy. Yet the TIL's require less interleukin-2 to remain alive and active in the body, and so in the future we may be able to administer less interleukin-2 and thereby reduce the side effects.

Both LAK and TIL therapy exploit cells that nature has provided to the patient, and each is helpful for some people with some cancers. Might the innate therapeutic properties of those cells be improved by making small, carefully designed changes in their genes? My laboratory is collaborating with two others to create and test such "designer lymphocytes." The heads of those laboratories are R. Michael Blaese of the National Cancer Institute and W. French Anderson of the National Heart, Lung and Blood Institute, who have been developing gene-transfer techniques in the hope of eventually correcting inborn genetic defects in humans.

In 1988 Blaese, Anderson and I devised a two-phase strategy for testing genetically engineered lymphocytes in cancer patients. In the first phase we planned to introduce a foreign gene encoding a protein that would simply be a marker, helping us to determine the fate of TIL's in patients and to recover the cells for further analysis. We settled on a gene for a protein that normally makes bacteria resistant to a form of the antibiotic neomycin. Because TIL's would be the only cells in the body producing this protein, the substance would give us an easy way to identify the transferred lymphocytes. In this phase, which is now under way, we have performed the first successful introduction of foreign genes into human beings.

In the second phase, not yet begun, we planned to insert a gene into TIL's that we thought could enhance their therapeutic potency. Among the candidates we are still considering are the genes for the cytokines tumor necrosis factor and alpha interferon (both of which are known to have antitumor properties) or perhaps even the gene for interleukin-2 itself.

Our proposal for accomplishing the first phase was straightforward. We would remove a tumor deposit from a patient with advanced melanoma and grow TIL's as before. After about two weeks, when all the cancer cells were dead, we would take a small sample of the TIL's and introduce the neomycin-resistance gene. Although there are many techniques that can be exploited for introducing genes into mammalian cells, only one of these, which depends on the activity of retroviruses (RNA viruses), is efficient enough to be practical for our purposes. We selected a mouse retrovirus that was genetically engineered so that it could introduce the gene of interest into the TIL's but could not itself reproduce: all of the gene sequences required for viral replication were removed and replaced by the neomycin-resistance gene [*see illustration on opposite page*].

Once the alteration of the TIL's was accomplished by the retrovirus, the altered human cells would then be multiplied in parallel with the original TIL's. After verifying that the new gene was inserted and expressed as protein in the TIL's, we would infuse the altered cells along with nontreated cells into patients. (The unaltered cells were included in order to provide the desired therapeutic doses of TIL's.) Interleukin-2 would be administered as well.

Because of the newness of the gene-transfer technology and the fact that no gene-transfer studies had ever been authorized in humans, the government carefully evaluated the practical and ethical questions raised by our proposed trial. We initiated the review process on June 20, 1988, by submitting our protocol to the Investigational Review Boards of the National Institutes of Health. We received approval from James Wyngaarden, then the director of the institutes, on January 19, 1989. The agency would permit us to begin a clinical trial of 10 patients with advanced melanoma, all of whom had a life expectancy of 90 days or less.

During the intervening months the institutes' Biosafety Committee and Recombinant DNA Advisory Committee as well as the FDA had conducted additional reviews. These groups insisted that we demonstrate the ability to insert the marker gene in human TIL's and induce the cells to synthesize the encoded protein. They also required us to show that the TIL's were not significantly altered by the insertion of the gene, that we could detect marked cells in laboratory animals and that there was low risk to the patient and no risk to the public. We satisfied them on all counts. Then, on the day Wyngaarden announced his approval of the trial, a biotechnology activist filed a lawsuit to prevent us from proceeding, claiming the study had not had sufficient review. We were delayed again, but fortunately, the suit was settled quickly.

We treated the first person ever to receive gene-modified cells on May 22, 1989. We plan to report the results on the first five patients receiving these cells by this summer. Within a year we hope to begin studying TIL's genetically altered to have an improved therapeutic effect. The feasibility of exploiting genetically altered TIL's for cancer therapy will probably take several years to determine.

The therapeutic possibilities of genetically altered lymphocytes obviously extend far beyond cancer treatment. The cells may prove to be suitable vehicles for introducing genes that can treat a variety of other diseases in addition to cancer. For instance, genes that direct the production of clotting factors might be introduced into the body for treating hemophilia. Genes that encode the enzyme adenosine deaminase might be exploited to treat severe combined immunodeficiency disease, which makes certain children abnormally susceptible to life-threatening infections.

What was once an intuition is now becoming a reality. Immunotherapy for cancer can be effective. The treatments developed thus far can help only a limited number of patients, have toxic side effects and are complex and cumbersome to perform. But perhaps they are only the beginning. Extensive efforts are under way in laboratories around the world to develop immunotherapy into a practical, effective way to treat human cancer.

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Archaeopteryx

Although sometimes misclassified or even derided as a fraud, the prehistoric flier Archaeopteryx *remains a rich source of information about the evolution of flight in birds*

by Peter Wellnhofer

With its reptilian body and tail yet undeniably birdlike wings and feathers, *Archaeopteryx* provides paleontologists with their most conclusive evidence for the evolution of birds from reptiles. This pigeon-size prehistoric bird is known from only six fossil skeletons and the imprint of one lone feather, but paleontologists have deduced a wealth of information from those few specimens. From the time of its discovery more than a century ago, *Archaeopteryx* has been the object of heated discussions between critics and defenders of Charles Darwin's theory of evolution. *Archaeopteryx* has nonetheless defended its reputation and evolutionary theory against all challenges—even recent allegations of fraud.

In 1985 the British astronomer Fred Hoyle charged that the *Archaeopteryx* specimen in the British Museum of Natural History was a fake. He claimed that a forger had created the specimen by first applying a thin layer of binding material mixed with pulverized rock to the fossilized skeleton of *Compsognathus*—a type of small dinosaur called a theropod—and then making impressions of feathers in it. Hoyle and his colleagues also suggested that the other *Archaeopteryx* fossils either were forgeries or did not really show imprints of feathers. In England, *Archaeopteryx* soon became known as the Piltdown chicken.

Because of the publicity surrounding the affair, the British Museum decided in 1987 to stage a special exhibition to accompany the scientific reexamination of its fossil. Various tests proved that the stone in which the feather imprints were found did not differ in structure or composition from the surrounding material. Notwithstanding the modern appearance of *Archaeopteryx*'s feathers, nothing pointed to their being forgeries. Moreover, the stone plates encasing the skeleton fit together perfectly, which would have been impossible if the fossil had been tampered with by adding a layer of cement.

Ironically, the features that Hoyle saw as proof of the fossil's inauthenticity—its mixture of *Compsognathus*-like bones and modern feathers—are some of the most important clues that paleontologists have for understanding how birds and bird flight evolved. Its combination of anatomical characteristics from two distinct classes of animals make *Archaeopteryx,* the oldest-known bird, a textbook example of a transitional form between reptiles and modern birds.

The original discovery of *Archaeopteryx* came as if custom-ordered by the Darwinists. In 1861, only two years after the publication of Darwin's *The Origin of Species by Means of Natural Selection,* a fossilized skeleton with imprints of feathers was discovered in the limestone quarry at Solnhofen in Bavaria and passed into the possession of Carl Häberlein of Pappenheim, who later sold it to the British Museum.

This fossil, usually called the London specimen, was not the first evidence that birds existed in the late Jurassic period, 150 million years ago. One year before the discovery of the London skeleton, a worker in the Solnhofen quarry had found the impression of a single feather. Until then the oldest bird fossils were known only from the Tertiary period, almost 100 million years after the Solnhofen limestone formed.

In 1861 Hermann von Meyer, a paleontologist at the Senckenberg Natural History Museum and Research Institute in Frankfurt, reported that the feather imprint "is a real fossil and that it matches the feather of a bird perfectly." In the same report he also mentioned the London specimen: "[T]he almost complete skeleton of an animal covered with feathers had been found in the lithographic slate. It is said to show many deviations from the modern birds. I will publish the feather that I investigated with an exact illustration. I deem the name *Archaeopteryx lithographica* appropriate for the animal."

With this, the scientific name for the bird from Solnhofen, *Archaeopteryx lithographica,* was introduced. The name *Archaeopteryx* means "old wing," and *lithographica* is a reminder that limestone from Solnhofen was usually called lithographic slate during the 19th century. Only the stone from the Solnhofen quarry was sufficiently hard, compact and fine-grained to be used in the lithographic printing process. These same qualities preserved the bones and imprints of the feathers of *Archaeopteryx* with incredible delineation and clarity.

The geologic conditions that led to the formation of the Solnhofen limestone explain the exceptional preservation of the *Archaeopteryx* fossils. During the latter part of the Jurassic period, the area of what is today the southern Franconian Alb was a tropical lagoon divided into various basins by submarine reef complexes. North of this lagoon was the landmass of what is now central Germany; south of it was the Tethys Sea.

The region was not a South Seas paradise: the water in the lagoon was too salty and contained almost no ox-

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ARCHAEOPTERYX, **a prehistoric bird that lived in the Jurassic period 150 million years ago, is a perfect example of a transitional form in the evolution of modern birds from reptiles. The Berlin specimen clearly shows the typically avian plumage of its wings and tail. The skull and nearly reptilian skeleton of the fossil are also exceptionally well preserved.**

ygen. It was therefore inhospitable to most forms of life. Occasional storms caused floods that flowed over the southern reef barriers and carried multitudes of marine animals and plants into the basins. These died quickly in the lagoon waters, sank to the bottom and were promptly buried by layers of lime-rich mud.

Plants and animals from the northern landmass and its outlying islands also reached the lagoon at Solnhofen. These lands were home to many types of life: conifers, cycad ferns, ginkgo trees, insects, dinosaurs and *Archaeopteryx*. Tropical storms could have brought flying creatures to the lagoon by blowing them out to sea; currents could also have carried plants and animal carcasses there. Because almost no carrion feeders or microorganisms lived in the salty lagoon, dead organisms decayed little before fossilizing in the lime-rich sediments.

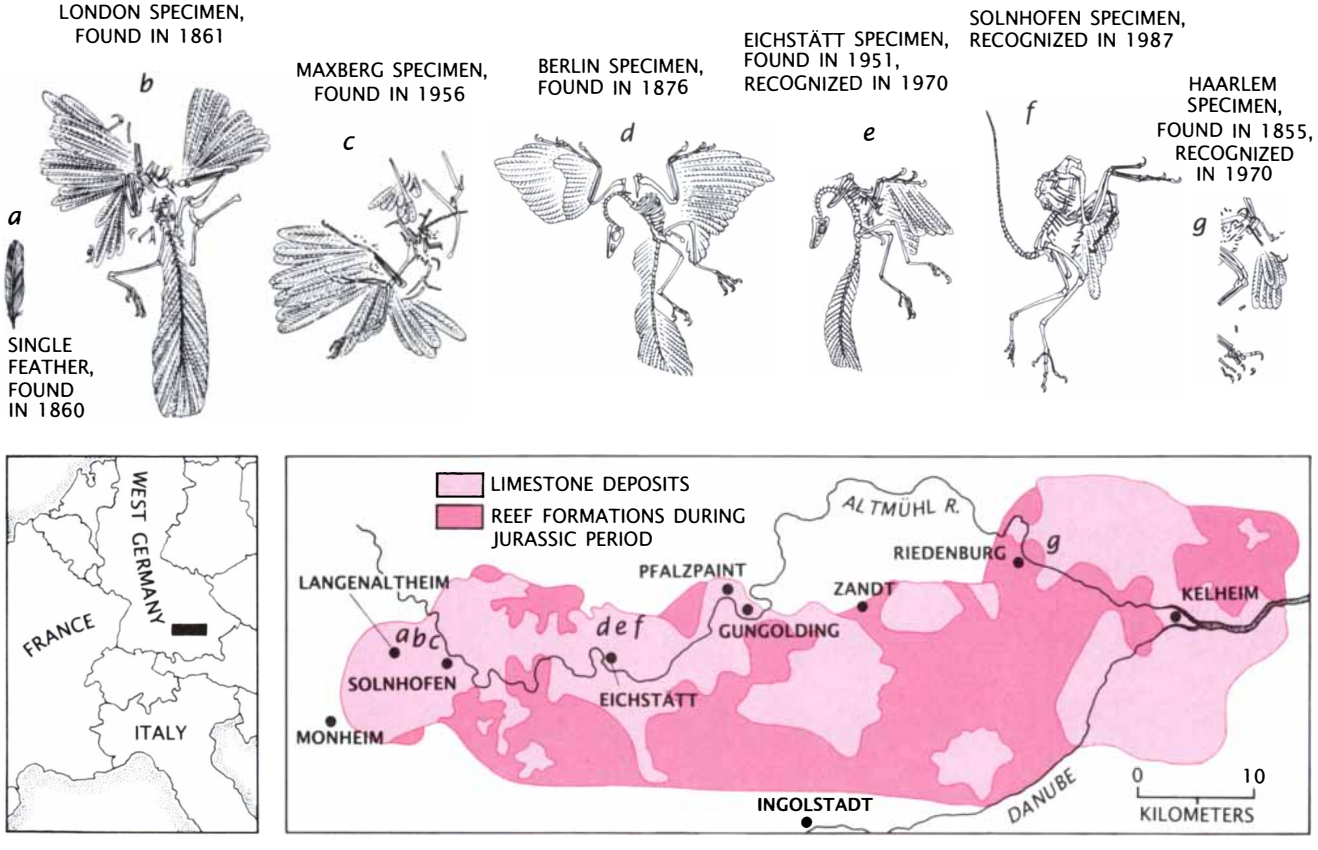
Six *Archaeopteryx* skeletons have been found so far, all in the Solnhofen limestone dating to the late Jurassic period. They are the oldest-known bird fossils. (Sankar Chatterjee of Texas Technical University in Lubbock has identified parts of fossil skeletons from much older Triassic strata in Texas as those of a bird that he calls *Protoavis*, but those skeletons are fragmentary and evidence for their avian nature has not yet been presented.) Each of these specimens contributes to the current understanding of the behavior and morphology of *Archaeopteryx* and of the origin of birds.

The London specimen represents almost the entire skeleton of *Archaeopteryx*. The skull, however, exists in fragments, and only the structure enclosing the brain and parts of the outer toothed jawbones have been preserved. In addition to the clear impressions of plumage on the wings and on the tail, another typical avian feature is present: the furcula, or wishbone, which evolved through fusion of the collarbones. Until only a few years ago the furcula was thought to be unique to birds; however, furculas have since been found in some dinosaurs from the Cretaceous period.

The second specimen was discovered in the fall of 1876 in a quarry near Eichstätt and later sold to Ernst Häberlein—the son of the man who called paleontologists' attention to the first specimen. He had initially categorized the fossil as that of a flying reptile. Only after Häberlein removed the overlying layers of stone did the well-preserved imprints of feathers come to light, prompting the reclassification of the fossil. The Museum for Natural History of Humboldt University in Berlin eventually acquired this *Archaeopteryx* specimen in 1881.

Known as the Berlin specimen, it is better preserved than the one in London. The articulated skeleton is in a natural position, which means that at the time of the animal's entombment at the bottom of the Solnhofen lagoon, decomposition had not yet begun. The skull has teeth like those of a reptile. The extreme backward bend in the neck, caused by the pull of the ligaments after the muscles relaxed, is a peculiarity of dead birds but has also been observed in fossils of flying reptiles and some other small dinosaurs with long necks, such as *Compsognathus*.

The wings of the Berlin specimen show the imprints of well-preserved feathers. The three "fingers" of the wing (or manus, as it is usually called by anatomists) were evidently mov-



SIX SKELETONS and one isolated feather imprint are the only known fossils of *Archaeopteryx*. All were recovered from a region in the southern Franconian Alb in West Germany (*left*), which was a tropical lagoon subdivided by reef formations during the Jurassic period. The letters on the map (*a–g*) show where each fossil was found. Some of the fossils were initially classified as pteranodons or other dinosaurs and were not recognized as *Archaeopteryx* until years after their discovery.

able and equipped with sharp, strongly bent claws. The fingers of modern birds are shorter, partially fused together and clawless.

The long, saurianlike tail of the Berlin specimen displays a biserial plumage; that is, there are two sets of tail feathers, each arranged symmetrically in a horizontal plane along the column of the tail vertebrae. The imprints of the feathers are especially rich in details because the entire structure of the feathers, down to the interlocking barbs, is visible.

After the discovery of the Berlin specimen, 80 years passed before another one was found. In a quarry not far from the site of the discovery of the London specimen, the fossil remnants of another winged animal were spotted in 1956. After analyzing them, Florian Heller, a paleontologist from Erlangen University, concluded that the specimen matched the one in London and was therefore *Archaeopteryx lithographica*. The fossil, which is privately owned, was lent to the Maxberg Museum near Solnhofen until 1974, which is why it is commonly known as the Maxberg specimen.

The Maxberg *Archaeopteryx* must have floated on the water for a long time after its death because its head and tail are missing: they must have separated from the body before fossilization occurred. The hind legs and the wings had detached from their natural positions but—judging from the orientations of the feathers—were still held together by tendons.

SINGLE FEATHER (*left*) from *Archaeopteryx*, which was unearthed in 1860, is virtually identical to the feathers of modern birds. These similarities extend even to the microscopic level, as shown in a close-up of tail feathers from the Berlin specimen (*right*), enlarged by about 500 percent. Detailed fossils of *Archaeopteryx* feathers have survived because of the hardness and fine grain of the Solnhofen limestone.

The fourth specimen of *Archaeopteryx* came to light after lying unrecognized in the inventory of the Teylers Museum in Haarlem, the Netherlands, for over a century. It was unearthed from a quarry in 1855 and was therefore actually found before the London specimen. Yet the specimen was misclassified as a pterodactyl as early as 1857. Not until 1970 did John H. Ostrom of Yale University recognize that its skeletal characteristics were typical of *Archaeopteryx*. The specimen was poorly preserved: all that remain are parts of bones from the left lower arm and wing, the pelvis and the hind legs. The claws on the wings and the feet are nonetheless remarkably well preserved.

The fifth specimen, too, was misidentified at first. It was found in a quarry in the area of Eichstätt in 1951, five years before the discovery of the Maxberg specimen. This skeleton is smaller than any of the others but is nearly complete; it was initially taken to be a small reptile similar to the chicken-size *Compsognathus*. Not until 1970 was it recognized as an *Archaeopteryx* by Franz X. Mayr of the University of Eichstätt, when he illuminated the fossil from the side to reveal the faint impressions of wing and tail plumage.

This Eichstätt specimen of *Archaeopteryx* has the best-preserved skull of any of the fossils. Recent computerized tomographic scans have shown that the articulation of the quadrate bone with the brain case is almost identical to that in modern birds. Based on the backward-bent neck and the good preservation and position—identical to those of the Berlin specimen—one can surmise that both animals died in similar ways.

Certainly the Eichstätt bird did not die of old age: the small skeleton suggests that the animal was only a juvenile. The metatarsal bones in the feet show no sign of fusion as those of the larger Maxberg specimen do. Also, the furcula is missing from the otherwise complete skeleton. The best explanation is that the immature furcula was still cartilaginous, not bony, at the time of death and consequently was not preserved in the fossil.

Another feature of the small Eichstätt *Archaeopteryx* is its relatively long hind legs. Their length indicates that the leg bones matured earlier than the wings and some other body parts. Young animals may have needed their hind legs for walking because their ability to fly may have developed only later in life.

The sixth and most recently discovered specimen of *Archaeopteryx* came to the world's attention in 1987, when Günter Viohl, the curator of the Jura Museum in Eichstätt, spotted the prehistoric bird in a collection of fossils belonging to Friedrich Müller, a former mayor of Solnhofen. No imprints of feathers were apparent, and most of the skull had been lost. Because of its long, strong hind legs and long tail, the fossil was initially mistaken for that of a *Compsognathus*. The fossil, which is on display in the Bürgermeister Müller Museum, now belongs to the village of Solnhofen.

All the recovered body parts in the Solnhofen specimen are in their natural, articulated position. Under low-angle illumination from the side, the left wing reveals small, curved impressions of shafts from the main feathers; the outer boundary of this wing is also well marked by impressions. There are no such signs on the right wing and the tail, but this can be explained by the position of the skeleton: the carcass of the prehistoric bird had sunk to the bottom of the Solnhofen lagoon on its left side, and its left wing had been deeply anchored in the protective mud on the bottom. The

feathers on the unprotected parts of the body could easily have been swept away by currents.

What is immediately striking about the Solnhofen specimen is its size. On the basis of the length of the wings, it is 10 percent larger than the London specimen—the largest previously known—and 50 percent larger than the small Eichstätt specimen. This *Archaeopteryx* was fully the size of a modern chicken.

Before one can make sense of the six fossil skeletons (and the single feather imprint), it is essential to address the important question of whether they are, in fact, all fossils of the same species. Indeed, their classification has always been controversial. Over the years many names have been given to the various specimens by paleontologists attempting to sort them into different species and even different genera.

The biological definition for a species—a group of actually or potentially crossbreeding populations—is useless for a paleontologist, who cannot test long-dead specimens by that criterion. Paleontologists usually have no choice but to define ancient species by their skeletal morphology. Working from incomplete information, paleontologists attempt to discriminate between the differing characteristics of species and the variations attributable to age, sex and other individual features. A species defined by paleontological deductions and one defined by biological traits are not necessarily identical.

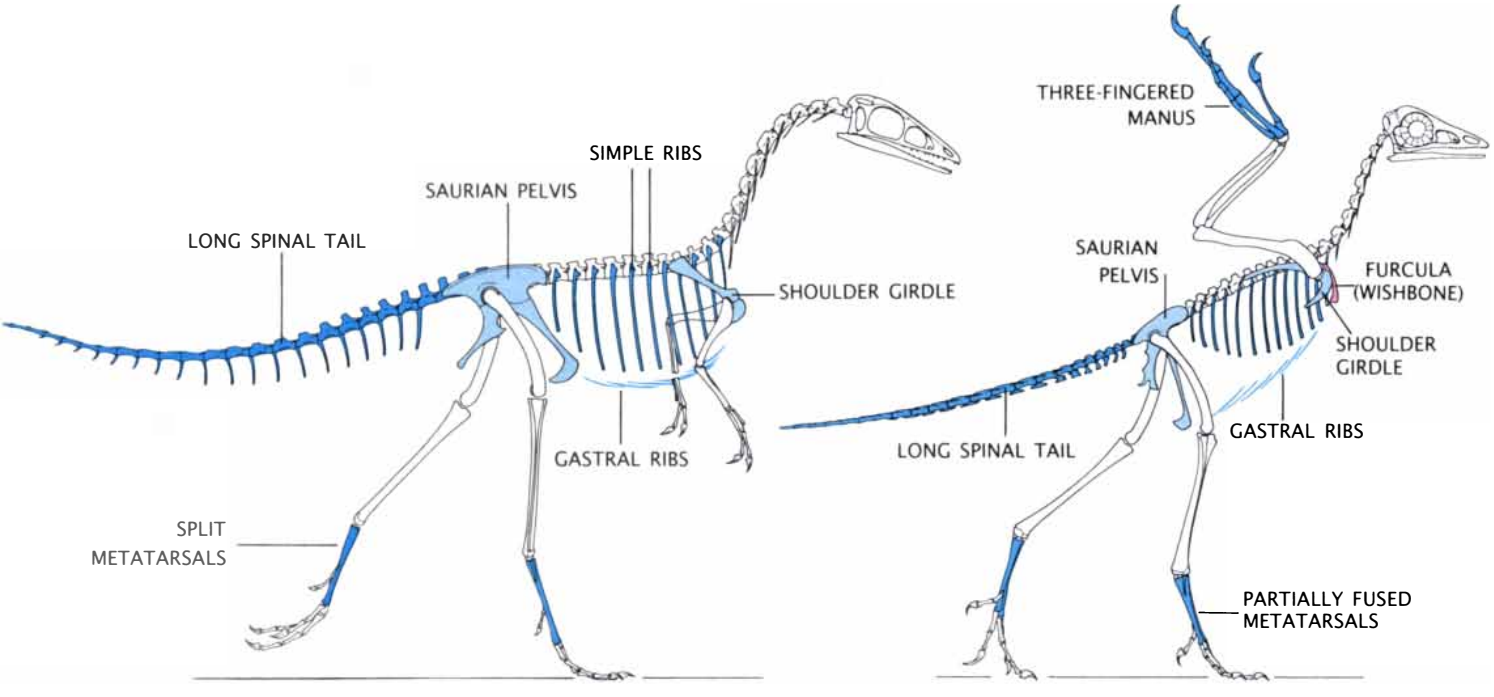
Part of the problem with classifying *Archaeopteryx* stems from ignorance of whether their growth pattern, as recorded in their bones, was more reptilian than birdlike. Reptiles grow throughout their lives (although the rate slows during advanced age); conversely, birds quickly attain a characteristic adult size. In reptiles the centers of growth are in the shafts of their hollow bones, whereas growth in young birds takes place at the bones' thick cartilaginous ends, called epiphyses. During the final stage of a bird's growth, its epiphyses turn from cartilage into bone, leaving a scar that disappears when the bird matures.

None of these *Archaeopteryx* specimens shows any such scars on its hollow bones. If the growth of these animals was birdlike, then the various specimens might indeed represent different species. On the other hand, if they had reptilian growth patterns—an assumption supported by the predominantly reptilian traits of the skeletons—then the specimens could clearly be members of the same species, differing in size and age. Recent studies by Marilyn A. Houck and Richard E. Strauss of the University of Arizona and Jacques A. Gauthier of the California Academy of Sciences support the view that the six specimens of *Archaeopteryx* represent different stages of growth of a single species.

These skeletal considerations and a complex set of other unknowns—such as whether the specimens lived hundreds of thousands of years apart or whether they differed in sex—lead me to conclude that the fossils should be assigned to one pragmatic classification: *Archaeopteryx lithographica*.

The birdlike appearance of *Archaeopteryx* raises the obvious question of whether or not the animal could fly. It is pertinent that no sternum, or breastbone, can be found in any of the specimens, even the large, presumably mature Solnhofen animal. Apparently, *Archaeopteryx* had not developed an ossified (or bony) sternum, a structure important to flight in today's birds.

The sternum of modern birds is a wide, arched shelf of bone that often extends from the chest to the pelvic area and serves as a protective, supportive bowl for the internal organs during flight. In the middle of the out-



COMPSOGNATHUS *ARCHAEOPTERYX*

ANATOMICAL COMPARISONS between the small dinosaur *Compsognathus*, *Archaeopteryx* and a chicken show that the evolution of flight involved structural changes throughout the body, as essentially avian features (*red*) evolved from reptilian ones (*blue*). *Archaeopteryx* had longer forelimbs than *Compsognathus*, but its three movable fingers were not short and fused together as in modern birds. *Archaeopteryx* did not have a bony sternum, which is essential for strenuous wing-beating, but it did have a furcula (wishbone). Like *Compsognathus*, *Archaeopteryx* had gastral (abdominal) ribs. Its foot and hip structures

er side of the sternum is a crest that acts as an anchoring point for the pectoral muscles. Compared with the rest of the body, the size of modern birds' pectoral muscles is unmatched by any other animal; these enormous muscles enable birds to fly by flapping their wings.

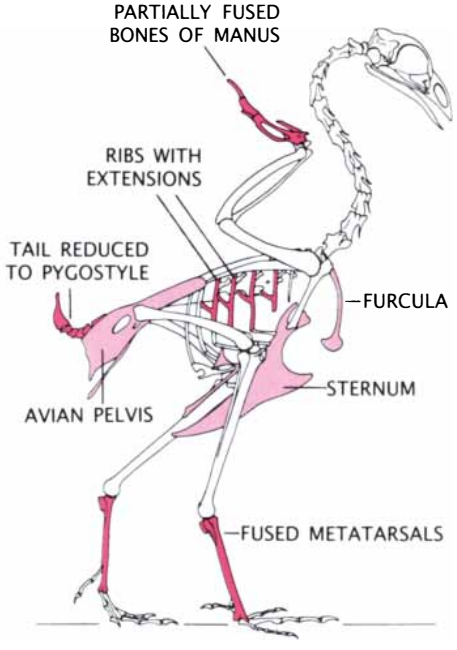
There are no indications that *Archaeopteryx* had similarly developed pectoral muscles. Instead of a sternum it had gastral (abdominal) ribs, just as its saurian ancestors did. Gastral ribs are thin, fishbonelike braces in the abdominal area that are not fixed to the rest of the skeleton. They are found today in lizards and crocodiles and were relatively common in early reptiles and amphibious animals. The gastral ribs may have protected the abdominal area and helped to support the internal organs of *Archaeopteryx,* but they could not have served as points of attachment for the pectoral muscles.

Yet *Archaeopteryx* did have a furcula like that of today's birds. In modern birds some of the pectoral muscles attach to that structure; *Archaeopteryx* may therefore also have had a small area of attachment for those muscles on its furcula. Its ability to fly, however, would have been rather limited.

There are other indications that the prehistoric bird was not a good flier. In modern birds, air bags extend from the lungs into the body and reach into the bones through small openings that are usually found at the top end of the upper-arm bone. These air bags enhance the capacity to breathe and help the bird to meet its heavy oxygen requirements during flight. *Archaeopteryx* lacks openings for air bags in its bones; therefore, it is questionable whether the animal had birdlike lungs.

Also, the bones in the manus of *Archaeopteryx* are not fused to support the wing as they are in modern birds. Its fingers could move independently of one another and were equipped with strong, pointed claws. The largest feathers of the manus originate from only the middle finger; the largest feathers of the arm come from the ulna, the largest bone of the lower arm. Yet the ulna is smooth, in contrast to that of modern birds, which has small knobs where the main feathers are anchored firmly to the bone by ligaments. It therefore seems that the main feathers of *Archaeopteryx* were not anchored in the skeleton.

The underdeveloped pectoral muscles, the reptilian lungs and the lack of firm anchoring for the main feathers all paint a picture of *Archaeopteryx* as a poor flier.



GALLUS (CHICKEN)

indicate that *Archaeopteryx* was adept at walking. Its tail had not regressed to become a stubby pygostyle and could have counterbalanced the weight of the body when *Archaeopteryx* walked or ran.

Nevertheless, the perfectly developed plumage of *Archaeopteryx* makes it certain that the animal did fly. No other vertebrates besides birds are equipped with real feathers; feathers must have played a decisive role in the evolution of flight.

It is currently thought that feathers evolved from reptilian scales. Did feathers or featherlike structures originally insulate warm-blooded dinosaurs from the cold? Did they protect cold-blooded reptiles from the heat and sun? Were the feathered arms used to attract mates and to battle with sexual rivals, or did they form a basket for catching insects? All these ideas and others have been proposed, but they remain only theories.

Only one point is certain: *Archaeopteryx* represents an advanced stage in the evolution of flight. Its main feathers show the asymmetric, aerodynamic form typical of modern birds. This similarity proves that the feathers of *Archaeopteryx* must have been used for flying. Their sophisticated form also hints that the hypothetical ancestor of *Archaeopteryx* must have had feathers of some kind, too, although it probably had not yet acquired the ability to fly.

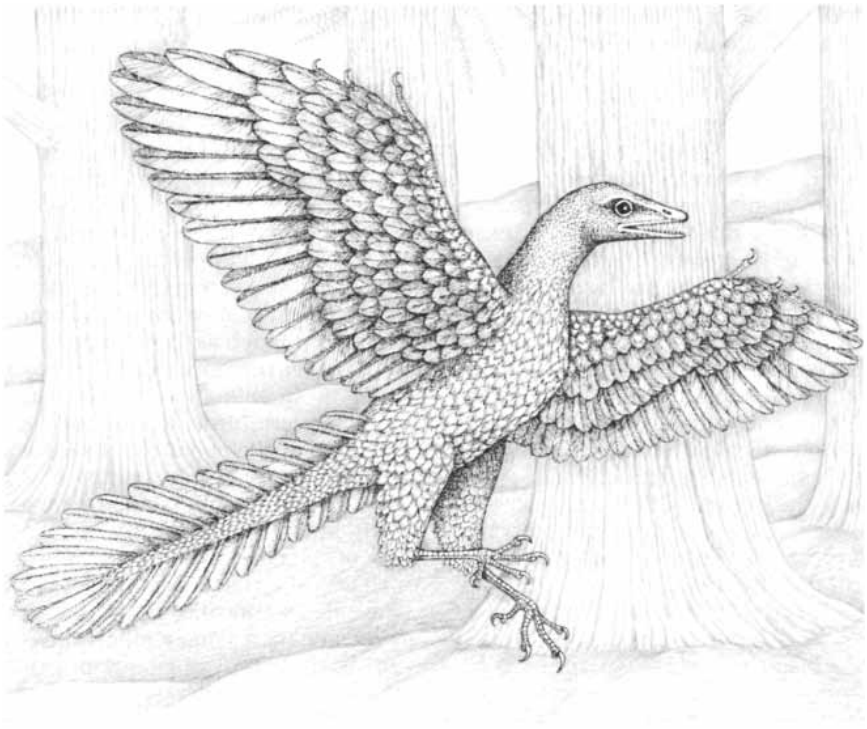
Although *Archaeopteryx* could not have flown long distances, it was capable of wing-flapping flight and was also a good runner. Indeed, the architecture of the pelvis and hind legs of the prehistoric bird suggest it was adept at moving on the ground. Its pelvis resembles the three-pronged design of the saurischian dinosaurs, especially the bipedal theropods such as *Compsognathus*. The pelvic and leg muscles of *Archaeopteryx,* therefore, must also have been roughly saurian.

Archaeopteryx must have stood on its hind legs much as *Compsognathus* and the other theropods did. The posture of these animals contrasts with that of modern birds, whose body is suspended at the pelvis like a seesaw when the thighbones are almost horizontal. Like *Compsognathus, Archaeopteryx* did not topple forward because of the counterweight of its tail, which was about as long as the body.

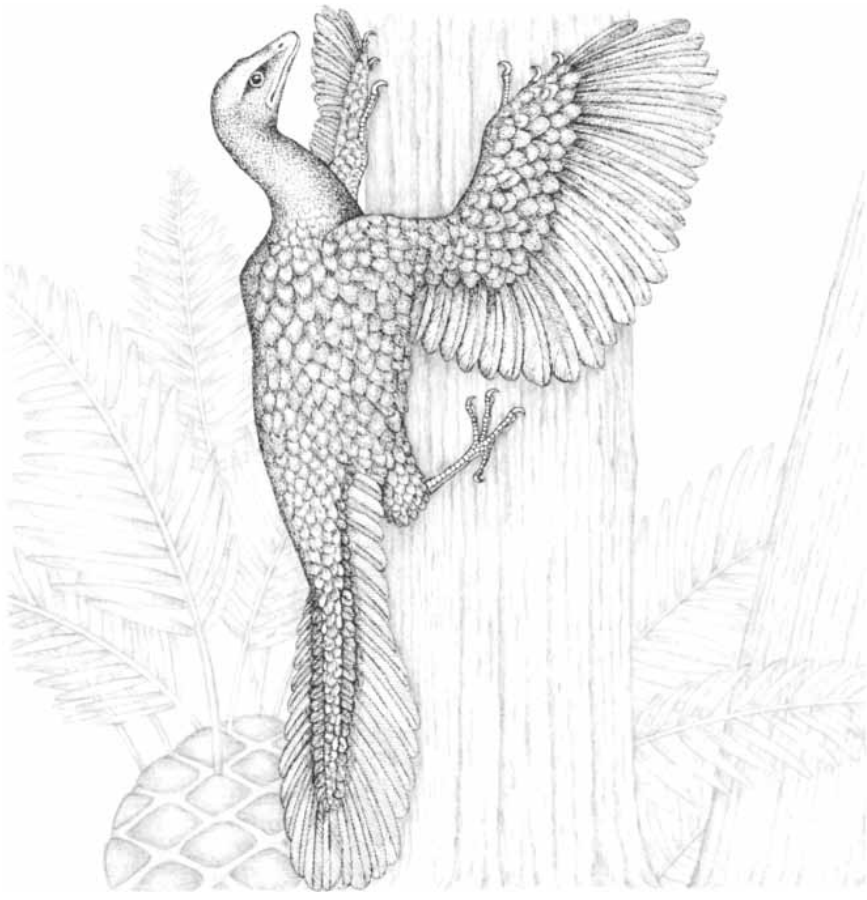
The tail was flexible near its base but became increasingly inflexible toward its tip because of bony protrusions on the 23 tail vertebrae. Such protrusions are present in some bipedal dinosaurs and in the long-tailed flying saurians of the Triassic and Jurassic periods. The rigidity of the tail helped the animal to balance itself during abrupt changes of direction while running or flying. In addition, the plumage of the tail provided an aerodynamically stabilizing horizontal surface.

In modern birds the tail vertebrae have shrunk and fused into a pygostyle, one of the few structures that are present only in birds. In the birds that immediately succeeded *Archaeopteryx,* the shortening of the vertebral column of the tail must have been accompanied by a gradual shift of the center of gravity toward the front. To compensate in part for this forward shift, the muscles in the pelvic region enlarged, and there was a corresponding increase of surface area on the pelvic bone to which muscle could attach. During the reorganization of the pelvis, the two fused pubic bones turned backward and separated. The job of supporting the internal organs was then taken over by the sternum, which developed simultaneously.

The foot of *Archaeopteryx* is definitely adapted to running and has features intermediate between those of reptiles and modern birds. In reptiles the metatarsal bones in the foot are separate; in modern birds these bones have fused into a single bone. X-ray studies of the Maxberg specimen by Wilhelm Stürmer, a physicist and paleontologist from the Siemens Company in Erlangen, have revealed that the metatarsals had partially fused. In the



ARCHAEOPTERYX **was not a strong flier but could launch itself from trees, according to the arbocursorial theory of the evolution of flight. The prehistoric bird might have made parachutelike landings on the ground; it then would have run to a nearby tree.**



CLIMBING with the sharp, bent claws on its fingers and toes, *Archaeopteryx* could have ascended a tree in preparation for a flight or to find food, mates or shelter.

biggest specimen, the one from Solnhofen, the bones had fused even more. These observations suggest that in *Archaeopteryx* the metatarsals ossified and fused with age.

Overall, the foot structure of *Archaeopteryx,* like that of its theropod ancestors, is birdlike, with three long toes and a short backward-facing toe. The sharp, bent claw on the backward-facing toe suggests this prehistoric bird might have been able to grasp objects with its feet and perch on a tree branch.

In summary, the evolution of flight was accompanied by the reorganization of more than the structures most needed for flying; the changes encompassed the animal's entire skeleton and physiology.

There are two basic, contradictory models for the evolution of flight. According to the arboreal model, flight involving the downward beating of the wings evolved from gliding and originated in animals that climbed and leaped from trees. The alternative, cursorial model posits that flying arose among bipedal animals making small jumps (to catch insects, for example) while running and flapping their forelegs simultaneously to extend the jumps. With progressive development of the wing structures, the jumps became longer and higher until the animals could eventually keep themselves on a flying course by beating their wings.

Evidence for the cursorial theory can be found in the physical adaptations of *Archaeopteryx* for walking and running. Yet the energy requirements for running with simultaneous wing-beating would be very high, particularly during the early stages of the evolution of flight. Moreover, flying up from the ground entails fighting gravity, whereas gliding down from a tree takes advantage of gravity and therefore requires less energy.

The arboreal model assumes that *Archaeopteryx* and its ancestors were able to climb trees. Do the claws of *Archaeopteryx* support this idea? Its claws are bent in the form of a sharp sickle, with a cutting edge on the inside and reinforcing material on the outside. Similar claws can be found in bats, squirrels and woodpeckers—all animals that climb tree trunks and cling to bark. The claws of predatory birds and animals that run along the ground are quite different. Today's birds climb exclusively with the claws on their feet; *Archaeopteryx* would also have been able to use the claws on its fingers, in particular the one on its

SNOUT of the small *Archaeopteryx* specimen in Eichstätt, West Germany, has been enlarged 6.5 times in this electron micrograph. Because of its backward-curved teeth, the fossil had once been classified as *Jurapteryx recurva*. Analyses of the bones now make it seem more likely that this specimen is an *Archaeopteryx lithographica* that had died before it matured.

flexible first finger, to hook and anchor itself, while the tail provided additional support.

A model that combines features of both the arboreal and cursorial theories might be called the arbocursorial theory or, more descriptively, the climber-runner theory and is based partly on the ideas of Walter J. Bock of Columbia University.

According to the arbocursorial theory, *Archaeopteryx*'s predecessors were small, probably bipedal reptiles that took to the trees during the late Triassic and early Jurassic periods, about 200 million years ago. Forests may have served as places for hiding, nesting and breeding; they may also have offered advantages in the search for food. The beginning of an arboreal life for these protobirds was probably linked to the evolution of warm-bloodedness and the simultaneous evolution of feathery structures as insulation for maintaining a constantly high body temperature. Life in the trees would also have promoted the development of stereoscopic vision and the ability to orient in three-dimensional space, both of which are prerequisite skills for flying.

Large air-resisting feathers, particularly those on the forelegs, would have softened the landings of these protobirds during leaps to the ground by slowing their descent. Gliding could have evolved out of these slow falls, and the ability to maintain a straight line of flight could have emerged by flapping the wings.

Because the feet of *Archaeopteryx* are adapted for running, the ability to move on the ground must have been important to the prehistoric bird and its protobird ancestors. Gliding between trees and landing on branches require precise steering ability, which in turn requires great coordination. Simple, parachutelike landings on the ground would therefore have been much easier for the earliest birds to control than complicated landings on trees. Once reaching the ground, the animals would have charged toward the next tree and climbed up in search of insects, nesting space or refuge.

Was *Archaeopteryx* the ancestor of all later birds? What can be deduced about avian evolution from the fossils of the succeeding Cretaceous period? The only relatively complete skeletons are from the latter part of that period (roughly 85 million years ago). Those birds had teeth and were partially adapted to a diving, aquatic way of life. The direct descent of such specialized forms from *Archaeopteryx* scarcely seems possible. Consequently, *Archaeopteryx* has often been regarded as an evolutionary dead end for birds.

Recently, however, bird fossils from the early Cretaceous period (roughly 125 million years ago) have been found that seem to represent an intermediate stage between *Archaeopteryx* and modern birds. In particular, the skeleton of a small bird found in the limestone of Las Hoyas in eastern central Spain in 1984 displays a combination of ancestral and modern characteristics. Its pelvis and hind legs seem more reptilian than those of today's birds; its shoulders and furcula seem more modern than those of *Archaeopteryx*. Its most intriguing characteristic, however, is its pygostyle, which has 15 fused vertebrae. This is longer than the pygostyle of modern birds (which has from four to 10 fused vertebrae) but shorter than the tail of *Archaeopteryx* (with 23 vertebrae).

The bird from Las Hoyas, like *Archaeopteryx* itself, illustrates that the early evolution of birds was strongly influenced by the physical requirements of flight. It is not currently possible to tell whether or not *Archaeopteryx* was the direct ancestor of the bird from Las Hoyas and of all other birds, but this correlation is not of major importance. What is significant is that the six known skeletons of *Archaeopteryx* and the single feather provide clues to how birds evolved. As Adolf Portmann, a zoologist from the University of Basel, said about the fossils in 1957: "They are documents without which the idea of evolution would not be as powerful."

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Bright Future

Innovative lasers begin an illuminating practice

Fortifying lasers, stalwart salt, fastidious network, costly degrees

At AT&T Bell Laboratories, invisible beams of infrared light criss-cross a complex arrangement of mirrors and circuit boards on top of a table. Unwieldy as it is, this contraption is the first functional optical processor. It gives engineer Alan Huang and his colleagues hope that one day light will replace electricity in high-speed parallel computers.

Many problems remain to be tackled before optical computers can become a reality. Not the least of them is the need for tiny, yet powerful, lasers that will let designers shrink optical devices to manageable size. For that, Huang and others are counting on developments in laser diodes, salt-grain-size crystals of gallium aluminum arsenide alloys capable of emitting a precise frequency of infrared light. "Five years ago no one would have guessed that laser diodes would be as powerful as they are now," Huang says.

The diode lasers that drive Huang's processor emit 10 milliwatts of energy, compared with three to five milliwatts generated by the diodes that read data on computer optical discs and compact disc recordings. But many other applications—and more advanced versions of Huang's processor—need more potent devices.

Although powerful lasers that emit a range of wavelengths of light have existed since the 1960's, most are simply too big, awkward and expensive to be employed in many settings. Overall, the problems rest with the source of light needed to "pump" energy into lasers. An Nd:YAG (a crystal composed of oxides of neodymium, yttrium and aluminum) laser gets its dose of light from an electric discharge in xenon gas, which is contained in a cumbersome and fragile glass flash lamp. Moreover, flash lamps emit a broad spectrum of light, so less than 1 percent of the electricity put into the system is transformed into laser light. The unused energy, in the form of heat, must be drained from the system so that it does not distort the final beam emitted by the laser.

Tiny laser diodes may provide the solution. They generate a narrower spectrum of light. Over the past two years researchers have made great strides in ganging together laser diodes. These can now put out enough power to pump Nd:YAG lasers. Yet an array of diode lasers can be small enough to build systems as compact and rugged as a ballpoint pen. Because the diodes are more efficient than flash lamps at converting electricity into light, they boost the efficiency of an Nd:YAG laser by roughly tenfold.

Still, one catch—and it is a big one—is the price. Whereas the devices in compact disc players cost less than $4 apiece, a 10-watt diode laser, the largest on the market, can fetch more than $10,000. Although the techniques for building laser-diode pumps and weaker diodes are nearly identical, the high-power devices are virtually made by hand because of low demand.

The cost difference is "strictly an issue of volume," says Donald R. Scifres, president of Spectra Diode Laboratories in San Jose, Calif. Diode makers sold more than 20 million of the tiny devices for compact disc players and computer printers last year just in the U.S. In contrast, the U.S. market for diode-pumped lasers barely topped 500 units, according to *Laser Focus World,* an industry magazine.

Much of the U.S. development of diode pumps is being supported by the Department of Defense. In Japan the Ministry of International Trade and Industry is sponsoring a project aimed at lowering the prices of high-power diode lasers.

The systems built in the U.S. consist of arrays of "diode bars," each about a centimeter long and studded with more than 100 laser diodes. One such project at McDonnell Douglas Electronic Systems in St. Louis, Mo., showed in February that an array of 624 diode bars could pump an Nd:YAG laser and produce a one-joule pulse of energy. That is more than enough for such military systems as range finders and target markers for precision-guided missiles, says George Dubé, who manages the laser and electro-optic lab at McDonnell Douglas. Fibertek, a military contractor in Herndon, Va., is producing similar pulses

EXPERIMENTAL DIGITAL OPTICAL PROCESSOR—which has about as much data-processing capacity as a semiconductor chip controlling a dishwasher—uses beams of infrared light generated by laser diodes instead of electrons to process data. Photograph courtesy of AT&T Bell Laboratories.

Television viewers will soon experience the sensation of sitting in the front row of a concert or stage production thanks to a new sound system that recreates the dynamic range of the original performance. The system, developed by Hughes Aircraft Company and called the Sound Retrieval System™ (SRS®), retrieves and restores spatial information present in all acoustic situations. SRS supplies the spatial cues which enable the human ear to discern the source or location of the sound. Listeners can turn their heads or move about the room and still hear the live effect, while the position of a soloist or vocalist at center stage is maintained. SRS operates on both stereo and monaural signals without the need for encoded program material.

Lower cost infrared detectors may be one result of research under way at Hughes. The U.S. Army is planning to use detectors made of platinum silicide on an infrared version of the Non-Line-of-Sight Missile. The detectors are made from silicon chips containing an electrode made of a compound of platinum and silicon. Staring arrays made from these detectors, and using fixed optics, perform better than more expensive scanning systems, and the staring arrays are inherently more reliable. Platinum silicide detectors may also be used to gather radiometric data on missile launches and in aerial reconnaissance.

More powerful, more versatile, body-stabilized satellites will soon provide Australia with direct television broadcasts and worldwide mobile communications. Australia's next generation communication satellites, AUSSAT B, built by Hughes and designated the HS 601, are body-stabilized, or three-axis, commercial satellites, and use internal momentum wheels to provide stabilization in orbit. They will make possible direct broadcast of television into small antennas, and their three-kilowatt power levels will allow AUSSAT Pty Ltd, Australia's national satellite company, to offer satellite communications to people in moving vehicles. Launch date for the first satellite is late 1991.

An automatic visual inspection system will soon verify the quality of solder joints in radar sub-assemblies. The system, now under development at Hughes, is comprised of a special light source, a video camera and a computer. The system verifies the quality of each solder joint flow and sends the results to a touch-up workstation where a human operator can correct any defects. Hughes currently creates about 100 million solder joints per year and expects to achieve a significant reduction in manpower requirements and an improvement in product reliability.

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HUGHES

Subsidiary of GM Hughes Electronics

with its collection of 400 diode bars.

Diode-pumped lasers may eventually help the semiconductor industry make the next generation of computer chips by providing a way to create more dense circuit designs. Some investigators are using X rays instead of light to etch circuit lines tinier than those possible with conventional photolithography. Generating a highly focused beam of X rays is tricky, however. One approach relies on a costly synchrotron; another uses a 30-joule pulsed neodymium laser, powered by flash lamps. Swapping flash lamps for arrays of diode bars could make such an approach more feasible.

Researchers are also exploring ways to increase the efficiency of laser diodes. One alternative consists of fabricating monolithic arrays of micron-size lasers on the surface of semiconductor chips. Because the laser arrays emit light from the relatively large area of their top surfaces—instead of their edges, as other diode lasers do—the output increases severalfold. Such arrays of surface-emitting lasers may prove ideal power sources for optical processors, Huang says. One advantage is reliability. If a single laser fails, the others are unaffected.

Huang has another item on his diode-laser wish list: a more precise beam with little wavelength dispersion. "And it might be useful to make the lasers slightly tunable" to achieve the optimal frequency, adds David A. B. Miller, who heads Bell Labs' research on photonics switching devices.

Efforts to develop tunable lasers that can be adjusted to many different wavelengths are being funded by the Defense Department. Several companies, notably Schwartz Electro-Optics in Concord, Mass., are now promoting tunable Ti:sapphire lasers, which use a sapphire crystal doped with titanium oxide. Such lasers emit light from the red to infrared parts of the spectrum (about 680 to 1,100 nanometers). And after "frequency doubling"—passing high-intensity light through nonlinear crystals to alter the frequency—the Ti:sapphire produces a range of blue-green light.

These developments could lead to one way of making the laser that industry is most keen to wield: a practical blue laser. Because blue light has a shorter wavelength than red light (approximately 400 nanometers), such a laser would enable workers to focus the beam into smaller spots and so pack more data on a compact disc.

There have been successes. Workers at the IBM Almaden Research Center have employed frequency doubling to generate nearly 40 milliwatts of blue light from a 140-milliwatt laser diode. At the Lawrence Livermore National Laboratory and the Center for Research in Electro-Optics and Lasers in Orlando, Fla., researchers are producing blue light by doubling the output frequency of fluoride crystals of chromium, lithium, strontium and aluminum. But the problem is money. No breakthroughs are required to make a blue laser, Dubé says. "It's just a question of somebody wanting to pay up and make it practical."

Similarly, moving Huang's optical processor from a demonstration device into a more feasible configuration will demand advances in many components, including laser diodes. "A lot of work has already been done," Huang says. "The potential is just waking up." —*Elizabeth Corcoran*

Trick of the Tongue

A unique mechanism of taste means no substitute for salt

For many consumers, salt has lost its savor because of its reputation for raising blood pressure. The food industry has long hoped to capitalize on that concern. But unlike other dietary villains that have succumbed to the hunt for alternatives—most recently fat and most profitably sugar—salt has researchers shaking their heads. The mechanism of salt-taste perception is so specific, scientists now realize, that it is highly improbable a salt substitute will ever be found.

"We've been trying to develop a substitute for salt since the 1960's," says A. Jack Sullivan, Campbell's Soup Company director of technology assessment and acquisition. But recent insights have brought the company to an unsatisfying conclusion. "For a long time to come, we'll be using potassium chloride and masking its flavor," Sullivan says. This chemical tastes salty at first but yields to a bitter aftertaste.

It should come as no surprise that salt is hard to mimic, says Gary K. Beauchamp, associate director of the Monell Chemical Senses Center in Philadelphia. "After all, there are hundreds of things that taste sweet, but only two that taste salty," he explains. One is table salt itself—sodium chloride—the other is lithium chloride, which is poisonous.

Investigators believe most tastes travel from mouth to brain when a particular component in food—such as sucrose or quinine—binds to a receptor on one of 100 or so taste cells present in every taste bud. This connection sparks impulses that travel up nerves to the brain. Sugar substitutes, which were discovered serendipitously, are believed to work this way and so cause the brain to register sweetness.

In contrast, researchers believe sodium ions enter the taste cells by passing through a specialized pore in the membrane called the sodium ion channel. As the ions begin flowing in, the taste cells depolarize. This reaction triggers the release of neurotransmitters that excite the nerves carrying the salt message to the brain. Only sodium and lithium can enter this channel; other compounds with something of a salty taste, such as potassium, cannot. This restricted pathway has frustrated the development of sodium alternatives.

Even so, some researchers are not giving up. Instead of a sodium substitute, "it may be possible to make a sodium enhancer, to get more bang out of a dose," suggests John A. DeSimone, a chemosensory physiologist at the Medical College of Virginia. "Some substance could be mixed with sodium chloride that would change the kinetics of the sodium ion channel, to make it behave in the way that it would for a much higher dose of sodium." For instance, the channel might be made more permeable, thereby allowing a faster influx of ions and consequently a stronger response. DeSimone has spent 18 months screening compounds found in food to determine their effects when mixed with salt. As yet he has found no good candidates for enhancers.

The constraints to developing salt substitutes are economic as well as scientific. Salt is cheap and, aside from its presumed effect on blood pressure, provokes few adverse reactions. An alternative, which would have to go through rigorous testing to gain approval from the Food and Drug Administration, would undoubtedly be more expensive.

While the government urges reducing sodium as part of the Nutritional Quality Guidelines for Food, conflicting opinion in the scientific community persists as to whether salt causes hypertension. There is agreement that sodium-sensitive people should lower their intake, but the only way to tell if individuals are salt-sensitive is to load them up on it. "We think the National Institutes of Health should be trying to identify by early blood testing who should eat less salt," Sullivan says.

Then a recent, but small, study

found that even among those who do have high blood pressure, 50 percent experienced no change after lowering dietary sodium. The study, conducted at the Medical College of Wisconsin in Milwaukee and reported at the American Heart Association meeting late last year, also found that severely cutting back on salt increased some subjects' blood pressure and level of low-density lipoproteins, the so-called bad cholesterol.

In the wake of this controversial news, some people may well throw up their hands in bewilderment, as happened last year when warnings of cholesterol's ills were suddenly toned down. But if the experience of salt-taste investigators is any indication, a majority of people will fold their hands primly in their laps and continue to engage in mass denial. "We have difficulty conducting studies because we almost can't find people who will admit to using salt shakers," Beauchamp sighs. "It's as though it's a moral flaw." Hear no evil, see no evil, eat no evil. —*Deborah Erickson*

Putting Down Roots

Genetically engineered plants head for the harvest

Bringing drugs produced by biotechnology to market has not been easy. But compared with introducing genetically engineered crops, it has been a picnic. Since 1987 the U.S. Department of Agriculture has issued over 50 permits for field tests of modified plants to such veteran agricultural companies as Monsanto and Du Pont, along with newcomers such as Calgene in Davis, Calif. More than 20 applications are pending. Being tested are tomatoes that ripen but will not rot, as well as soybeans and cotton that resist diseases and tolerate pesticides and herbicides. Yet it will be at least the middle of the decade before any of those plants are available to farmers.

The reason is that almost everyone who can has gotten into the act. The USDA trials are intended to demonstrate that the plants are environmentally benign. But some of the trials have also drawn the watchful eyes of the Environmental Protection Agency, which wants to be sure that genes conferring pesticide resistance do not spread through cross-pollination. The Food and Drug Administration will review the plants as well, to ensure that these new foods are safe for human consumption. Meanwhile various environmental groups are determined to make the way to market as difficult as they can.

Modifying plants has proved to be more difficult than compelling bacteria and other cells to produce human proteins, such as the insulin and blood-factor products that became the darlings of Wall Street. Only a single gene is needed to instruct cells to make those pharmaceutical products. But the plant traits that consumers would pay a premium for, such as taste and texture, are controlled by more than one gene. So the plant companies chose to focus their attention first on characteristics that would benefit farmers more than consumers. The U.S. government has also treated agriculture as a stepchild in its funding priorities. Of the $3 billion spent on biotechnology research in 1989, only one tenth, or $300 million, went for plants.

Despite the difficulties, plenty of genetically engineered plants have already made it out of the greenhouse and into the field. Of these, two varieties of tomatoes are closest to market. By the end of this year Calgene will request that the FDA begin considering its tomato with longer shelf life for market approval. The firm will not ask the USDA for exemption from additional field trials until it has accumulated enough seed to grow the plants in commercial quantities.

Calgene's tomato contains a gene to make "antisense" DNA. Antisense works like Velcro, sticking to and blocking an exactly opposite DNA sequence—in this case, the enzyme that degrades pectin and causes rotting. The tailored tomatoes ripen in every other regard, turning red and developing taste components not found in the disappointing pink varieties that predominate in supermarkets simply because they ship well.

The other designer tomato, from Monsanto, is also likely to emerge from field tests soon. A prenatal vaccination of sorts makes this variety resistant to the common tomato-mosaic virus. The plant contains a piece of DNA from the virus's coat, so that when the tomato is attacked in the field, it is already "cross-protected" against infection.

Whichever company moves first, the request for an exemption from the regulated field trials will kick off a chain of public notifications. The USDA will have 180 days to decide whether to sign off on the field trials. "Everything will be decided on a case-by-case basis," says Terry Medley, director of biotechnology at the USDA.

Ditto at the FDA, which has not yet decided how it will regulate genetically engineered plants. "We're considering it carefully, but the burden is always on industry to show what is safe," explains James H. Maryanski, biotechnology coordinator for the FDA's center for food safety and applied nutrition.

Currently there is no provision for premarket approval of food itself. Food additives have been regulated since 1958. Other foods have been considered GRAS, or generally recog-

COTTON PLANTS engineered by Calgene* (above, inner rows) *can withstand three to four times the normal dose of Rhône-Poulenc's herbicide Bromoxynil because of the inclusion of a new gene. Tomatoes tailored by Calgene* (left at bottom) *are likely to be the first plants submitted to the FDA for market approval. They contain an "antisense" gene that delays rotting.

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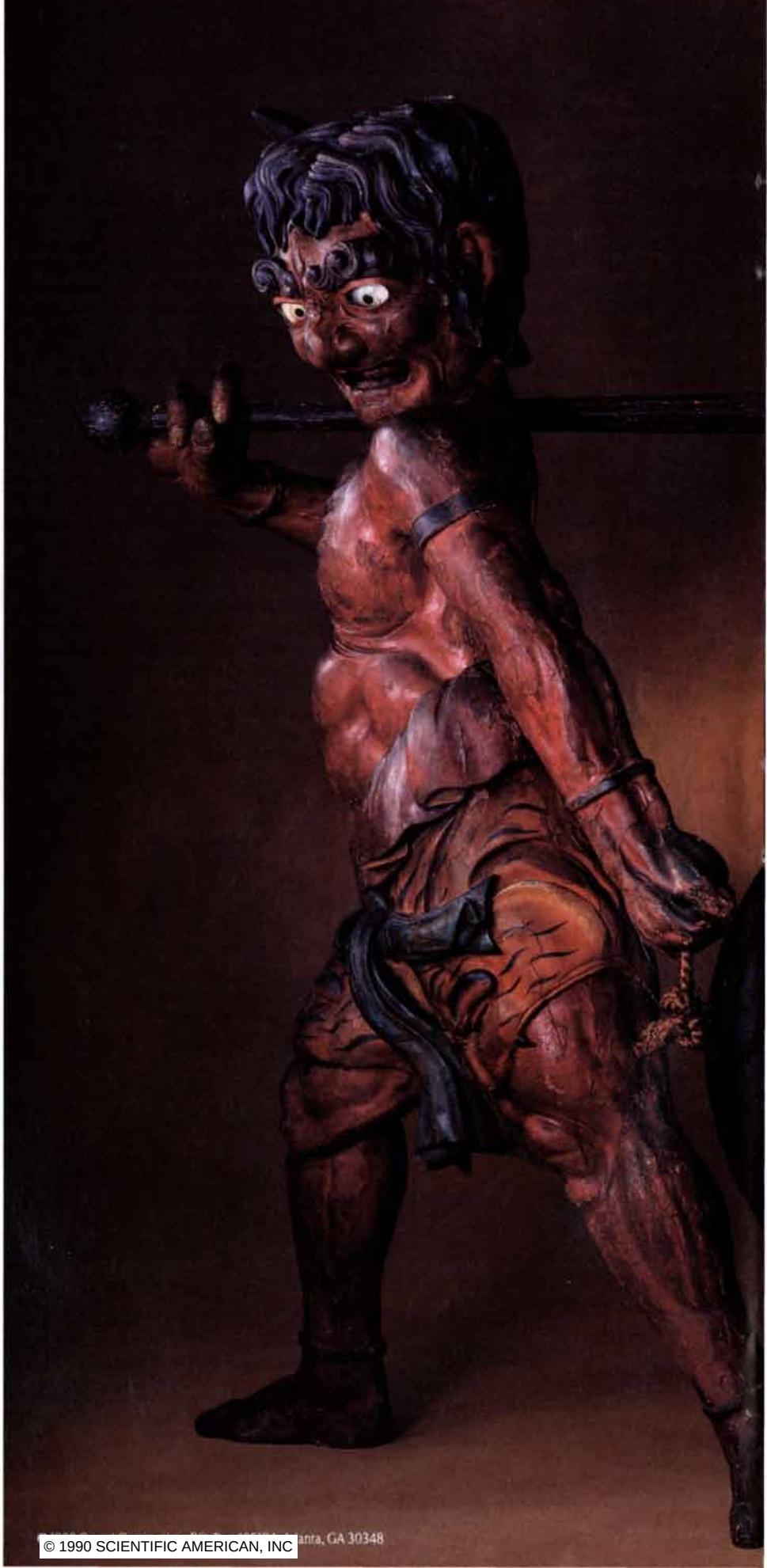

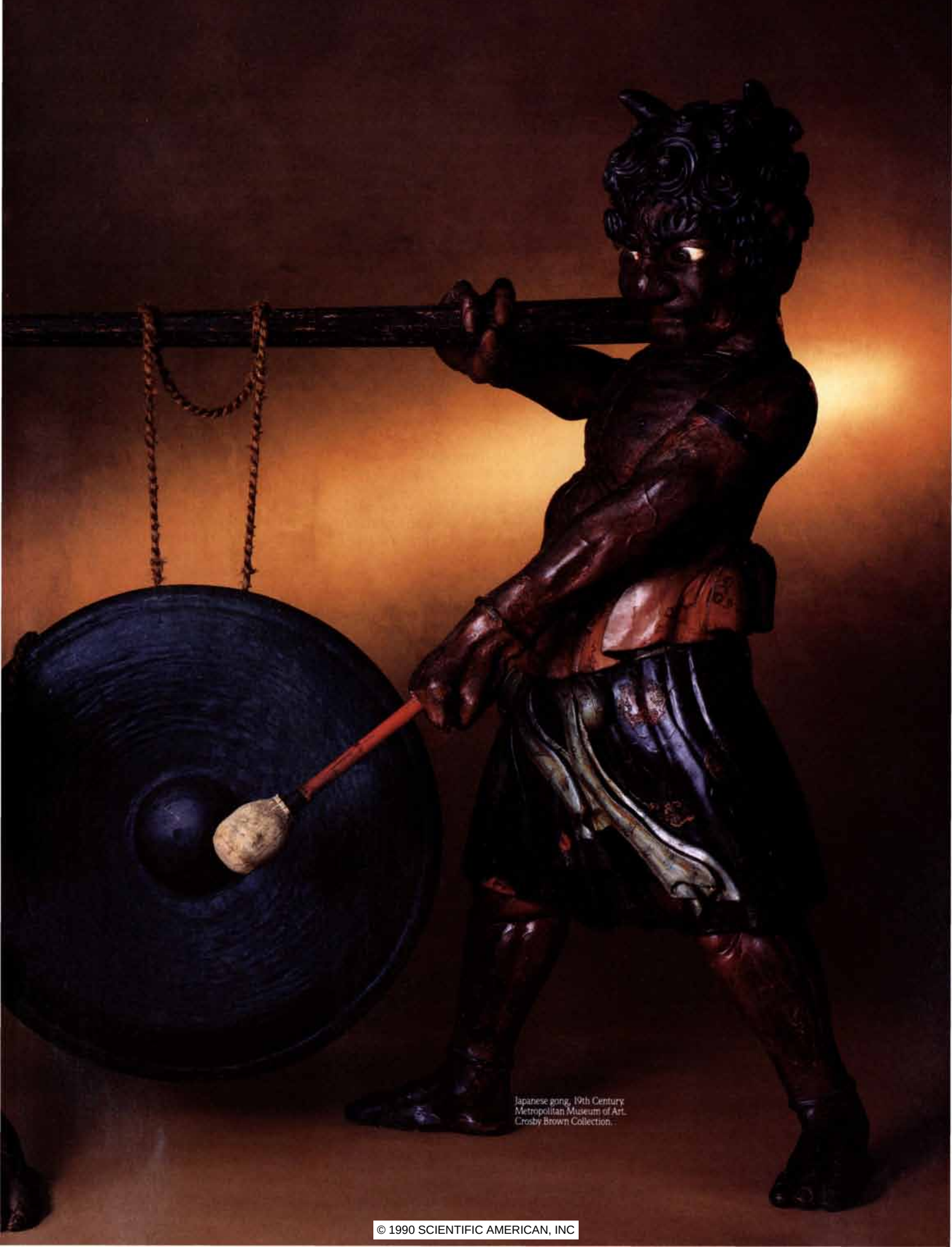

Japanese gong, 19th Century
Metropolitan Museum of Art.
Crosby Brown Collection.

nized as safe, sometimes by dint of FDA review but more often without challenge. "Our traditional food supply has a history of safe use," Maryanski says. "We want to make sure that the new technologies don't introduce new risks."

The FDA's attentions are all to the good as far as companies are concerned. The firms want FDA backing to help them get through public scrutiny, which is likely to be the most difficult trial of all. Some environmental groups favor forcing genetically engineered foods, such as milk from cows treated with bovine growth hormone, to be labeled as such. A few states, including Minnesota and Wisconsin, have already considered such measures. But companies argue that labels would cause chaos in the processing industry. "A tomato is a tomato," insists Frank S. Serdy, registration affairs director at Monsanto's plant sciences division.

Opponents of genetic engineering are also skeptical of attempts to produce crops that are resistant to certain herbicides. They argue that this is simply a scheme to lock farmers into relying on a particular manufacturer's product; it will lead to heavier use of agricultural chemicals, the environmentalists say. They also fear that tailoring a large variety of plants to defend themselves against insects will engender the same kind of resistance in the pests that chemicals now do.

Both Monsanto and Calgene dispute those claims and have launched programs explaining their positions. Roger H. Salquist, Calgene's chief executive officer, engages in what he calls "infrastructure marketing" to educate the government and the press about biotechnology. Monsanto gives lectures about genetic engineering and tours of its facilities to everyone from President Bush to members of garden societies.

While engineered plants flourish in open-air tests, researchers in laboratories are working to expand the battery of transferable characteristics. One early goal workers have is to lower the saturated fat content of soybeans and of the popular oilseed canola. These plants might be designed to incorporate genes for healthy Omega-3 fatty acids, found naturally in oily fish like mackerel and salmon. Researchers are also attempting to express genes in specific tissues to make, for instance, only a plant's roots resistant to soil insects. For now, agricultural biotechnology appears a healthy seedling. But the industry still has a long row to hoe. *—D.E.*

Cancer Catcher

Neural net catches errors that slip through Pap tests

Imagine staring through a microscope for seven hours a day, knowing that someone's life may hang in the balance if you fail to spot one cancer cell hidden among multitudes of healthy ones. That is the daunting task of the cytotechnology lab workers who screen Pap smears for evidence of cervical cancer. Many cytotechnologists screen 100 slides in a day. Every slide may have 100,000 or more cells on it; as few as 30 cells in a specimen from a woman in the early stages of the disease may be abnormal.

An experimental system now in clinical trials may be able to relieve much of the cytotechnologist's burden and improve the accuracy of the tests. Developed by Neuromedical Systems, Inc. (NSI), a start-up company based in Suffern, N.Y., PAPNET is a computerized imaging system that uses neural-network-emulating software to help spot cancerous cells. Neural nets are information processors that mimic a living brain's ability to learn from experience; they excel at recognizing subtle, hard-to-define patterns.

The robotic front end of PAPNET is a black steel framework, roughly two feet square, that holds the system's video cameras, magnifying lenses and other instruments. NSI technicians jokingly refer to it as "the Rock," because it sits atop a three-inch slab of granite that damps out vibrations.

When PAPNET goes to work, its robotic arm first removes a slide from a box and places it under the machine's camera for inspection. The primary screening system evaluates the condition of the cells according to geometric rules and identifies up to about 1,000 that seem unusual. The secondary screening system, the neural network, assigns a score to each of the 1,000 cells to rate their apparent abnormality. Finally, the positions and magnified color images of the 64 most suspect cells are recorded on an optical disc. A cytotechnologist calls up these images later on a video monitor and scrutinizes them. Cells that the cytotechnologist deems worrisome are marked and passed on to a pathologist for a final diagnosis.

PAPNET could be used for many types of cytological examinations, but there has been a particularly vocal demand for something like it to screen Pap smears. Since use of the Pap test became widespread more than 40 years ago, mortality from cervical cancer among U.S. women has fallen by about 70 percent. Still, Pap tests are dangerously fallible.

According to Leopold G. Koss, chairman of the department of pathology of the Montefiore Medical Center of the Albert Einstein College of Medicine in the Bronx, N.Y., the false negative rate of Pap tests—that is, the frequency with which precancerous conditions are overlooked—ranges between 20 and 30 percent at some busy laboratories. Part of the reason for the high false negative rate is the tedious nature of the cytotechnologist's job. Mark R. Rutenberg, president of NSI, likens the task to the challenge of proofreading: "A misspelled word by itself is easy to recognize, but finding one buried in a 100-page document is much harder. People are bound to make mistakes."

Previous attempts to automate the screening of Pap smears have failed for two reasons, Rutenberg says. It is difficult to program a computer with reliable rules for discriminating between precancerous cells and overlapping normal cells. PAPNET can sidestep that problem because its neural network does not need such rules. Also, other machines have tried to make cytotechnologists obsolete by classifying Pap smears completely without human assistance. Rutenberg believes such an accurate "red light, green light" system is beyond current technology. He adds that in preliminary internal tests, cytotechnologists using PAPNET have produced no false negative results.

So far, the Food and Drug Administration has authorized the use of PAPNET only as a quality control for retesting Pap smears that were screened manually. NSI is concluding deals with SmithKline Beecham and hospitals and laboratories to place 12 systems for that purpose this summer. Rutenberg also hopes the FDA will soon approve PAPNET for the screening of specimens. NSI will make PAPNET machines available to laboratories on a per-slide rental basis, initially for $5 a slide. *—John Rennie*

Play It Again, WABOT

Japan's robots aspire to service-sector jobs

In a laboratory in Japan's Waseda University, workers are trying to build a robot that can play Liszt. An earlier model, named WABOT, could scan sheet music for simpler tunes, such as "The Way We Were," bang out a

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NORTHWEST AIRLINES

TEN-FINGERED WABOT, a robot built by engineers at Japan's Waseda University, can tap out a tune on the piano after scanning the sheet music for 15 seconds. It also takes requests. Photograph by Frederick S. Myers.

round on the piano or organ, then ask for another request. The new model, the Waseda researchers promise, will master the challenging finger work of more complex scores.

These mechanical musicians are the forerunners of Japan's next generation of robots. Even as sophisticated automatons continue to run factory assembly lines, Japanese researchers at universities and companies are hoping to build more anthropomorphic robots to supplement Japan's aging work force, particularly in jobs that are hazardous or lack sufficient manpower. "I have no interest in industrial robots that can only carry out simple, predetermined routines," says Kuniji Asano, chief research scientist at Toshiba's Energy Science and Technology Laboratory. "I like more complicated, autonomous robots."

Topping the list of new careers for such robots are fire fighting, decommissioning nuclear power plants and even constructing buildings. This year Japan's Ministry of International Trade and Industry (MITI) is winding up a $140-million, eight-year program that aimed to build a four-legged, two-handed smart machine to work in hazardous occupations. The program has not produced an autonomous robot with a functional vision system. Investigators say, however, that much headway has been made in mechanics such as very small actuators and improved servomotors.

The companies that worked on pieces of the MITI project—say, an arm or leg—are also now trying to put those components into more complex, service-oriented robots. "Making a robot for use in hospitals or homes with people is much more difficult than making one for a nuclear power plant," Asano says. Such robots must be functional, gentle and—some contend—even personable.

The robots in Ichiro Kato's laboratory at Waseda do have some social skills. For instance, when a Waseda robot accompanies singers on the piano or organ, its auditory-sensing system monitors whether the singer is straining to hit the notes; if so, the robot switches to another key.

Other investigators take issue with Kato's belief that robots should resemble humans. "I am very much interested in applications and the configurations that might be useful in the near future," declares Shigeo Hirose of the Tokyo Institute of Technology. As a result, Hirose's research team is experimenting with distinctly unhumanlike robots, some of which alternate between multiple pairs of legs and sets of wheels. Both Hirose and Asano have also built snakelike robots that can gently wrap themselves around an object and tug it across a room.

Because Japanese researchers are having more success developing robotic hardware rather than software, the first troops of robots that find jobs in hospitals are likely to boast far more brawn than brain, investigators say. Toshiba's "master-slave" robot, for instance, is a long steel arm with a flexible pincher that is remotely controlled by a human wearing an electronic glove. As the operator goes through the motions of, for example, assisting a patient, the mechanical arm does the work, saving nurses from shoulder and back strain.

Still cumbersome electronic gear limits robotic mobility, however. "We cannot design an autonomous, lightweight, multi-degree-of-freedom robot unless we develop [better] hardware, small batteries and a very, very fast computer," Asano says.

Just how long it will take researchers to design the necessary hardware and endow it with smarts is anyone's guess. Hirose believes it may take 30 to 40 years "for walking, peoplelike robots to get into hospitals." Kato more optimistically projects only another 10 to 15 years of research. Eventually, he prophesies, "man will be able to live like a man by turning robots humanlike and using them in place of humans working like robots." *—Frederick S. Myers, Tokyo*

THE ANALYTICAL ECONOMIST

Green economists

It has been a promising spring for environmental economists. Four U.S. government agencies were slated to release models assessing the costs of reducing pollution in late March. Workshops and symposiums have been convened. And then there was the 20th anniversary of Earth Day.

That the national Earth Day organizers did not plan an event centered on economics comes as no surprise. For many years economists have been at odds with environmentalists. Since much economic theory aims to find ways to bolster growth, economists have in the past often chosen to dismiss such externalities as rising pollution or dwindling timberlands. An environmental disaster or two could even improve a country's gross national product if money were spent to clean up the mess.

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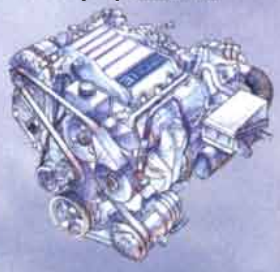

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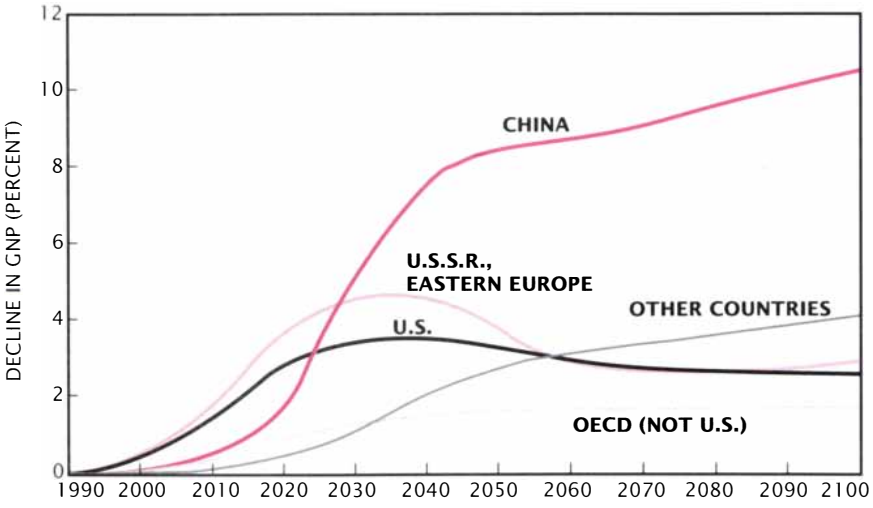


***REDUCING CARBON EMISSIONS** by 20 percent could divert a significant share of countries' future gross national products, according to calculations by economists Alan S. Manne of Stanford University and Richard G. Richels of the Electric Power Research Institute. Those who fare best are the members of the Organization for Economic Cooperation and Development (OECD)—Western Europe, Canada, Japan, Australia and New Zealand—excluding the U.S.*

mental problems are squashing the belief that economists can ignore pollution. There are international proposals to cut atmospheric carbon emissions by 20 percent. Congress is entertaining at least two bills on the subject. Here at last is an environmental job for economists: How much will such measures cost?

Although the economists are rising admirably to the task of estimating the costs (if not the benefits) of emissions controls, "environmentalists feel uncomfortable with economic assessments of the problem," says Alan S. Manne, an economist at Stanford University.

Consider a recent model, devised by Manne and Richard G. Richels of the Electric Power Research Institute. Using conservative estimates of the availability of alternative fuels and the emergence of more energy-efficient technologies, Manne and Richels calculate that to cut carbon emissions by 20 percent by the year 2100 the U.S. will have to divert about $3.6 trillion. A more optimistic scenario, in which demand for energy declines and clean coal is widely used, trims the figure to only $800 billion.

Their international forecast is more muddled. Cutting carbon emissions by 20 percent could slash the gross national products of different nations by between 1 and 10 percent [*see illustration on this page*]. Permitting countries that are hardest hit by the constraints, such as China, to double their carbon emissions would spread the costs of pollution control more fairly; it would also force industrialized countries to slash their emissions by nearly 70 percent to attain a worldwide reduction of 20 percent.

These cost estimates are frightening; they may also be wrong. The four government reports, not yet published at press time, were expected to present differing conclusions. Sources say a model from the Environmental Protection Agency projects lower costs than do Manne and Richels; one from the Department of Energy reaches much higher estimates. The Congressional Budget Office is reportedly in accord with Manne and Richels. (The Office of Technology Assessment also was to present findings.)

There are no simple explanations for the disagreement. Nevertheless, at the crux are likely to be very different beliefs about how big a role conservation may play in the future, as well as about the difficulty and cost of adopting alternative energies.

On the face of it, many economists may argue that the market for energy is "efficient"—that if an innovation would save money, the marketplace would push it forward. Others are not convinced the market is working. They point out, for instance, that builders have little incentive to pack a new home with insulation even if it would trim future utility bills; the builder wants to keep the purchase price low. As a result, much energy can be saved with only a modest investment in insulation, they argue.

The key issue is how important—and ultimately, how costly—these inefficiencies are, points out Richard L. Schmalensee, a member of the Council of Economic Advisers. Economists who believe the market is very inefficient will estimate higher savings for conservation and arrive at lower costs for reducing emissions.

Equally contentious are questions about what alternative energies may be developed and adopted—and at what cost. No one knows how much it will cost the economy to bring prototype systems into real use. If oil prices remain low, companies will have little incentive to spend research dollars on more expensive alternatives. On the other hand, if solar power, biomass and liquefied natural gas quickly become competitive alternatives to coal and oil, the cost of reducing carbon emissions will fall. The amount of energy provided by nuclear plants will also dramatically affect cost estimates.

Differences in a range of other assumptions may also help lead economic models to varying conclusions. Predictions of slower growth translate into more gradual changes in energy demands and lower costs. A growing service sector may well generate less pollution than the existing industrial base. "Short-run economic forecasting is hard enough. Long-run goes beyond hard," Schmalensee says.

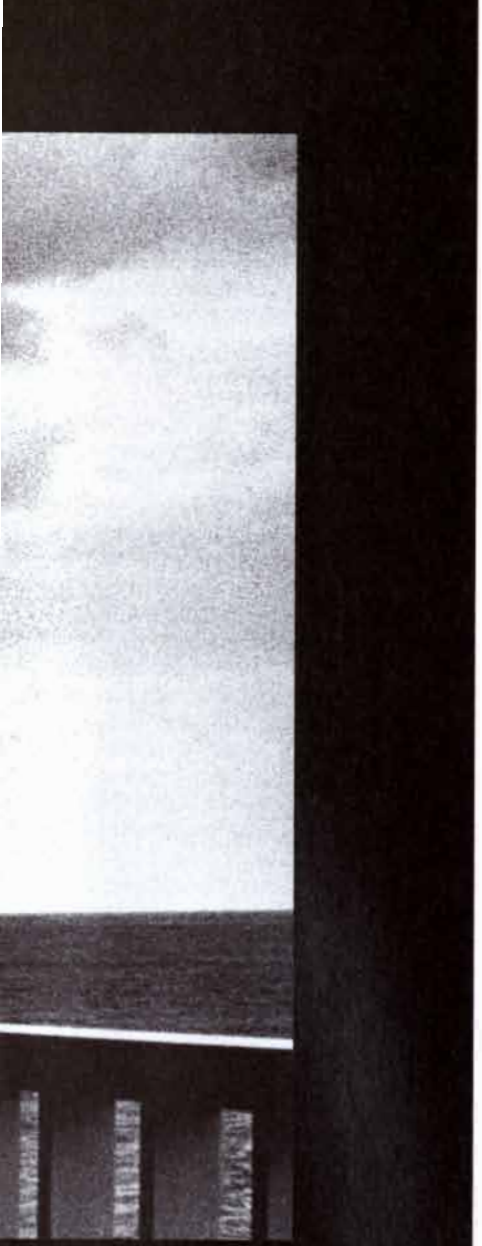
Pinning down the benefits of cutting carbon emissions is even harder than assessing the costs. William D. Nordhaus of Yale University is one of the few economists attempting to establish a framework for modeling benefits. His efforts concentrate on trying to synthesize some of the previous models. Nordhaus's work, nonetheless, is filled with caveats.

In theory, economists would like to estimate the benefits of reducing atmospheric carbon by calculating how a small temperature change might affect agricultural growing patterns or sea level and so translate into losses in farm production or real estate. But investigators studying the physics of global change cannot nail down the specific effects of temperature changes, and so economists are at a loss to assess the costs of such shifts.

Economists do seem to agree on one point: research on energy alternatives will lower the cost of controlling emissions. And the modeling will go on. "In the 1970's energy and economic growth seemed to be limited by a scarcity of resources," Richels says. "Now we're realizing that the real constraint is the ability of the environment to absorb [waste] by-products."

—Elizabeth Corcoran and Paul Wallich

Andre Kertesz, *January 1, 1972, Martinique*



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The Shape of Things to Go

Automakers turn to high technology in the search for a car that is clean, safe—and fun

by Karen Wright

In the automotive industry it is the best of times and the worst of times. From Detroit to Stuttgart, Tokyo, Paris, Turin and Seoul, automakers face a conspiracy of global issues that makes the energy crisis of the early 1970's look like a fire drill. Competition among manufacturers has never been more aggressive; congestion in cities worldwide has never been worse. The issue of automobile safety looms ever larger. And now that industry has finally acceded to emissions standards set years ago, the threat of global warming is pointing the finger at another villain: carbon dioxide, an enemy no catalytic converter can vanquish.

Yet the industry is also riding the crest of a technological wave. New materials, designs and devices—many of them co-opted through mergers with aircraft and electronics corporations—offer opportunities no automaker can afford to ignore. Alternative fuels and engines could lessen the automobile's impact on urban air quality, without sacrificing vehicle utility or performance. Lighter materials could improve fuel economy by reducing friction in the engine. More aerodynamic designs could boost efficiency by eliminating drag and yield better handling as well.

Perhaps the most unorthodox solutions come from electronics. "Smart" roads and even smarter cars could thin urban smog by speeding journeys and decreasing idling time. Real-time communications with traffic control centers could help drivers to avoid congestion and accidents. On-board digitized maps that flag vehicle and destination could guide a voyager through unfamiliar territory. Even the seasoned commuter could use the power of a microprocessor to evaluate traffic conditions and calculate the fastest route to travel to and from work each day.

Clean fuels, alternative engines, lightweight materials and sophisticated electronics are a powerful antidote to the ills befalling the industry. The tension between economic and environmental imperatives, and a not entirely rational attachment to the automobile, will decide the shape of things to go.

Stalking the Clean Car

Until recently the history of automotive technology was one of convergence. In 1895 a Panhard & Levassor motorcar won the great Paris-Bordeaux-Paris race, demonstrating the viability of the gasoline-powered vehicle. Yet at the turn of the century, 40 percent of U.S. automobiles were still steam-powered; 38 percent ran on electricity and just 22 percent used gasoline. Then in 1901 the Spindletop gusher erupted near Beaumont, Tex., and the discovery of vast petroleum reserves on American soil propelled the gasoline-powered engine—and the U.S.—into the lead in the automotive industry.

In the past 20 years automakers could well have grown nostalgic for those heady days, as developed countries have instituted increasingly strict standards for safety and performance. In the U.S. two legislative initiatives provide the regulatory context for domestic manufacturers and for offshore

AUTOMONTAGE reveals a kinship in the aerodynamic designs of French, Japanese and American manufacturers. Automakers worldwide are facing demands for stricter safety and emissions standards; some of the industry's solutions are similar, but technology has broadened the spectrum of possibilities.

producers targeting the world's largest single auto market. The corporate-average fuel economy (CAFE) laws, established in 1975, currently require that manufacturers maintain an average fuel efficiency of 27.5 miles per gallon in their foreign and domestic fleets. And the Clean Air Act of 1970, soon to be amended, limits the hydrocarbon, carbon monoxide and nitrogen oxide emissions that are permitted in tail-pipe exhaust.

Both measures have already succeeded in wringing sizable improvements from the descendants of Nikolaus Otto's original four-cycle engine. Since 1970 tail-pipe emissions from new cars have decreased by 96 percent, and the average fuel efficiency of a new vehicle has doubled.

Yet transportation, which consumes more than 60 percent of all the petroleum used in the U.S., still accounts for 40 percent of all hydrocarbon emissions and two thirds of carbon monoxide emissions. So automobile exhaust continues to come under fire. "We seem to be a handy target," observes Robert A. Frosch, vice president in charge of General Motors Research Laboratories.

Some kind of requirement for the introduction of clean cars may be included in the amended Clean Air Act. Fortunately, there is no shortage of options for alternative fuels. In Detroit the Big Three have long-standing programs on methanol, ethanol, natural gas and electricity, as well as some marginal interest in hydrogen and liquid petroleum gas. Ford and GM have each delivered hundreds of clean-fuel cars to the bellwether state of California, and this year they'll be sending thousands more.

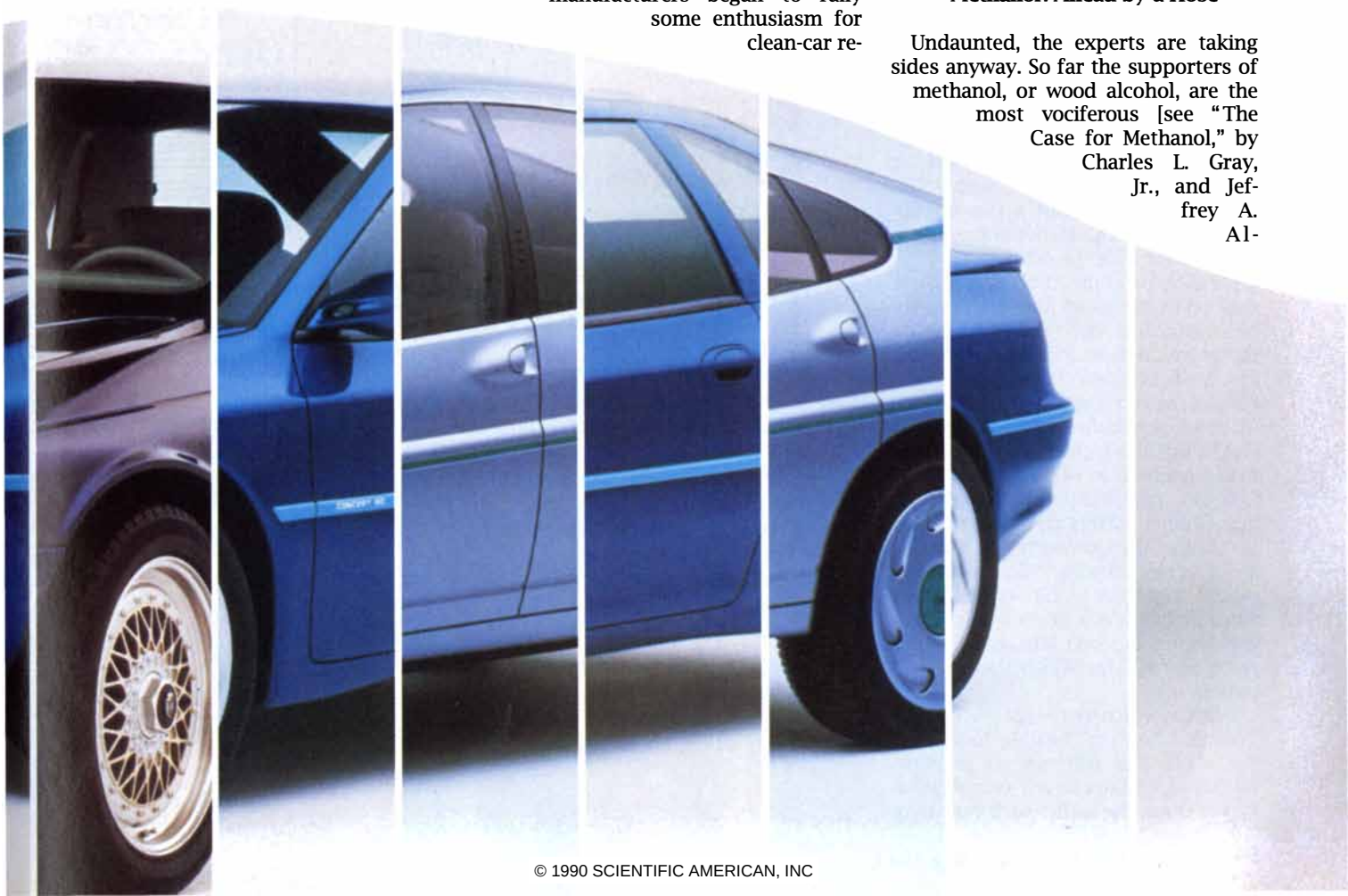
Japanese manufacturers have hit the ground running, too. Late in 1989 Nissan provided the California Energy Committee with a prototype car that could run on gasoline or methanol. This month Toyota and Mitsubishi will launch clean-car experiments in Nagoya, and Nissan and Isuzu plan to test prototype vehicles in Yokohama. Methanol-powered trucks already collect garbage in Tokyo and Osaka. "It pains me to say so, but they seem to have more scientists and engineers working on these problems, and it seems to be paying off for them," says Roberta J. Nichols, manager of the alternative-fuels department of Ford's Environmental and Safety Engineering Staff.

European programs have generally trailed U.S. and Japanese efforts, but manufacturers began to rally some enthusiasm for clean-car research when the Commission of the European Communities tightened its emissions standards last year. Most recently France announced a Fr 1.2-billion ($205-million) program on pollution-free cars, jointly funded by the government, Peugeot and state-owned Renault. Volkswagen and its new East German partner IKA-Kombinat said they plan to build clean cars for sale throughout Europe. And Fiat is in the middle of a three-year pledge to spend 1,200 billion lire ($948 million) on measures to protect the environment, such as free installation of catalytic converters.

All that is lacking is a consensus on which alternative-fuel technology will win out. "You're talking about a multibillion-dollar decision," says Steven E. Plotkin, a senior associate at the Congressional Office of Technology Assessment (OTA), who is preparing a broad analysis of fuel replacements. "People are lined up on every side of it, fighting. The only way to beat this is to get unimpeachable data." Yet Plotkin claims that in the U.S. only three studies with a total of four vehicles have detailed the contributions to ozone formation of each of the 20 to 30 compounds in tail-pipe exhaust.

Methanol: Ahead by a Hose

Undaunted, the experts are taking sides anyway. So far the supporters of methanol, or wood alcohol, are the most vociferous [see "The Case for Methanol," by Charles L. Gray, Jr., and Jeffrey A. Al-



son; SCIENTIFIC AMERICAN, November, 1989]. Methanol burns more cleanly than gasoline, yielding as little as one tenth the hydrocarbon emissions per mile, according to data from the Environmental Protection Agency. It can be made from natural gas (methane) or coal, both of which are abundant in the U.S. and many other countries. It also delivers more horsepower and a higher octane rating than gasoline, which is why methanol is the fuel of choice for the Indianapolis 500.

But conventional cars have to be redesigned to burn methanol. The fuel-system components of methanol-powered vehicles, for example, have to be made of materials that resist corrosion. And for practicality's sake, the fuel tank itself must be larger than the average gas tank because methanol has 40 percent less energy per gallon than gasoline.

Burning methanol also releases formaldehyde, a possible carcinogen. Concern over the potentially harmful effects of formaldehyde emissions recently prompted the Japanese Ministry of International Trade and Industry to finance a three-year, 1.25-billion-yen ($8.3-million) study. Gasoline engines produce formaldehyde, too, but in smaller quantities. In the U.S. only California has so far put a cap on the amount of formaldehyde emissions permitted in tail-pipe exhaust.

Ethanol, or grain alcohol, is a close relation of methanol and shares many of its attributes and failings, including the production of formaldehyde. GM, Fiat, Saab, Scavia, Volvo and Mercedes-Benz all have considerable experience in building ethanol-powered cars for sale in Brazil, which began a transition to alcohol fuels in 1975.

But the popularity of both methanol and ethanol suffers from what Daniel Sperling of the University of California at Davis has called a "chicken-and-egg stasis": suppliers won't set up outlets when demand for a given fuel is scarce and motorists won't buy cars that operate on fuels for which there are no outlets.

Industry's answer to that stasis is the "variable fuel" or "flexible fuel" vehicle: a car that can run on gasoline, methanol, ethanol or any combination of the three. Typically, such cars have an optical sensor in the fuel tank that determines the composition of the fuel mixture. The sensor relays that information to an engine-control module, which adjusts the air-to-fuel ratio and other operating parameters.

Circuit City

Having hedged their bets with the variable-fuel vehicle, manufacturers still aren't scrambling to roll out cars that run on alternative fuels. "We have to start worrying in earnest about marketing," says Ford's Nichols. In many ways, being the first on the scene with an alternative-fuel vehicle might not be an enviable position. After more than a decade of research on alcohol fuels, Sperling suggests, most automakers have enough know-how to match quickly innovation by a competitor.

Consequently, the pioneer in the market would have very little time—Sperling says Ford estimates between six and nine months—to capitalize on its monopoly before rivals appeared.

Electric vehicles suffer the same mar-

Car ads capture the spirit of an industry and the evolution of consumer consciousness

THEY CAME AND WENT

1910

The automobile owes at least some of its mystique to the art of creative peddling.

Through the years advertisements have faithfully documented the qualities people admire most in their cars.

Some campaigns were signs of the times: paeans to gas-guzzling engines had become ballards of fuel economy by the 1970's, and the "man" who owned a Packard would just be a "person" today.

Other pitches have timeless appeal: consumers still respond to the car as status symbol, as sound investment and as good (if no longer clean) fun. —*K.W.*

1954

George B. Selden (U.S.) designs a **gasoline-powered automobile**

U.S. organizes the first **speed traps** (20 mph limit)

1892 | 1895 | 1900 | 1903 | 1905

Rudolph C. K. Diesel (Germany) patents a **compression-ignition engine**

SELDEN

The R. E. Dietz Company (U.S.) introduces kerosene **headlamps**

The first **car theft** is reported in St. Louis, Mo.

keting disadvantage. Such vehicles have often been promised, rarely delivered. This year manufacturers seem to have decided to dust off their lab notes and try again. Peugeot and Fiat have announced intentions to market electric passenger cars for private use in Europe; GM has said it will decide this month whether to produce its two-seater electric prototype, the Impact.

Even the technology's advocates say electric cars will not have much appeal outside of limited commercial applications. "We don't know how to build the batteries for a really good, general-purpose electric car yet," notes Frosch of GM's technical center. The Impact's lead-acid battery gives the vehicle a range of about 120 miles at 55 miles per hour, close to its top speed. The battery, which would probably cost around $1,500, requires a six-hour recharge and would have to be replaced every 20,000 miles, according to GM.

Many automakers and chemical and electric companies are investigating sodium-sulfur and nickel-iron batteries that could have longer lifetimes. Recharging, however, would still be inconvenient, and long trips out of the ques-

1926

1937

1949

1962

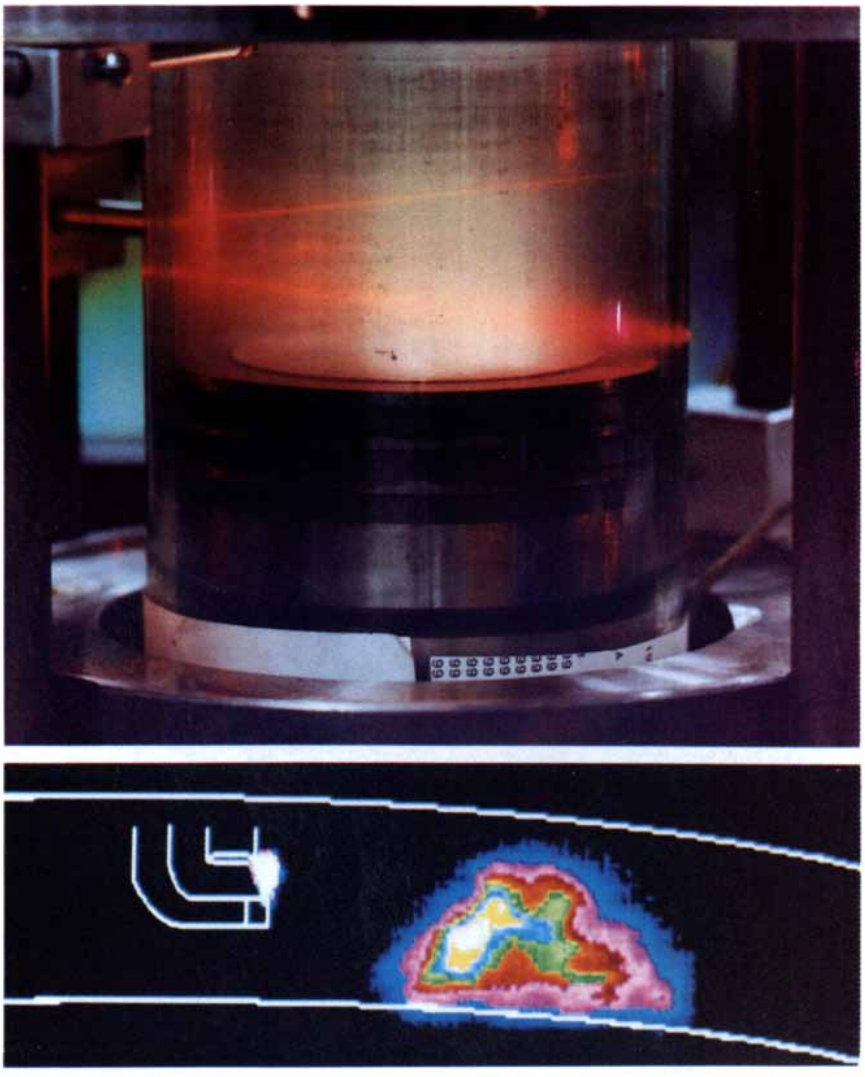
1965

1974

tion. So some automakers propose a hybrid. "We are exploring the possibilities of bimodal traction systems in which an electric-motor drive coexists with a conventional thermal engine so as to satisfy both urban and long-journey requirements," says Paolo Scolari, manager of industrial design and development at Fiat.

Electric vehicles have been described as the "holy grail" of vehicle alternatives because they produce no emissions. The appellation may not be justified. Energy for the batteries would have to come from somewhere; if the source is a utility plant that burns coal, oil or gas, electric cars would simply push the "fossil-fuel error" further upstream.

The only truly clean-burning fuel is hydrogen, which on combustion gives off steam. Several manufacturers, particularly those in Europe and Japan, are avidly pursuing the technology for hydrogen engines. But gaseous fuels such as hydrogen and natural gas pose problems in automotive applications because they are hard to store on board a vehicle. Difficult, but not impossible: successful hydrogen-powered prototype vehicles were built years ago, most notably by Daimler-Benz, and about 10 percent of cars in New Zealand already run on natural gas.



TRANSPARENT CYLINDER of a piston engine (*top*) helps scientists at General Motors Research Laboratories to understand combustion. Computers record how the flame spreads from the spark plug (the L in the bottom image) throughout the chamber. Curved lines represent the chamber ceiling and the top of the piston.

Enginuity

In spite of all the interest in alternative fuels, the gasoline engine probably will not bow out anytime soon. In 1988 the 300 automotive experts polled by David E. Cole and his colleagues at the University of Michigan Transportation Research Institute (UMTRI) for their biannual "Delphi" (as in "oracle at") forecast predicted that between 10 and 18 percent of the vehicles produced in North America will be using alternative fuels by 1995.

That leaves a good many gasoline engines on the road. And the petroleum industry will probably continue to fight for gasoline's viability by reformulating fuels. But all that runs on gasoline need not be an engine of the old-fashioned Otto variety.

"This looks like an engineer's nightmare," says Nicholas E. Gallopoulos, standing in a lab at GM's tech center, where he heads engine research. "And in many ways it is." The source of his derision is a jumbled pile of multicolored wires, belts and steel that nearly fills the bottom half of the room. It's a working facsimile of a piston engine that helps researchers study how fuel burns in the milliseconds after a spark plug ignites it.

The centerpiece of this unruly objet d'auto is a single cylinder whose walls are made of transparent sapphire. When the engine is running, computers equipped with optical sensors can "watch" the combustion process through the walls of the cylinder.

Models such as the sapphire cell help researchers to learn how to improve engine efficiency. The timing and placement of the spark, the size and shape of the chamber, the number and position of the valves and the turbulence created in the mixture of gas and air can all affect how well fuel burns.

Already a detailed understanding of the combustion process has influenced

the development of multivalve engines, variable-geometry turbochargers and electronic fuel injection. Advances in the drivetrain, such as the continuously variable transmission (which allows the engine to run optimally at any speed), will also contribute to the performance and efficiency of the traditional four-cycle engine.

Now engineers are trying to coax engines into running with lower air-to-fuel ratios than they ought to. Such "lean burn" engines would block pollution at its source. Automakers have also begun to explore alternatives to conventional engines, and when they do, the name that comes up most often is "two-stroke."

The two-stroke, or two-cycle, engine has been used for decades in outboard motors, chain saws and snowmobiles. As its name suggests, the engine does in two cycles what the conventional gasoline engine accomplishes in four. Instead of assigning one stroke each to the intake, compression, power and exhaust stages, the engine performs both intake and compression in one stroke and power and exhaust in the other. Because every other stroke is a power stroke, the two-cycle design has the potential to be much more efficient than a four-cycle engine.

Yet in practice it has some annoying quirks. It burns oil and spews out unburned fuel, and, as anyone who's ever mown a lawn knows, it makes a lot of noise. Except in East Germany, where thousands of two-cycle Trabant and Wartburg automobiles trail noxious blue smoke, the engine has been relegated to specialty machines.

The Two-Stroke Strikes Back

In the past several years the development of new fuel-injection technology has eliminated the undesirable attributes of the engine and given it a 25 percent advantage in fuel consumption over comparable four-cycle engines. The reconstituted two-stroke's most conspicuous innovator and champion is an Australian real-estate mogul named Ralph T. Sarich, who heads the Orbital Engine Company in Perth. Orbital's two-stroke is about half the size and weight of the conventional automobile engine. And because it has fewer parts, the Orbital engine costs 25 percent less to manufacture, the company says.

Sarich says he has succeeded in getting engine emissions substantially below current U.S. requirements, a goal that has eluded many other companies. Ford and GM, for example, have been working on two-strokes for years without attaining similar results. Now both have licensed Sarich's technology and say they will have engines on the market by the end of the decade. But researchers at the companies claim their products will be based on their own development efforts, not Sarich's.

Peugeot and the French Petroleum Institute have jointly designed a two-stroke engine as well. "The engine is great from the point of view of performance, pollution and simplicity," says the institute's André Douaud. "But can we produce it on a large scale?" Toyota may well be asking the same question of its own two-stroke prototype. The 3.0-liter Japanese engine is much more complicated than Sarich's version and is targeted at the luxury-car market.

Meanwhile Sarich has signed an agreement to manufacture, starting in 1991 at Tecumseh, Mich., the first two-stroke Orbitals. Sarich has a dream of the world running on two-strokes; other people see it differently. "This is not the device that's going to completely replace every other engine over night," cautions Ian MacPherson, who heads drivetrain research at Ford. "We don't know if people will like it; we don't know if it'll measure up in terms of robustness and mileage." Cole's Delphi forecast puts two-cycle engines in 2 percent of passenger cars by 2000.

"The carrot on the stick for us is the packaging and design flexibility," says GM development engineer Paul E. Reinke. He points out that the two-cycle can be seven or eight inches shorter than a conventional engine because it has no valves or valve train. That low profile is well suited to the bullet-nosed aerodynamic designs that seem to be the market's current infatuation.

But MacPherson says manufacturers might get more bang for their buck by trying to improve on known technology such as diesel engines. In fact, European and Japanese manufacturers are working to reduce the particulates in diesel exhaust so that it will survive the tightening of emissions controls.

Material Gains

Then there's the recalcitrant turbine. "There's a lot to be said for continuing to develop the gas-turbine engine," MacPherson points out, although he acknowledges that such engines will not become practical for cars in the foreseeable future. Gas-turbine engines realize significant gains in efficiency and power only at very high temperatures, and automakers have not yet found low-cost engine components that can take the heat.

Such components would presumably be made of ceramics, tough but brittle solids that are neither metal nor polymer. The atoms making up ceramics are locked together in inflexible chemical bonds that can withstand high temperatures and chemical attack. Unfortunately, the strong bonds also make ceramics extremely vulnerable to minute structural flaws. To prevent cracking, engineers have to minimize flaws through painstaking processing techniques.

Ceramic turbine blades have been manufactured that perform without a hitch at temperatures of up to 2,500 degrees Fahrenheit. That's in the ballpark of how hot an economical gas-turbine engine for the automobile would have to be. The trouble is, the whole engine has to be made of ceramics. "Now we need the other parts," GM engineer Albert H. Bell III says with a grin.

Researchers also have to figure out how to get the parts to hold up under rapid changes in temperature, how to shield the surrounding structure from heat and how to seal off certain parts of the engine. "Then you have to figure out how you can process these things so that if you make a zillion of them, they're all going to work," adds Peter Beardmore, manager of the materials science department at Ford.

Japan has put a heavy emphasis on the development of ceramic parts for gas-turbine engines. Toyota and Nissan have joint ventures with ceramics manufacturers; other companies, including Isuzu, have set up their own ceramics-research labs. But even Japanese automakers admit the gas-turbine engine is

still a long way from production in cars.

Fortunately, ceramics and other new materials are much closer to the marketplace in conventional engines. Titanium, aluminum, polymers and metal composites—in addition to ceramics—are being fashioned into valves, pistons and piston pins, connecting rods and spring retainers, oil pans, cylinder blocks and intake manifolds. Strong and lightweight, such materials will improve fuel efficiency by decreasing the weight of the car and improve engine performance by reducing friction.

But the hottest area in automotive materials is probably composites, particularly structural ones. A car in which all the body structural components are made of polymer-based composites could be 30 percent lighter than current production models. And composites make assembly faster and easier because parts that ordinarily need to be welded or bolted can be combined in a single module. The 400 steel parts that make up the body structure of the Taurus, for example, were integrated in just five composite sections in one of Ford's concept cars.

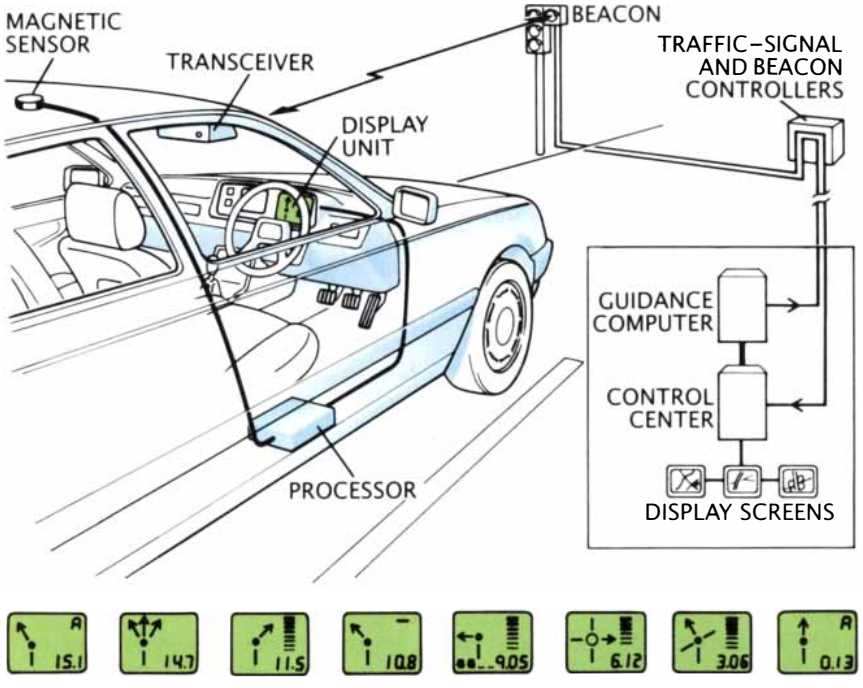
The plastic composites used in the automotive industry generally consist of resins such as polyester, epoxy, vinyl ester and urethane reinforced with glass, graphite, mica and other materials that impart structural strength. GM's introduction of the 1953 Corvette marked the first appearance of glass fiber-reinforced plastic "skins" in mass-produced cars; composites have been creeping onto steel car bodies as fenders, bumpers, tailgates and hoods ever since. Most recently GM's Fiero demonstrated the feasibility of building an entire car body of plastic panels bolted onto a steel space frame.

But manufacturers would like to use composites under the skin panels as well, on the parts of the vehicle that bear most of load and are most highly stressed. Such structural elements require a stronger composite, which is currently made by a laborious process called reaction-injection molding (RIM).

In reaction-injection molding, a preform resembling a blanket of white glass fibers is wrapped around a foam insert and put into a mold; resin is then squirted into the mold, and the whole structure is allowed to cure. Lotus has used this procedure for years. But the curing takes hours; Lotus turns out only two cars a day. Automakers want to find a way to incorporate RIM in a manufacturing process that turns out a car every three minutes.

"Composites require a transition in the way we design, manufacture and assemble cars," says Irvin E. Poston, manager of composites on GM's advanced engineering staff. He adds that most of the composite parts on the market now were made with a fabrication process called compression molding, which is based on the metal-stamping procedure used to form steel parts. Compression molding is fast, but, like stamping, it won't work on a large, highly integrated mold. And the so-called sheet-molding compound (SMC) required for compression molding is not strong enough for structural applications.

Ultimately, plastic composites could be foiled by one of the attributes that most recommends them: their durability. There are indications, particularly in Europe, that automakers will not get the green light on composite cars unless they can demonstrate how they would recycle them. But efforts to improve the recyclability of composites could also weaken them structurally, asserts James P. Womack, director of the International Motor Vehicle Program based at the Massachusetts Institute of Technology. "It's a problem if they deteriorate, and it's a problem if they don't," he says.



SMART CAR in London's Autoguide navigation system lets a motorist enter a destination on a hand-held remote unit (not shown); the car's processor then communicates with a control center by way of infrared signals and beacons. A dashboard display tells the driver how many kilometers remain in the journey (*numbers*), whether to go straight or to turn (*arrows*), how close a critical intersection is (*bars*) and whether the intersection is an ordinary one or a "roundabout" (*open circle*).

Street Smarts

At least one other material promises to play an important role in the future of the automobile: silicon. In today's engines, microelectronic devices more or less run the show. Computers supervise most of the operational aspects of an engine—the air-to-fuel ratio, the recycling of exhaust and its distribution

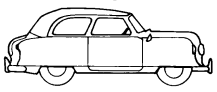
Rover (U.K.) builds the first **gas-turbine car engine**

Tubeless tires are standard equipment

Fuel injection is introduced on production cars

1950 1951 1954 1956 1957

NASH



Power steering becomes available

Felix Wankel (West Germany) demonstrates the **rotary engine**

among the cylinders. They also take part in climate control, seat-belt warnings and dashboard displays.

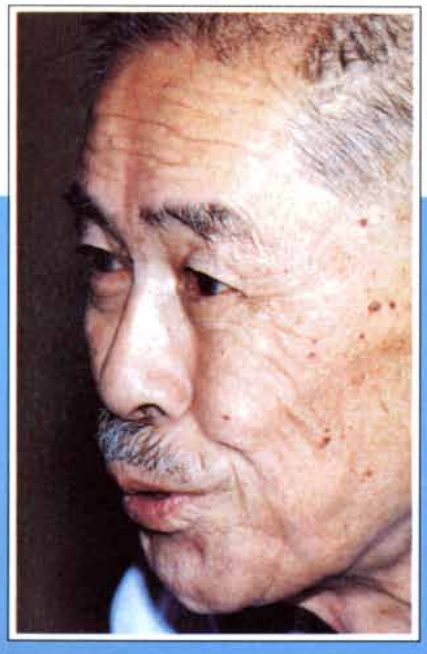
Electronic systems currently make up about 6 percent of a car's value. Delphi panelists think that figure will climb to 20 percent by 2000 as antilock brakes, active suspensions and other computer-dependent technologies move into full production. But much of the added computing power will probably get plowed into new technology for smart cars and smart roads, or IVHS (intelligent vehicle/highway systems). The term refers to a varied assortment of electronics that provide real-time information on accidents, congestion, routing and roadside services to drivers and traffic controllers. IVHS also encompasses devices that would make vehicles more autonomous: collision-avoidance systems and lane-tracking technology that alert drivers to impending disaster or allow a car to drive itself.

The most organized IVHS efforts are going on in Europe, where two umbrella groups unite academic and industry researchers, private and government organizations and manufacturers and suppliers. The $800-million PROMETHEUS (Program for European Traffic with Highest Efficiency and Unprecedented Safety) is an eight-year consortium that was launched in 1986 under the auspices of the Economic Community's EUREKA program to improve European competitiveness. Its members include 12 major European automakers, more than 70 research institutes and universities and more than 100 electronics and supplier firms.

The DRIVE (Dedicated Road Infrastructure for Vehicle Safety in Europe) program, which began in January of 1989, concentrates on the road infrastructure rather than vehicle technologies. Its funding totals $140 million for three years; half comes from the European Commission and the other half from government and industry in participating countries. In addition to DRIVE and PROMETHEUS, Europe has half a dozen smaller groups under EUREKA focusing on specific problems in IVHS.

One of the more celebrated developments to have come out of such programs is the Leit-und Informations-system Berlin (LISB) network in West Berlin. LISB connects about 500 cars with route-guidance information over an area covering 3,000 kilometers of road, 4,500 intersections and 1,300 traffic signals. The cars transmit and receive data from 250 infrared roadside beacons at the rate of eight kilobytes (8,000 characters) per second. LISB is sponsored by the West German Federal Ministry of Research and Technology, the Berlin Senate, Siemens and Bosch. London has borrowed the LISB technology to institute a similar program, called Autoguide [*see illustration on page 96B*].

In Japan the Advanced Mobile Traffic Information Communications System (AMTICS), sponsored by the National Police Agency and the Ministry of



Japan's Henry Ford

Taiichi Ono does not exude the aura of an industrial revolutionary. Ono, 78, retired from his position as executive vice president of Toyota Motors in 1978 and now spends his time "fooling around," he says. But he still delivers a lecture or two on "lean" production, the style he pioneered that has gradually supplanted mass production in automobile manufacturing worldwide.

"The U.S. doesn't know what it's aiming at. Productivity is not quantity."

Lean production combines the principles of "just-in-time" inventory management with other measures that streamline manufacturing. Ono devised the system after World War II, when Japanese automakers produced just 30,000 vehicles a year. Consumers were demanding an increasing variety of cars and trucks, and Ono reasoned that Henry Ford's philosophy of offering a limited product line in massive quantities would not work in Japan. He also thought that by stockpiling parts and supplies "just in case" they were needed, American assembly lines wasted time, space and money.

Toyota's founder, Kiichiro Toyoda , had promoted the idea of just-in-time production instead: pulling components to the production line as they were needed, rather than keeping them in reserve. Ono embellished Toyoda's cause with his own ideas about eliminating waste. By 1953 every man in Ono's shop was operating an average of from five to 10 machines. By 1962 Ono had cut the time it took to change stamping dies from several hours to 15 minutes. By the 1970's Toyota's factories were running with just a few hours, rather than a few days, of inventory.

Toyota considered the system so powerful, Ono claims, that the company deliberately coined difficult and even misleading words to describe it. "If in the beginning the U.S. had understood what Toyota was doing," Ono says, "it would have been no good for us."—*Frederick S. Myers, Tokyo*

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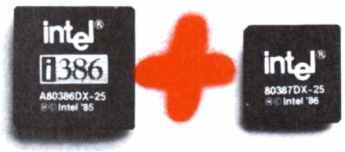

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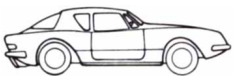
U.S. creates the **Department of Transportation**

1966

STUDEBAKER



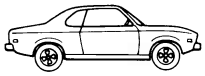
1971

Engines are designed for **unleaded fuel**

New cars are equipped with **catalytic converters** (U.S.)

1974

BUICK



Posts and Telecommunications, supplements dead-reckoning and map-matching navigation equipment on the car with teleterminals connected by cellular radio to a traffic control center. About 50 companies participate in AMTICS; another 25 are involved in RACS, the Road/Automobile Communication System, which is administered by the Public Works Research Institute of the Ministry of Construction.

While government initiatives in Europe and Japan have been key to organizing efforts on IVHS research, U.S. companies have been left to their own devices, so to speak. "Their knowledge of the science is not ahead of ours," says Mounir M. Kamal, executive director of engineering sciences at GM's research labs. But he says the federal government needs to help industry coordinate research on the various elements of IVHS.

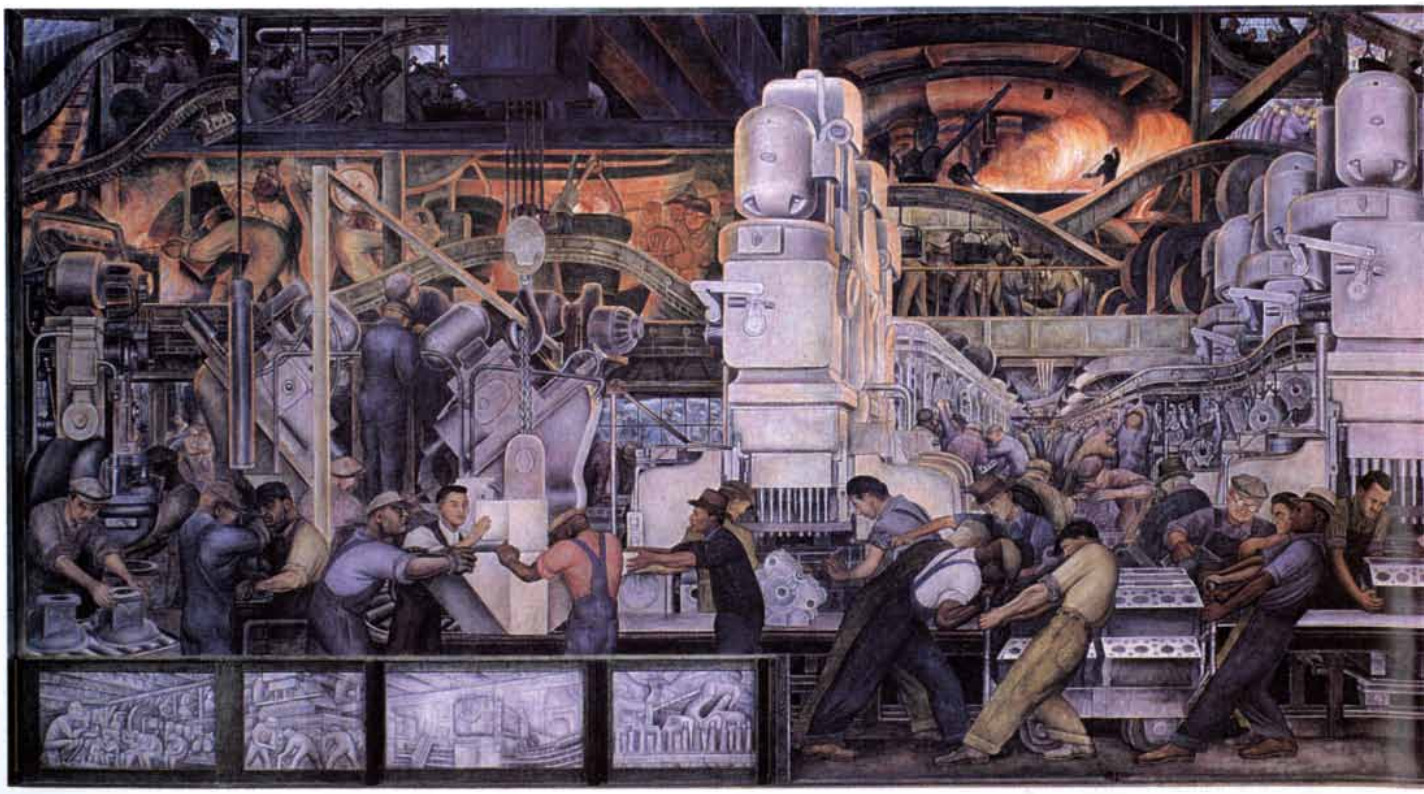
The OTA has recommended that the government establish such a national agenda for IVHS technology, and both the General Accounting Office and the National Academy of Sciences are investigating the feasibility of IVHS research. IVHS proponents hope Congress will set aside some money for IVHS research when the Highway Trust Fund is reauthorized this year.

So far, state support for IVHS has put the federal government to shame. California has been the technology's most aggressive promoter. In Los Angeles, the Smart Corridor project, funded by local governments and the California Department of Transportation, provides designated drivers on a 12-mile stretch of the Santa Monica Freeway and surrounding arterial streets with traffic information through highway-advisory radio broadcasts, changeable message signs, menu-driven telephone information systems and videotex. In Richmond, the California Program on Advanced Technology for the Highway (PATH) studies roadway electrification and automated control that would allow hands-off driving.

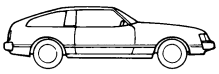
No Hands

In some respects, U.S. industry has been as slow to mobilize as the government. Steven E. Shladover, technical director of California's PATH, says he staved off the eager advances of Japanese and European companies for years, waiting for U.S. industry to show some interest in the 26 projects administered by his program, the largest in the country.

"Some of the people in the auto industry like to pooh-pooh what we're doing," he maintains. "But we need to make a quantum leap in freeway capacity, or our cities are going to strangle themselves." Shladover points out that even the 10 to 20 percent improve-



DEPRESSION-ERA ASSEMBLY LINE is captured in this detail of the 1932–1933 fresco *Detroit Industry,* by Mexican artist Diego M. Rivera. The grim workers were seen as an indictment of mass production. Factory automation has

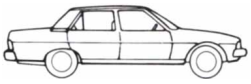

TOYOTA

Fleets of **methanol-powered cars** are deployed

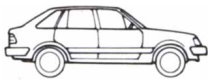
Nissan (Japan) offers **electronic navigation systems** as original equipment

1983 1984 1989 1990

PEUGEOT



FORD



Mercedes-Benz (West Germany) introduces **antilock brakes**

HONDA

Fiat (Italy) and Peugeot (France) market **electric passenger cars**

ment in roadway efficiency that the OTA predicts for conventional IVHS represents just one or two years of growth in California.

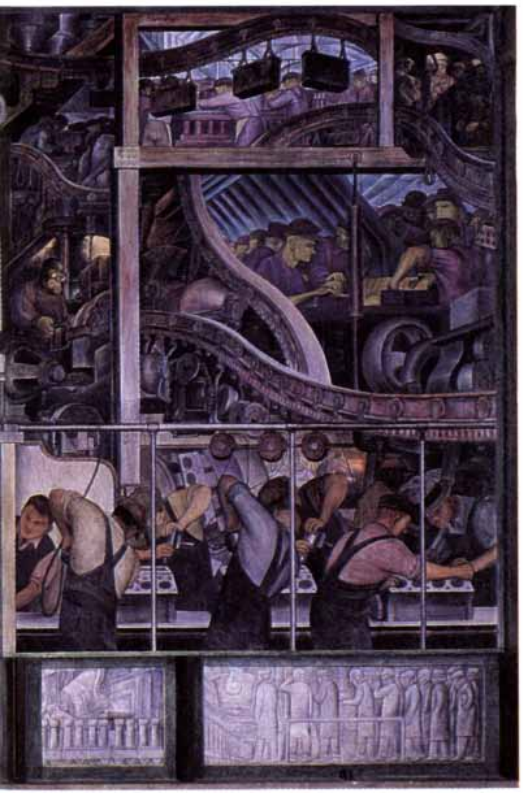
Shladover thinks the most effective solution to California's woes is "platooning": squeezing cars closer together on highways by providing them with collision-avoidance, lane-tracking and other systems for automated control. Such systems generally operate by bouncing radar or sonar signals off surrounding automobiles and using machine vision to locate lane markings. The automated-control system then steers, accelerates or brakes the car when necessary.

Currently freeways can sustain about 2,000 vehicles per lane per hour, Shladover says; above that figure, the traffic flow becomes "turbulent" to the scientist, stop-and-go to the motorist. If the vehicles are traveling 60 miles per hour, the average density of cars in each lane is one every 132 feet. If a vehicle is, say, 15 feet long, then 117 feet of freeway is being wasted. With platoons filling longitudinal vacancies, up to 7,200 vehicles per lane per hour could be packed together—one every half second.

Those same calculations work laterally, Shladover says. To compensate for the vagaries of the individual driver, freeway lanes are anywhere from 50 to 100 percent wider than they have to be. With lateral platooning, San Francisco's Bay Bridge, which has two decks of five lanes each, could accommodate seven lanes and sustain a 40 percent increase in traffic flow.

Shladover admits that even improvements of that magnitude would only be buying time. And all IVHS technology faces the trials of user acceptance and cost-effectiveness. The liability issues could also be titanic, says University of Michigan electrical engineer Kan Chen, who coined the term intelligent vehicle/highway systems. With platoons, he points out, "if something goes wrong, you could have 200 cars in a crash," and you could sue no less than three institutions: the other people involved in the crash, the car or electronics manufacturers and the highway department.

And Womack of M.I.T. thinks people would demand stricter assurances of safety of automated vehicles than they expect of drivers. "The presumption is that it's quite okay for 50,000 people a year to be killed by cars driven by humans, but the number of people that can be killed by cars driven by computers is vanishingly small," he says.



changed assembly-line work, but people still do some jobs better than machines.

Shapes of Things to Go

New fuels, new engines, new materials, new electronics—so many possibilities, it's hard to imagine all of them packed into one vehicle. What will the car of the future be like?

"Depends on which kind you want to buy," says Frosch of GM. "What are your tastes?"

The car of the future, managers and engineers alike say, isn't a single model that will roll out of assembly plants everywhere several years hence, the consummate technological cure for the ills begotten by a century of exuberant automobility. The car of the future will be many cars, and barring extreme government intervention, they'll be just what the customer ordered.

"You try to meet a market demand in competition within a set of constraints that have to do with societal requirements," Frosch continues. "But you can't put meeting societal requirements ahead of actually selling vehicles to customers."

The globalization of the automobile industry and of the challenges confronting it has brought about an unmistakable convergence in industry philosophy that extends to all facets of the business, from body design to manufacturing techniques. But experience has shown that the customers won't tolerate unrelieved homogeneity among new car models. The sudden popularity of the pick-up truck in two-car families underscores the fact that a vehicle's allure cannot be reduced to its practical elements.

"As far as we can see down the road, the customer will be in the driver's seat in the industry," quips UMTRI's Cole. The need for creative solutions to government standards could also invite a diversity of automotive technologies that has not been seen since the early days of the automobile.

So one of the aims of the industry in the coming century is to achieve a flexibility in manufacturing processes that Henry Ford would never have dreamed of. The new paradigm of "lean" production will loosen the grip of economies of scale [*see profile on page 98*]. With the help of computer-aided design and the discriminate use of automation, manufacturers should be able to update models quickly, cater to market niches and respond more readily to swings in consumer taste.

"There will be many losers in this restructuring as well," Cole warns in a summary of the latest Delphi forecast. He anticipates hard times for "rigid" and "risk-averse" organizations and a significant loss of employment in the automotive industry worldwide. But Cole is not morose. In concluding his summary, he sounds like Rhett Butler describing the fall of the South. "For those who seize change as an opportunity," he writes, "these may be the very best of times."

The Spawning of the Capelin

This fish lays its eggs on Newfoundland's beaches, where the hatchlings linger for up to a week. They leave the land for the sea in response to complex signals conveyed by wind and water

by William C. Leggett and Kenneth T. Frank

In June immense schools of small, silvery fish called capelin enter the hundreds of bays that dot the east coast of Newfoundland to perform a fascinating ceremony. The males and females separately approach the gravel beaches and are borne ashore in waves so laden with their bodies as to be virtual walls of fish. There, on the gravel, the females lay their eggs and the males fertilize them; then most of the fish die. The eggs adhere to the gravel and are buried as deep as 20 centimeters by the waves, packing the ground so densely that it can feel like a foam mattress underfoot. Tiny larvae hatch from two to four weeks later and then linger in the gravel for anywhere from hours to days before abruptly and simultaneously abandoning their landlocked nurseries and heading out to sea.

The larvae of no other such terrestrial spawner enter the sea at such unpredictable intervals. What governs the timing of the emergence, and what adaptive advantage does the timing provide? These questions are of both intrinsic and economic interest since the capelin (pronounced CAPE-lin) supports a commercially important fishery and provides a large part of the diet of many fishes, birds and mammals in the North Atlantic.

WILLIAM C. LEGGETT and KENNETH T. FRANK have collaborated extensively in the study of marine ecology. Leggett is dean of science and professor of biology at McGill University in Montreal. He obtained a B.A. in English and history from Waterloo University College in 1962 and then shifted to ecology, earning an M.Sc. from the University of Waterloo in 1965 and a Ph.D. from McGill in 1969; he joined McGill's faculty the next year. This is his second article for *Scientific American*. Frank is a research scientist in the marine fish division of the Department of Fisheries and Oceans at the Bedford Institute of Oceanography in Dartmouth, Nova Scotia. He earned a Ph.D. in biology from the University of Toledo in 1978 and did postdoctoral work at McGill before joining the institute in 1983.

The capelin (*Mallotus villosus*), a marine cousin of the freshwater smelt, attains a length of 20 centimeters and a weight of 20 grams in its third or fourth year, when it becomes sexually mature and ripe for the fisherman's net. Only the egg-laden females are marketed (a selection facilitated by the fish's tendency to school by age and sex), because they alone are prized as food. Most of the Canadian catch is now sold to Japan, where sushi bars serve it as *shishamo*, a lightly fried delicacy. Capelin has never had a vogue in North America, despite efforts to popularize it in the form of a dried snack and in other ways.

Capelin's circumpolar distribution supports commercial fisheries near Hokkaido, near Iceland, in the Barents Sea and off Newfoundland and Labrador, where its arrival is formally celebrated in many fishing villages. The villagers welcome the fish in part as a herald of the far more important cod, which follow the capelin in their migrations and prey on them.

Capelin, like many other marine fish, vary in numbers dramatically. Between 1975 and 1979, for example, the biomass of capelin in the eastern Newfoundland stock dropped from nearly four million to less than half a million metric tons, a boom-and-bust cycle that had a great effect on the Newfoundland economy and on the populations of other species in the Northwest Atlantic food web. Investigators have long sought answers to the question of what regulates these frequent and striking changes in the abundance of marine fish. Our interest in this general problem, coupled with the decline of capelin during a period of rapid expansion in the commercial fishery, led us in the spring of 1978 to initiate a series of studies of the factors regulating capelin abundance. The work was conducted with subventions from the Natural Sciences and Engineering Research Council of Canada and the Canadian Department of Fisheries and Oceans. We began at Bryants Cove, a spawning site about 60 miles northwest of Newfoundland's capital, St. John's.

The general life history of capelin was well known, but details of its early stages were not. We therefore concentrated on the developmental stages between spawning and the metamorphosis of larvae into the juvenile form, which is characterized by reorganization of the digestive system and pigmentation of the once transparent body. This early period, lasting about 10 months, accounts for up to 99 percent of the mortality in fish species for which estimates exist.

We began by systematically sampling the Bryants Cove beach with a corer similar to those for extracting soil samples. More than 60 percent of the eggs were found near the upper limit of the beach, where they are submerged for only one or two hours a day, at high tide. The remainder, distributed at the intermediate- and low-tide levels of the beach, are submerged for periods ranging from two to 24 hours a day. Most capelin eggs, therefore, incubate in a semiterrestrial environment whose thermal regime is dominated by meteorological conditions, such as the temperature of the air and the intensity and duration of direct sunlight. The thermal variation is amplified by the twice-daily tidal inundation of the eggs by North Atlantic waters at temperatures between zero and eight degrees Celsius.

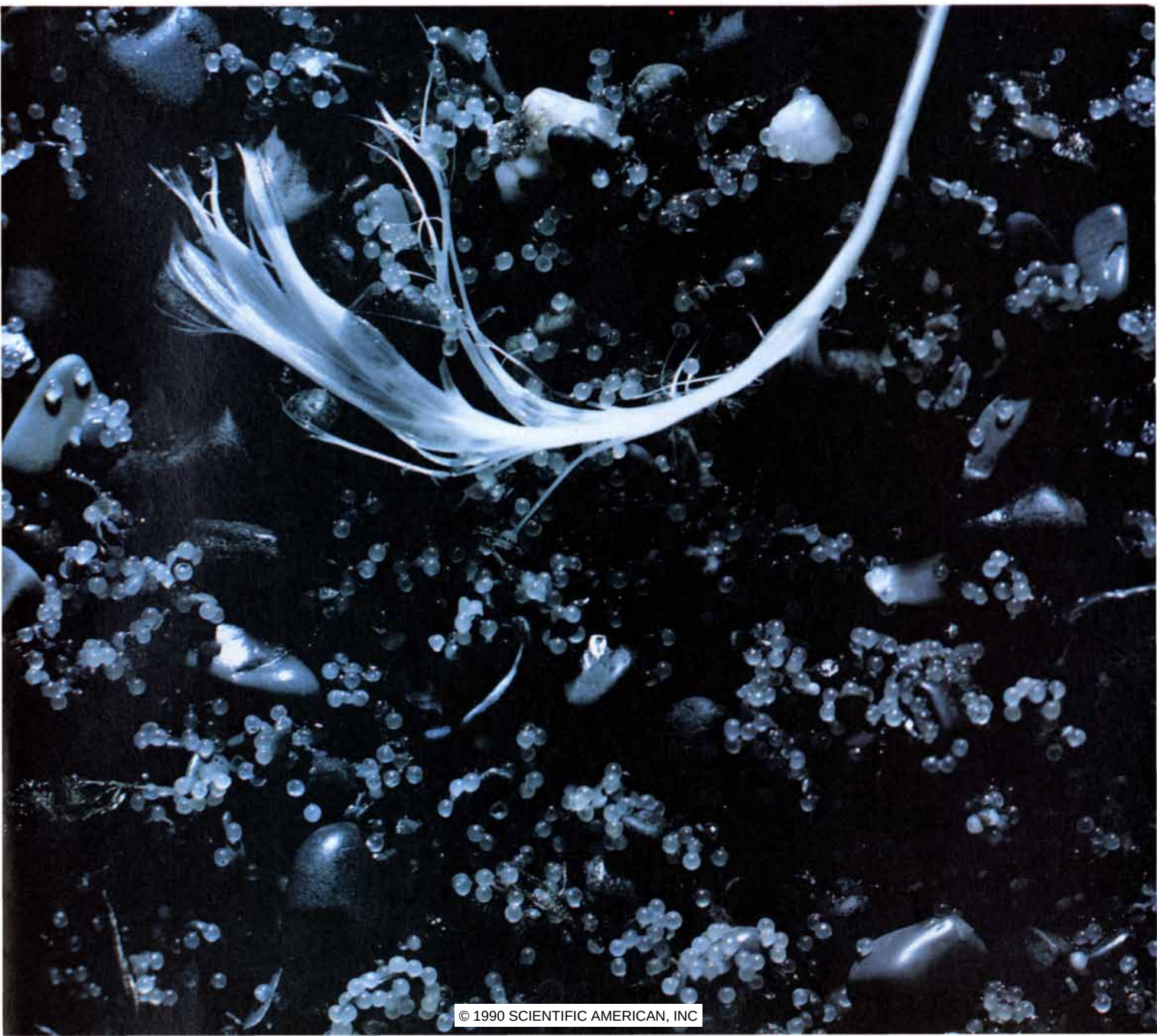
GRAVEL BEACH shelters eggs laid and fertilized by mature capelin, the majority of which die of exhaustion soon after spawning. Larval fish hatch within a few weeks and then linger in the gravel for hours or days, until all of them suddenly emerge into the sea and begin to forage.

We found that 85 percent of the variability in median hatching times could be attributed to variations in average daily incubation temperatures. This relation was consistent from year to year and from site to site and in different cohorts of eggs. (The week-long spawning period produces from two to three such cohorts.) We were able to verify our results by comparing them with records of capelin spawning since the late 1920's, which showed that spawning dates are virtually synchronous along the coast but vary by as much as three weeks from one year to the next.

Meteorological and oceanic conditions affected not only the eggs' rate of hatching but also their prospects of survival. Egg density also affected the survival rate: the greater the density, the lower the rate (possibly because of depletion of oxygen). These variables can be analyzed to make very reliable predictions of hatching success.

A curious aspect of the hatching process intrigued us: the number of larvae in the beach gravel would repeatedly increase from nearly zero to more than one million per cubic meter over the course of about a week and then suddenly decline again to nearly zero. We sampled the waters near the beach for larval capelin and found a pattern of abundance over time that was the inverse of larval densities in the sediments. When the beaches were accumulating larvae, fewer than 10 free-swimming larvae could be found in each cubic meter of water; when the beaches were empty of larvae, the free-swimming population soared to more than 4,000 per cubic meter. Clearly, larvae were accumulating in the beach gravel as they hatched until something induced them to go into the water all at once, a process that recurred until all of the larvae had hatched and departed.

No such contingent pattern of emergence occurs in any other marine fish that spawn on beaches. The California grunion, for example, spawns on the beach during the highest (spring) tides of the lunar cycle, and the eggs hatch during inundation by the next spring tide, two weeks later; larval emergence

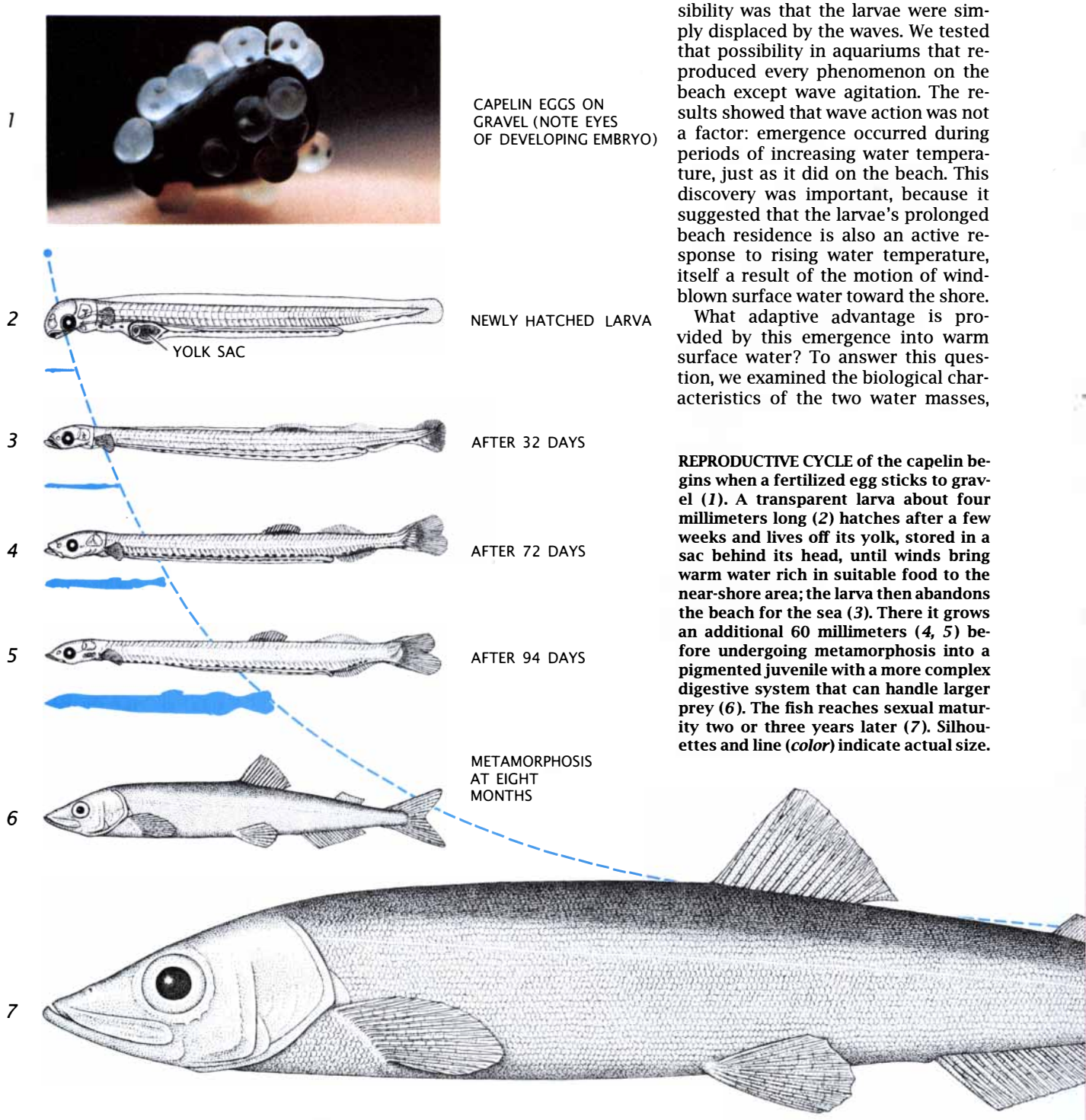


follows immediately. We found, however, that capelin larvae are indifferent to cycles of tide or light and to the simple passage of time. Indeed, they react only to a single meteorological variable: changes in the direction of the wind.

The prevailing summer winds in eastern Newfoundland are offshore, or from the southwest. Onshore winds are fleeting and quite rare, averaging one occurrence every five to six days, although the frequency is highly variable. In 1954 Wilfred Templeman, then at the Canadian Department of Fisheries and Oceans in St. John's, suggested that the prevailing offshore winds blew the warm surface water seaward, to be replaced by cold water welling up from the depths. Onshore winds, however, would drive warm surface water landward, where it would sink, displacing cold subsurface waters and warming the entire near-shore region. Christopher T. Taggart, a doctoral student working in our laboratory, was able to confirm Templeman's hypothesis in a series of physical oceanographic studies conducted at Bryants Cove. His work demonstrated that the synchronous mass releases of capelin larvae coincided with the arrival of warm surface waters blown landward and up onto the beach by onshore winds.

The next step was to determine the immediate cause of emergence. The onshore wind disturbed beach sediments significantly, and so one possibility was that the larvae were simply displaced by the waves. We tested that possibility in aquariums that reproduced every phenomenon on the beach except wave agitation. The results showed that wave action was not a factor: emergence occurred during periods of increasing water temperature, just as it did on the beach. This discovery was important, because it suggested that the larvae's prolonged beach residence is also an active response to rising water temperature, itself a result of the motion of windblown surface water toward the shore.

What adaptive advantage is provided by this emergence into warm surface water? To answer this question, we examined the biological characteristics of the two water masses,



REPRODUCTIVE CYCLE of the capelin begins when a fertilized egg sticks to gravel (*1*). A transparent larva about four millimeters long (*2*) hatches after a few weeks and lives off its yolk, stored in a sac behind its head, until winds bring warm water rich in suitable food to the near-shore area; the larva then abandons the beach for the sea (*3*). There it grows an additional 60 millimeters (*4, 5*) before undergoing metamorphosis into a pigmented juvenile with a more complex digestive system that can handle larger prey (*6*). The fish reaches sexual maturity two or three years later (*7*). Silhouettes and line (*color*) indicate actual size.

warm and cold. We found that the warm water was dominated by tiny zooplankton (which feed on diatoms and other tiny plants) and immature copepods (a larger kind of zooplankton)—particles having diameters between 30 and 100 microns. This food is ideal for first-feeding larvae, whose jaws cannot accommodate larger prey. In contrast, the cold water was dominated by larger zooplankton; it also harbored many more jellyfish and related invertebrates that prey on fish larvae. We hypothesized that warm surface water furnishes the capelin larvae with both food and sanctuary, constituting what we call a safe site.

We wanted to evaluate the importance of safe sites in experiments that separately tested the importance of prey size and the role of predators in different water masses. Such experiments have generally been conducted in small laboratory containers holding no more than 10 liters, but we doubted that such environments could accurately reproduce natural conditions: they tend to place the predators too close to their prey. We therefore developed a large enclosure that could be maintained in the sea for in situ experimentation. Each such "mesocosm" (whose design owed much to Yves de-Lafontaine, a doctoral student in our laboratory) encloses nearly 4,000 liters of water in a dacron cylinder one meter in diameter and five meters in depth. Several mesocosms were suspended from a floating platform to mirror natural variations in temperature, salinity and dissolved oxygen at all depths. The dacron's low porosity let us manipulate the size and abundance of the zooplankton as well as the abundance of capelin larvae.

We tested how wind-induced variations in the zooplankton might affect first-feeding larvae by stocking each mesocosm with 1,000 newly hatched capelin and then alternately adding zooplankton typical of warm surface water and of deep, cold water. Larvae fed on warm-water prey grew twice as fast as those fed on cold-water prey and died at only one third the rate. Clearly, the larvae emerge when they do partly because the food is better then.

But it is not enough to eat; an animal must also avoid being eaten. We wondered if the capelin larvae avoided total depredation mainly by emerging in numbers vast enough to satiate predators, so that a remnant could survive. (This is the strategy of the cicadas that emerge synchronously every 17 years, thus presenting their avian enemies with an embarrassment of riches.) DeLafontaine demonstrated that capelin did not satiate jellyfish, one of their principal predators. He showed first that jellyfish can consume up to 25 percent of the larvae in a mesocosm in a day and then that they do not stop feeding—a sign of satiety—even in the presence of very high concentrations of larvae.

We concluded that capelin larvae time their emergence, in part, to avoid jellyfish and other predators typically associated with the cold-water mass. This explanation may have broad significance, because it seems to limit the application of a widely cited model of predator-prey oscillation. (A common example is the case of lynx and snowshoe hares in Canada: the lynx eat the hares until too few are left to support the predators; the lynx then die in droves, enabling the hares to multiply freely and thus trigger a resurgence in the lynx population.) Capelin were numerous when their predators were scarce not because of that kind of dynamic relation but simply because the capelin emerged into safe sites where there were few predators.

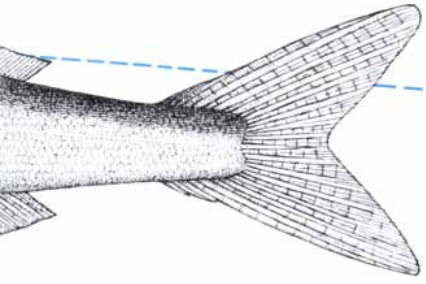
Our theory finds confirmation in studies of the abundance of the larvae of three species—winter flounder, radiated shanny and sea snails—that spawn on the bottom of shallows off Newfoundland's shore. Our findings led us to scrutinize some of the many studies of the reciprocal oscillations of predators with such prey as the larvae of tuna, winter flounder, anchovy, goby, herring and plaice. We found considerable evidence that the patterns in those studies, too, had resulted from selective occupation of safe sites. Clearly, workers should be much more cautious in applying the classic model of population oscillation to larvae and their predators.

Of course, our own results from Bryants Cove also had to be treated cautiously until they could be corroborated by studies of much larger areas. We therefore monitored five additional capelin spawning beaches dispersed along several hundred kilometers of Newfoundland's east coast. At each site we measured temporal variation in water temperature and in the abundance of emergent capelin larvae and their predators and prey. We found that major changes in near-shore water temperatures and in the numbers of capelin larvae, their prey and their predators were consistently related to the pattern of the winds, which were virtually synchronous at all sites. Apparently our results in Bryants Cove were indeed a faithful representation of what happens along most of Newfoundland's coast.

In 1982 Taggart confirmed the results of our mesocosm studies with data gathered from the sea. He estimated the mortality rates for individual larval cohorts, that is, classes of larvae that emerged in response to discrete onshore-wind events. He was able to exploit peculiarities of the capelin and of Bryants Cove to avoid two common sources of error in assessing fish mortality rates: tendencies to confuse one cohort with another and to record as dead those larvae that have merely dispersed out of the monitoring area. The problem of cohorts was effectively eliminated because capelin larvae emerge synchronously within discrete intervals, or "windows." The distortion caused by larval dispersion was solved by measuring and modeling the flow of water out of the monitoring area.

Taggart found that several cohorts of larvae emerging in 1982 and 1983 suffered mortality rates ranging from 3 to 100 percent and averaging 60 percent. This pattern was unrelated to the abundance of edible zooplankton—a finding that contradicts the leading model for the survival of larval fish. The model, formulated by Johan Hjort, a distinguished Norwegian fisheries scientist of the early 1900's, links annual variations in larval survival to changes in the abundance of food of the proper size. For capelin—and perhaps for other species—it appears that behavioral responses to oceanographic signals can largely eliminate the effects on mortality of the size and abundance of food.

There was also only a weak long-term relation between larval mortality and the number of such predators as jellyfish and the finned, wormlike invertebrates called chaetognaths. This finding was what might be expected from the capelin's selective emer-



gence strategy. It is noteworthy, however, that capelin mortality on a given day was strongly correlated with the abundance of predators, which varied over time even in the warm-water mass. This supports the view that predation may be an important regulator of larval survival in cases where larvae and predators coexist.

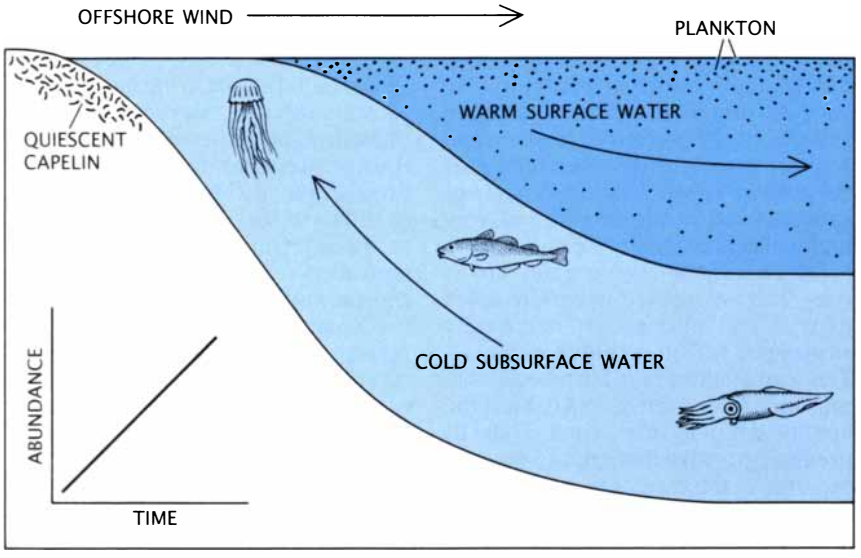
Taggart's findings also corroborated our theory that the capelin's strategy of emergence helps them find food and avoid predators. Yet it is important not to overlook the costs of such a strategy: the larvae must live off the yolk reserves they retain after hatching while they wait for conditions to improve. They steadily deplete the yolk for an average of 5.5 days after hatching. After that, larvae that cannot engage in successful foraging must draw the necessary energy from their own body tissues, initiating a process of physical deterioration that is visible within two days and fatal in four.

The costs inherent in delayed emergence led us to conclude that the duration of beach residence may itself determine early larval survival. If it takes too long for a favorable wind to blow, the larvae either die or enter the water in such a debilitated condition that they cannot find food or evade enemies. Taggart found evidence of this in an association between mortality rates and the frequency of onshore winds. In 1982 there were more onshore winds than in 1983, and overall larval mortality was 20 percent lower. Weekly variations in the frequency of onshore winds were also correlated with differences in survival rates in 1982.

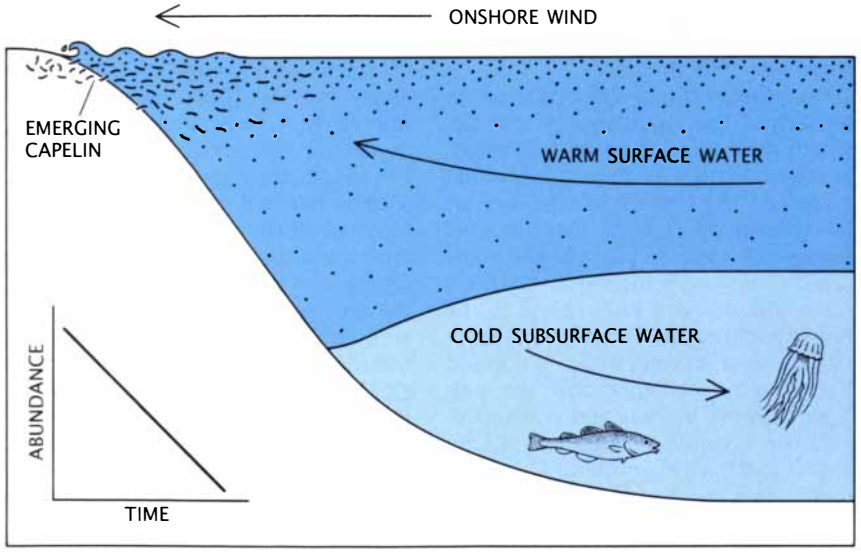
We further pursued the importance of winds to capelin survival by joining forces with James E. Carscadden of the Northwest Atlantic Fisheries Center, part of the Canadian Department of Fisheries and Oceans. Carscadden had independently detected a relation between the reproductive success of capelin spawned in a given year (or "year class") and water temperature during the larval period. We reviewed his records of the estimated abundance of specific year classes in the eastern Newfoundland stock to assess whether wind events during the hatching period had contributed to the reproductive success of capelin. We began by comparing reproductive success with the frequency of onshore winds during the 10-day interval in which most larvae hatch and accumulate in the beach gravel. Starting with a knowledge of spawning dates, daily hours of sunlight and mean air and water temperatures, we were able to predict the timing of the hatching window. We then calculated the interval between onshore winds within this window in each year and related that to the corresponding abundance of adult capelin two years later.

This simple wind-based model explains approximately 40 percent of the year-to-year variability in abundances of two-year-old capelin off the east coast of Newfoundland. It is interesting that the average of 5.5 days to yolk-sac absorption in capelin closely matched the average 6.3-day interval between onshore winds during the previous 20 years. This correlation suggests that the quantity of energy stored as yolk may represent an adaptation to the average conditions experienced by larvae during their residence on the beach.

Environmental conditions should also influence the survival of larvae after they emerge into the water, Carscadden reasoned. We tested this prediction by tracking a single variable—the mean surface temperature of the water—from the period of



NEWLY HATCHED LARVAE accumulate on land as long as offshore winds prevail. The winds drive surface water seaward, so that colder water rich in predators and poor in prey wells up in its place, making the near-shore region inhospitable to the larvae.



FIRST-FEEDING LARVAE leave their gravelly strongholds for the sea in vast numbers when onshore winds blow warm surface water onto the beach, signaling the relative abundance of suitable food and the relative scarcity of predators, such as jellyfish.

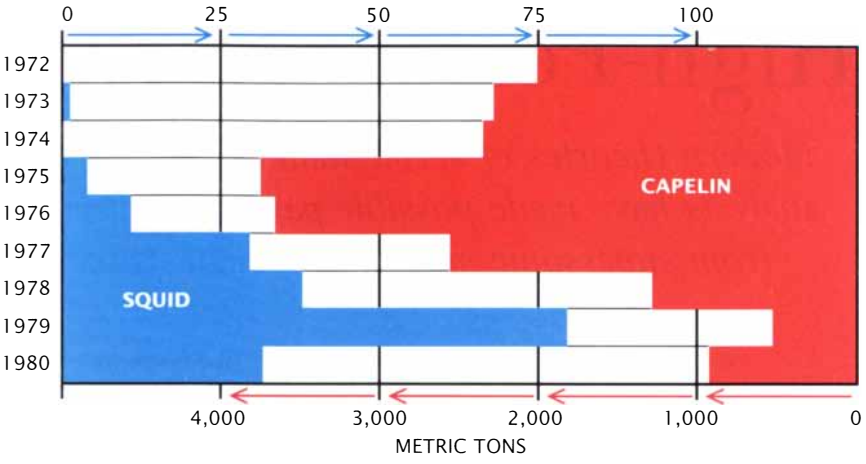
emergence until December of the first year of life, in the hope that it would stand in for a host of relevant biological processes, such as the availability of suitable food. The addition of this variable produces a combined wind-temperature model that accounts for more than 70 percent of the interannual variation in the abundances of two-year-old capelin.

We wondered whether the great predictive power of the temperature variable might be linked to the rate at which the larvae mature. It was known that in capelin, as in most other marine fish, the death rate drops substantially after metamorphosis. Might a favorable temperature shorten the vulnerable larval stage, allowing much greater numbers of capelin to survive in the long run?

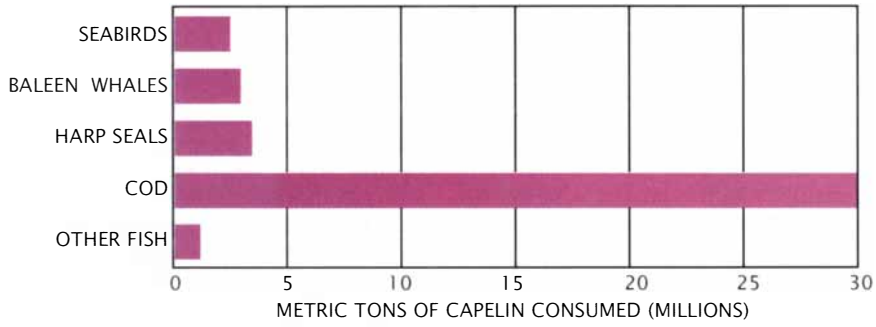
Christopher R. Chambers, a postdoctoral fellow in our laboratory, tested this hypothesis by analyzing variations in the size and age of larval fishes at the onset of metamorphosis. He demonstrated that age is several times more variable than size and that the duration of the larval period is closely coupled to the growth rate of the larvae. His work indicates that variance in the rate of growth, and hence in the time it takes to reach metamorphosis, can induce more than a hundredfold variation in the numbers of larvae surviving to the juvenile stage.

As we have mentioned, capelin serve as prey for birds, mammals and fishes; they also compete for food with other plankton-feeding organisms. Variations in their numbers that result from meteorological changes therefore have a ripple effect up and down the food chain. When the capelin biomass dropped dramatically between 1975 and 1979, for example, more than 300,000 metric tons of zooplankton per day were freed for consumption by other organisms, according to calculations by J. Pascal Vesin, a graduate student working in our laboratory. In the same period, the populations of squid and Arctic cod, which have a diet similar to that of capelin, increased markedly in waters off northeastern Newfoundland where these species typically occur together. This finding suggests that there is strong competition among these three species for the available zooplankton in the region.

Colonies of the Atlantic puffin, a bird that feeds its young with capelin, declined in tandem with the capelin biomass after 1975. The puffin's plight alarmed the Canadian Wildlife Service, which is charged with protecting the bird, and led it to accuse the Department of Fisheries and Oceans of having allowed overfishing of capelin. Our findings helped to defuse the ensuing debate by showing that the capelin had declined as a result of reproductive failure caused by adverse winds and water temperatures.



COMPETITION FOR FOOD is evident: capelin abundance and the inshore squid catch are inversely correlated. A cyclic decline of capelin frees millions of tons of plankton, its normal prey, to be consumed by squid, whose numbers consequently soar.



ECOLOGICAL IMPORTANCE of capelin is indicated by the significant annual consumption of the fish by seabirds, baleen whales, harp seals and cod and other fish.

In another investigation Hal Whitehead, then at Memorial University of Newfoundland, and Carscadden studied the relation between the distribution of humpback whales in eastern Newfoundland and the abundance of immature capelin, on which the whales feed heavily. They found that when immature capelin are abundant offshore, the whales remain offshore and are rarely sighted. When years of reproductive failure have lowered the capelin population offshore, on the other hand, whales typically pursue the mature capelin into near-shore waters when the fish migrate there to spawn. In such years humpback whales often roam the shallows and do much damage to local fishing gear. Whitehead and Carscadden successfully adapted our capelin population model to predict the abundance of whales in the near-shore region.

Our model can reliably forecast changes in capelin abundance three years in advance on the basis of summer weather patterns, a rare example of ecological forecasting. Beyond this, our work suggests that behavioral adaptations to meteorological events in the ocean may well have evolved in many other species that receive vital signals from sun, wind and tides.

FURTHER READING

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High-Performance Parachutes

Modern theories of aerodynamics, advanced materials and computer analysis have made possible parachutes that can decelerate a capsule from supersonic speeds to a snail's pace in a matter of seconds

by Carl W. Peterson

With engines on full afterburners, an F-111 fighter jet dives toward the floor of the Nevada desert. After descending from an altitude of nine kilometers to only 100 meters, the jet levels off. It is traveling slightly faster than the speed of sound (Mach 1.2). The F-111 tears through the air, generating shock waves that kick up clouds of sand. I can see the aircraft half a kilometer away, yet I hear nothing. It has just released a test capsule, which contains a newly designed parachute named B83 and a host of cameras and instruments that will record the parachute's success or failure. Just after the B83 parachute emerges from the tail of the test capsule, the sonic boom from the jet startles me.

During the next four seconds my colleagues and I will find out if a parachute traveling faster than a rifle bullet can endure the strain of slowing a capsule weighing more than a family car. If all goes according to plan, the B83 parachute will decelerate from Mach 1.2 (about 1,500 kilometers per hour) to 70 kilometers per hour while falling only 50 meters. To meet these specifications, we have designed the B83 to provide a maximum decelerating force of more than 14,000 newtons, or 100,000 pounds. (A force of the same magnitude would stop a car traveling at 100 kilometers per hour within one meter.)

I believe the B83 parachute can outperform anything we could have dreamed of 20 years ago. At that time the aerodynamic principles of rapidly decelerating parachutes were only partially understood, and the materials that could support such applications were not available. Yet even with advanced materials and elaborate computer models, designing a supersonic parachute is one of the toughest challenges in aerodynamics today.

The project to build the B83 kept my colleagues and me at Sandia National Laboratories in Albuquerque, N.M., busy for three years. We sought to minimize the weight of the parachute while maximizing its decelerating capabilities. We ran a series of computer simulations to predict the parachute's behavior during inflation. We built small-scale replicas of the B83 for tests in wind tunnels.

Yet we understand that no simulation or experiment can duplicate the dynamics of the parachute during the rapid inflation stages of flight. For that reason we are particularly apprehensive as we stand in the desert watching the test of the B83. Will the parachute get tangled in the turbulent air? Will it inflate too rapidly and be ripped to shreds? Will it deflate in mid-flight, causing the capsule to fall at great speed?

As I recover from the sonic boom, I realize I have already missed the most critical stages of the test. The parachute has inflated to its full-flight diameter of 10 meters, and the test capsule is swinging from it like a pendulum. A second later the parachute lands safely on the earth. My co-workers and I celebrate a small victory. Yet we will spend many months studying the data from this test before we pass final judgment on the B83. A parachute must do much more than just survive to meet today's performance standards.

Throughout history investigators have strived to build parachutes to perform from ever greater heights, to decelerate at ever quicker rates, to withstand ever faster speeds, to provide ever gentler rides and to deliver ever heavier loads. Two thousand years ago parachutes were designed in China and were later worn by Chinese acrobats to slow their falls. During the 15th century Leonardo da Vinci boasted of even loftier feats: "If a man has a tent of linen without any apertures, ... he can jump from any great height without danger to himself." It is not known whether da Vinci built or tested a parachute. In 1772, however, Canon Desforges constructed a parachutelike contraption and leaped from a tower, injuring himself only slightly.

During the next 130 years other enthusiasts built and wore parachutes to perform death-defying leaps. In 1802 the French aeronaut André-Jacques Garnerin strapped himself to a parachute and then tied it to a balloon. He ascended to an altitude of about 2,400 meters and cut himself loose. The balloon exploded, he and the parachute fell rapidly, but he managed to land safely. It was perhaps the most famous jump until 1912 when Captain Albert Berry of the U.S. Army was the first to bail out of an airplane.

During World War I balloonists wore parachutes as safety devices, but airplane pilots found them impractical. It was not until World War II that parachutes became an indispensable part of aeronautical hardware. Parachutes were used to land troops, to drop supplies, to stabilize airborne weapons and to decelerate aircraft during landing. From the 1960's to the present the parachute has played a key role in facilitating the safe return of both

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Soviet and American spacecraft to the earth.

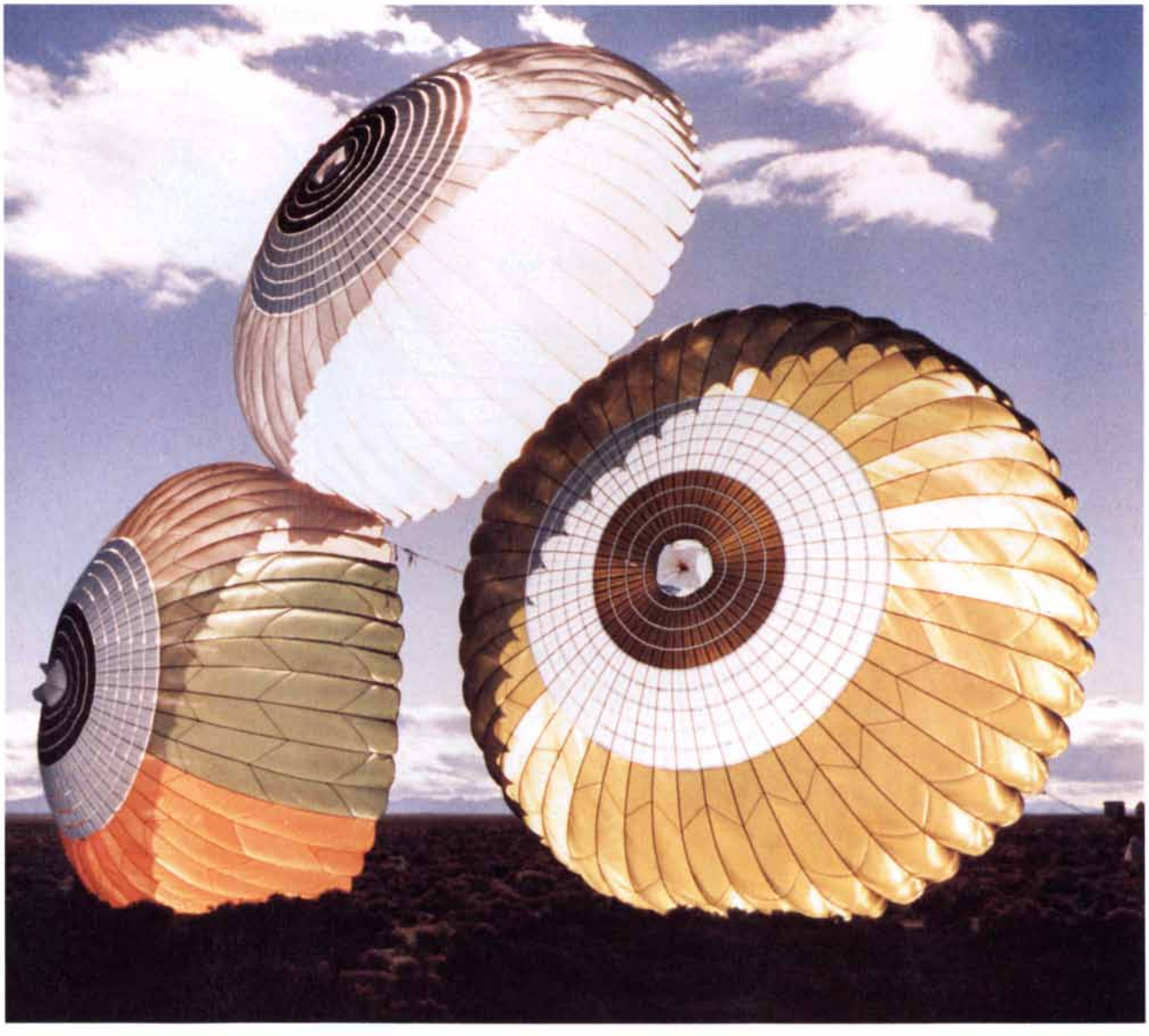
As the parachute became commonplace—first in balloons, then airplanes and finally spacecraft—many of its basic design features became more or less standardized. Most inflated parachutes were hemispheric in shape. They were made from either silk, cotton or nylon. And they were efficiently designed by trial-and-error methods.

Then during the 1970's parachute technology made significant advances. The impetus was a desire among military and civilian engineers to design parachutes for release at low altitudes and high speeds. Such parachutes were needed for escape modules in fighter jets and for the delivery of supplies, bombs and missiles.

For low-altitude deliveries the parachute is deployed while the capsule that contains it is traveling horizontally. The parachute must slow the capsule down and orient it vertically before the capsule hits the ground. This requirement forced designers to develop parachutes that decelerated the capsule more rapidly than ever before.

In an attempt to build such rapidly decelerating parachutes, engineers sought new lightweight, high-strength textile materials. The most promising of these materials was Kevlar, an organic fiber developed by the Du Pont Company. Gram for gram, Kevlar has a tensile strength two times greater than that of nylon and 10 times greater than that of stainless steel. At the time designers correctly anticipated that a parachute partially composed of Kevlar could provide twice the decelerating force of an all-nylon parachute and would not compromise structural integrity nor exceed weight or volume limitations.

When the development of Kevlar and other materials made low-altitude, high-speed parachutes feasible, engineers began to confront the unsteady aerodynamic problems associated with a parachute that decelerates rapidly. They found that many of their intuitions about conventional para-



HIGH-PERFORMANCE PARACHUTES remain inflated after a flight test at Tonopah Test Range in Nevada. The parachutes, which can slow a payload to 28 kilometers per hour, are part of a system that was designed for crew-escape modules in fighter jets. The parachutes are composed of Kevlar and nylon; each one is 15 meters in diameter and weighs only 13.6 kilograms.

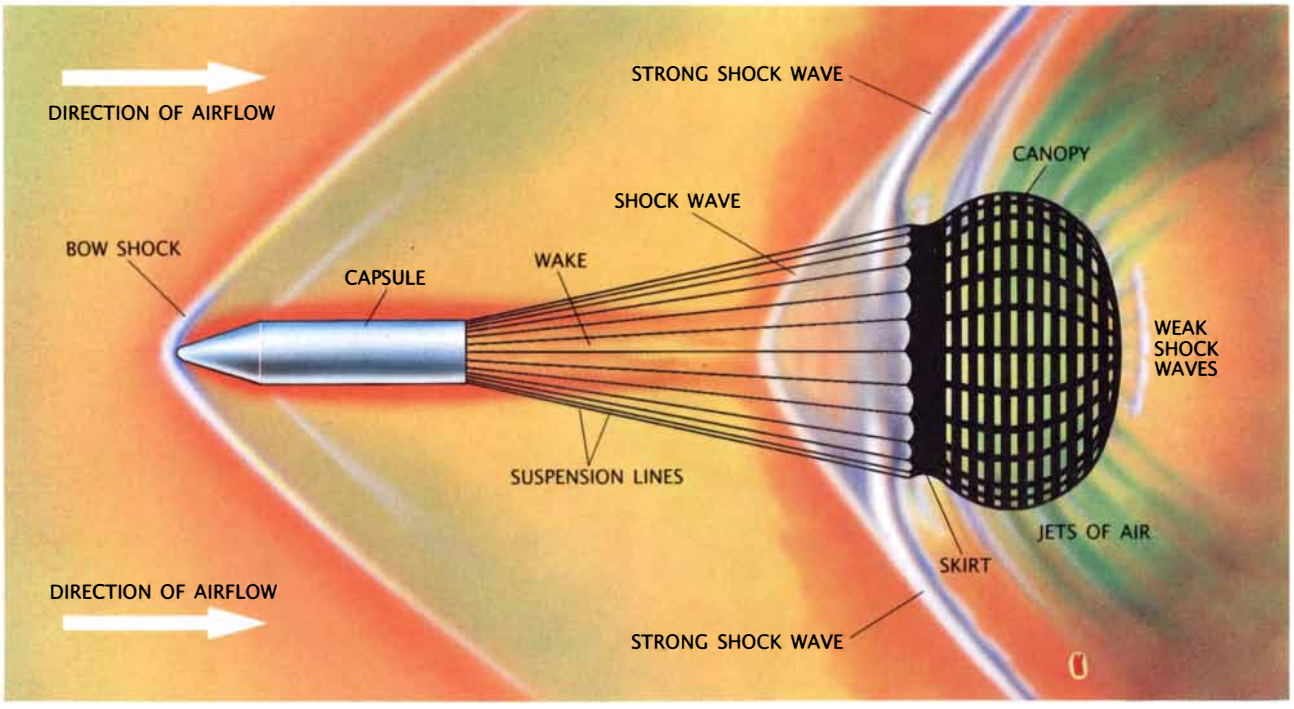
chutes could not be applied to low-altitude, high-speed designs. At about the same time, they realized that designing high-performance parachutes by trial-and-error methods was too expensive and time-consuming to be practical. These factors motivated aerodynamicists to develop computer models of parachute deployment, inflation and performance.

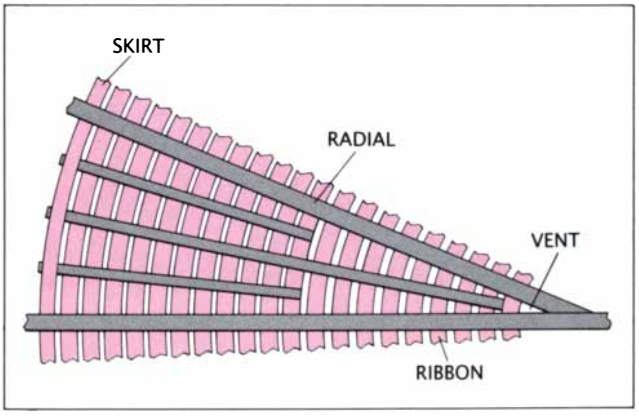
Such modeling had not been attempted before—even for conventional parachutes. To predict the behavior of a parachute as it inflates, an engineer must deal with several of the most difficult problems in aerodynamics. The first is that small changes in a parachute's size, configuration and composition can have a surprisingly large effect on its performance. Because a parachute reacts so sensitively and erratically to seemingly small changes, its behavior is almost impossible to predict with mathematical methods. (In more technical terms, the equations that describe both the behavior of the parachute and the motion of the air are nonlinear.)

A second problem is that both the shape and velocity of the parachute change rapidly as the parachute inflates. This same problem makes parachute inflation more troublesome to model than, say, the flight of an airplane, whose shape is nearly constant and whose flight environment changes relatively slowly. Other formidable problems arise because of the airflow through the parachute, the influence of the capsule on the airstream and the effects of supersonic flight.

Parachute engineers have recently turned to computers to solve these extraordinary dynamic problems, and by doing so they hope to predict not only the parachute's trajectory but also the stresses on its components. Although the behavior of a parachute cannot be predicted in all circumstances, computer simulations can describe (with varying degrees of accuracy) the parachute's behavior during four critical stages: deployment, inflation, postinflation and terminal descent.

The stage of deployment begins when an aircraft drops a capsule that contains the parachute, a support system and the payload one wishes to transport. The support system often includes a timer that sends out a signal when the capsule has fallen a safe distance from the aircraft. The signal triggers a small explosion at the aft end of the capsule, launching





RIBBON PARACHUTE traveling at supersonic speed generates a complex airflow. Blues and whites indicate regions in which the pressure is changing very rapidly. Greens and yellows denote small pressure gradients. The diagram is based on photographic data from a wind-tunnel test. The canopy of the ribbon parachute (*section at right*) is a configuration of ribbons and radials, which provide more strength than the panels of a solid canopy. A 1.5-meter parachute of similar design has decelerated a 360-kilogram projectile traveling at twice the speed of sound.

a metal plate into the airstream. The plate tugs a small pilot parachute into the air, which inflates and, in turn, pulls out a deployment bag containing the main parachute.

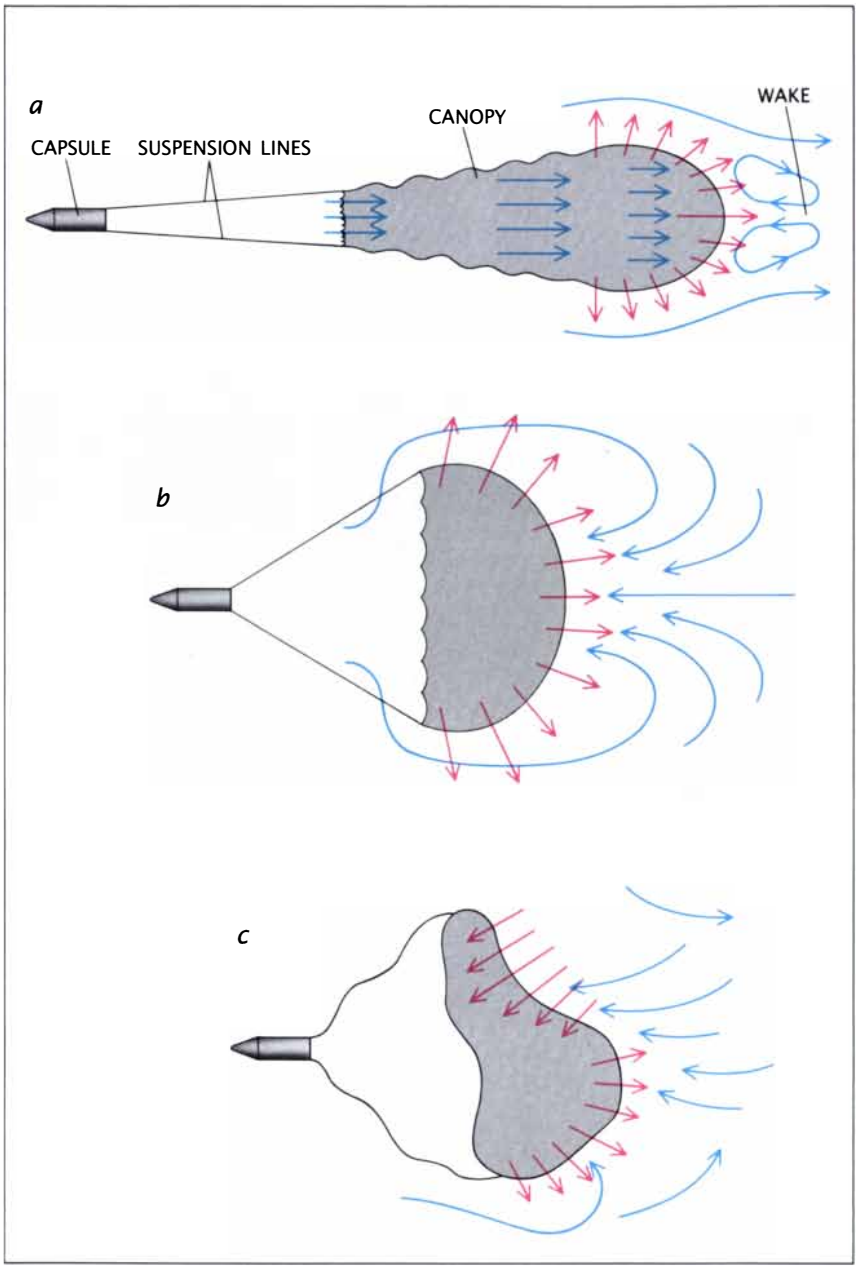
High-performance parachutes can be packed into a deployment bag at a density of about 650 kilograms per cubic meter, which is roughly equivalent to the density of an oak log. The pilot parachute should deploy the main parachute smoothly and quickly (that is, within a few tenths of a second). First to emerge from the deployment bag are the suspension lines, which connect the canopy to the capsule. Once the suspension lines are extended, the canopy itself begins to emerge from the deployment bag. If the parachute inflates before it has been completely removed from the bag, it can snag, tangle or tear.

To predict a parachute's behavior during deployment and so minimize the likelihood of mishap, parachute engineers have developed a computer program called LINESAIL. The program keeps track of friction between the various parts of the parachute as they are pulled into the airstream and takes into account the aerodynamic forces acting on the components that have already entered the airstream. In addition, the model determines the rotation and translation of the capsule and deployment bag with respect to the parachute.

LINESAIL was used to identify and correct a deployment problem observed in an early flight test of the B83 parachute described at the beginning of this article. The problem was that shock waves generated by the F-111 aircraft pitched the nose of the capsule upward. As a result, the suspension lines were pulled out of the deployment bag prematurely by the supersonic airstream. This early deployment caused the lines to sail, the bag to rotate and the canopy to tear. When the failure was simulated with the help of LINESAIL, the engineers realized that the pilot parachute was too small to control deployment of the suspension lines adequately. They then turned again to LINESAIL for help in designing a larger pilot parachute.

After deployment, a parachute enters the inflation stage and starts to decelerate rapidly. When the canopy first opens, it captures a certain volume of air, some of which flows through the canopy, but most of which is accelerated to the speed of the parachute. In this way, the canopy transfers some of its kinetic energy to the surrounding air and thus decelerates. The inflated canopy then pulls on the suspension lines, which pull and slow the capsule. As the canopy captures and accelerates more air, the capsule decelerates further.

The decelerating force and air friction, which together are known as drag, can be controlled by changing a parachute's geometry and porosity, but drag is ultimately limited by the strength of the materials. One parachute design that is particularly strong is known as the ribbon parachute. Instead of having a solid cloth canopy—as is the case for conventional cargo and crew-escape parachutes—ribbon parachutes have a canopy made of "radials" and "ribbons." The radials are strips of material that extend from the suspension lines to the top of the canopy; the ribbons form rings that



AIRFLOW (*blue*) and differences between inside and outside pressures (*red*) change quickly and dramatically as a parachute inflates. During the early phase of inflation (*a*), the canopy captures air, creating a pressure differential that causes the parachute to "drag" through the air. By the time the parachute inflates fully (*b*), it has transferred substantial energy to the air, generating a wake behind the parachute. As the parachute slows, air from the wake can overtake the canopy (*c*), pushing it from behind and causing it to collapse. If this occurs, the parachute will accelerate.

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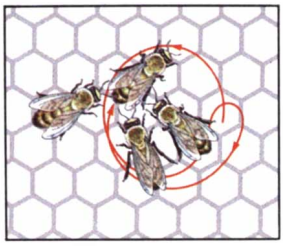

From The Honey Bee, *foragers dance to indicate a food source; drawing by John Hatzakis, adapted from K. von Frisch,* Tanzsprache und Orientierung der Bienen.

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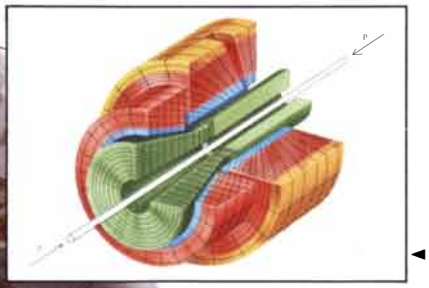

◄ *From* From Quarks to the Cosmos, *a schematic of a particle collider detector; drawing by George Kelvin.*

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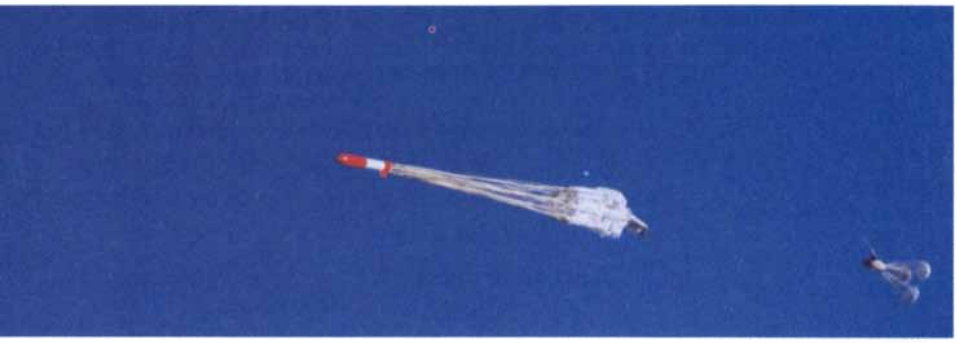
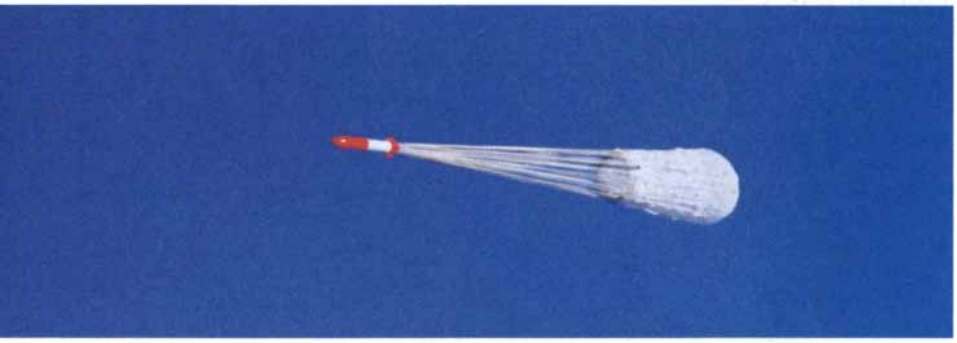
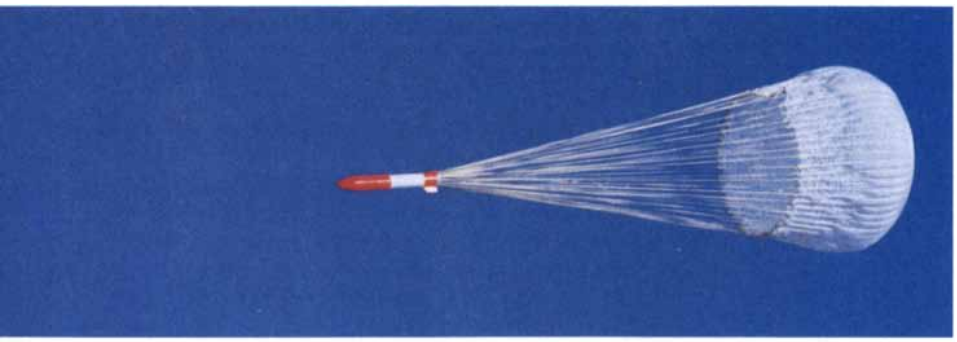
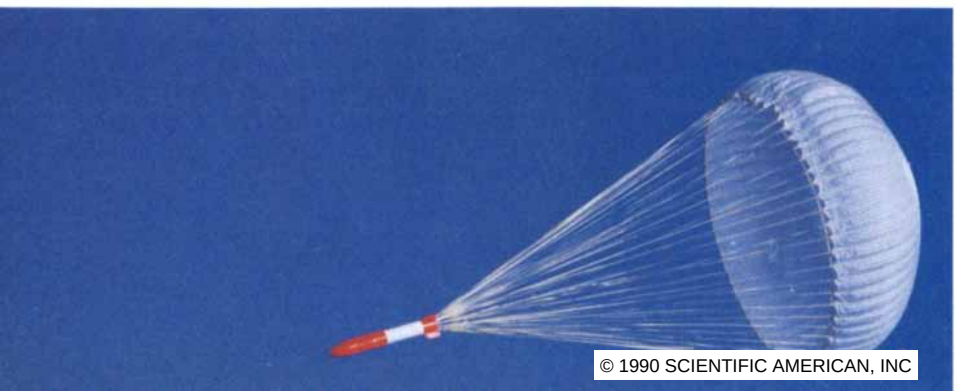








are perpendicular to the radials. The radials and ribbons are sewn together in a gridlike pattern, leaving gaps in the canopy. Although the ribbon parachute sacrifices drag for strength, it is often the most desirable design for high-performance applications.

Not all of the pressure exerted on the canopy by the airstream contributes to drag; a component of the pressure causes the canopy to inflate and ensures that the parachute remains open during its descent. As a parachute inflates, it first assumes the shape of a tall drinking glass but later looks like a light bulb and then a mushroom cap.

The inflation stage presents the investigator with a serious problem: a parachute's shape depends on the aerodynamic forces acting on its canopy, but the airflow, which generates aerodynamic forces, depends on the shape of the canopy. Adding to the complexity is the fact that the parachute and its capsule are decelerating rapidly. Each of these phenomena is difficult to describe mathematically and makes the modeling task extremely complicated.

To predict the exact behavior of a parachute, one has to solve the equations of motion for the parachute while at the same time solving the equations of motion for the air around the parachute. No one has yet succeeded at this task. But investigators can simplify the problem by focusing on a particular state of a parachute's flight or by neglecting certain parameters, which are not important in the inflation process. They can then test the accuracy of their approximate predictions by comparing them with data obtained from actual test flights and wind-tunnel experiments. In this way, they can determine the important parameters for each stage of inflation and adjust their computer models to reproduce the phenomena observed experimentally. The strategy has proved effective in many cases.

One such computer model is called CALA (which stands for CAnopy Loads Analysis). CALA was developed in 1985 by W. David Sundberg of Sandia and was based on work done at the Northrop Corporation in Los Angeles, the University of Minnesota at Minneapolis and Sandia. Before the CALA program can be run, an engineer must enter the dimensions of the canopy and the material properties (weight, tensile strength) of both the canopy and suspension lines. CALA then breaks down each part of the parachute into a number of computational elements. For each element the engineer is expected to enter the difference in pressure between the inside and outside of the canopy. CALA then calculates the steady-state position of each element, the forces between elements and the stresses in each element.

Predictions obtained from the CALA program have been verified in wind-tunnel measurements. The program has been particularly useful in revealing the maximum amount of stress that a parachute can bear, and so it has enabled parachute engineers to select the lightest materials that can handle the aerodynamic stress.

The predictions of CALA and other such programs are limited, however, because engineers lack adequate information about the pressure distributions around the canopy. Such data are difficult to obtain experimentally primarily because a pressure gauge attached to a parachute is usually torn off by high-speed airflow.

The simulation of airflow and pressure distributions is also an unwieldy problem during the postinflation stage when the parachute is fully inflated and its speed has decreased considerably. As a parachute decelerates rapidly, it accelerates a large volume of air. If this rapidly moving air mass subsequently catches up to the parachute, it will push the parachute from behind. The forward push of air causes the canopy to deform, reducing drag dramatically. In cases of severe collapse, the capsule can actually accelerate.

To forecast the conditions under which a canopy might collapse, a computer program that can model the airflow around the parachute is needed. Because parachute flight involves a tremendous volume of air—typically several million cubic meters—it is impossible for any computer to solve the full equations of motion throughout the parachute's entire descent. Therefore, the investigator must reduce the computer's work by introducing clever analytical techniques and valid simplifying assumptions.

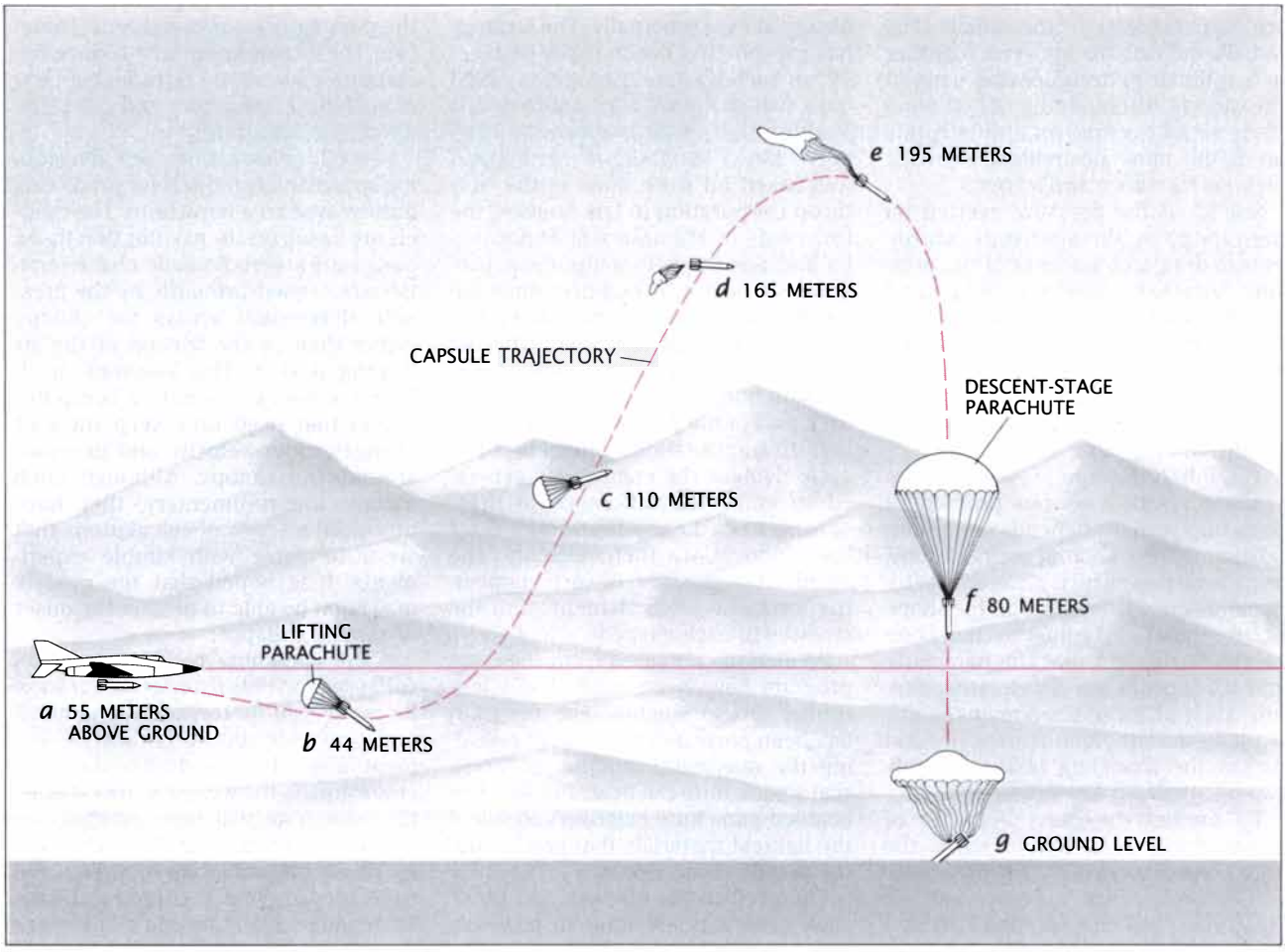
Several investigators are developing approximate models for predicting airflow around a parachute. The models are based on the assumption that a parachute's aerodynamic characteristics are caused primarily by the pressure differential across the canopy rather than by the friction of the air flowing past it. This assumption allows engineers to create a computer model that need only keep track of changes in air velocity and pressure around the canopy. Although such models are rudimentary, they have produced a series of calculations that seem to agree with simple experiments. It is hoped that the models may soon be able to predict the onset of canopy collapse.

If the parachute recovers from its collapse or avoids it altogether, it soon loses most of its forward momentum and descends only vertically. A moment later, when the drag of the parachute equals the weight of its capsule, the parachute will have entered the terminal-descent stage. Of all the stages, this is the only one for which the trajectory of the parachute can be determined exactly. Many parachutes are designed solely for their performance during the terminal-descent stage. Indeed, for most of these parachutes, problems such as canopy collapse are not a concern. Nevertheless, many high-performance parachutes are designed to land before they ever reach the terminal-descent stage. Ironically, the only stage of parachute flight that can be described exactly is a phase the high-performance parachute may never experience.

High-strength materials and advanced design techniques have produced a new generation of parachutes that exceed all previous performance standards. Such advanced parachutes have set new speed records. A parachute weighing only 270 grams and measuring .5 meter in diameter has decelerated the nose of a reentry vehicle traveling at 3,500 kilometers per hour, or Mach 2.8. (The parachute is composed entirely of Kevlar, because aerodynamic heating would melt a nylon parachute moving at Mach 2.8.)

Advanced parachutes have made it possible to land heavier payloads than ever before. A 16.5-meter parachute is installed in each of the space shuttle's

B-1 BOMBER cruising over the Nevada desert at 1,000 kilometers per hour releases the B83 parachute system. During the first .6 second, the system simply falls a safe distance away from the aircraft. Then a small explosion drives a metal plate into the air. The plate pulls along three pilot parachutes, which deploy the main parachute within 1.1 seconds of flight. During the next second, the main parachute inflates to a diameter of 10 meters and swings the capsule around toward the ground. Four seconds after its release, the parachute has descended 45 meters and touches down at a velocity of 85 kilometers per hour.



LIFTING PARACHUTE allows capsules to soar above their release altitude. The capsule falls (*a*) until the lifting parachute inflates (*b*). As the inflated lifting parachute moves forward at tremendous speed, the parachute generates more lift than drag (*c*). The lifting parachute is discarded after several seconds of flight (*d*), and a second, conventional parachute is deployed (*e*). The capsule then descends toward the ground (*f*). The parachute and capsule land safely on the ground (*g*).

solid-rocket boosters. After the boosters have propelled the shuttle into orbit and have separated from it, the parachutes are deployed. Each parachute can deliver a maximum decelerating force of 38,000 newtons to each one of the 87,000-kilogram boosters. Once the parachute slows the solid-rocket boosters, it deploys a cluster of three ribbon parachutes, which lower the solid-rocket boosters into the ocean at 90 kilometers per hour.

Some advanced parachutes can even carry their payloads to higher altitudes than the height at which they were released. For instance, a ribbon parachute can generate lift as well as drag if the gaps between the ribbons are blocked at the top of the parachute. When the parachute is deployed at high speed, the lift will exceed the weight of the capsule and payload, which causes the parachute to climb. One such lifting parachute, which bore a 1,100-kilogram missile, climbed 140 meters above its release altitude before it deployed a larger conventional parachute that then lowered the capsule gently to the ground.

Parachutes continue to provide the most efficient and cost-effective method for decelerating payloads in the atmosphere. The next two decades promise still greater advances in parachute technology. Computer models are now being developed that keep track of changes in parachute shape, deceleration and aerodynamic forces during the entire flight of the parachute. New high-strength materials, such as fabrics made from carbon fiber, may lead to the development of parachutes that can be deployed at up to five times the speed of sound. These hypersonic parachutes would assure that astronauts could safely escape from a damaged spacecraft. In the near future parachutes may also be combined with other technologies, such as sensors, real-time computers and control systems, which would enhance performance by actively controlling drag during inflation. I wonder if the parachutes built 20 years from now will seem as strange and spectacular to me as today's parachutes would seem to da Vinci.

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High Fertility in Sub-Saharan Africa

Birth rates and population growth have begun to decline everywhere else in the developing world. What makes this region different?

by John C. Caldwell and Pat Caldwell

In generations to come, it may well be decided that the greatest contribution made to the long-term well-being of humanity in the decades following World War II was the onset of a nearly worldwide decline in fertility. Of all the changes the half century has seen, only that one has the potential to guarantee a stable global population of less than 12 billion and a balance between population and resources. It may also eventually make possible a reasonable living standard for all.

Declining fertility has been the product of tremendous—and largely unplanned—strides toward the creation of a global society and of revolutionary efforts in family planning. It has probably been hastened by breakthroughs in contraceptive technology such as the Pill and intrauterine devices (IUD's). Since the turning point in about 1965, birth rates and population growth rates have begun to fall in the developing world and also in Europe, North America and Australasia.

There is one exception to this pattern: sub-Saharan Africa. No independent nation of sub-Saharan Africa has shown definitive evidence of fertility decline, and in many nations population growth is accelerating. As a result, the continent as a whole, which accounted for 9 percent of the world's population in 1950, accounts for 12 percent today. Africans will probably constitute more than a quarter of the human race by late in the next century and for a long time thereafter.

What makes sub-Saharan Africa different from the rest of the world? Some observers point to levels of income, education, health and urbanization lower than in other world regions and to the fact that even those levels were achieved more recently than in other comparable parts of the world such as Asia. These factors, however, do not really explain the continuing high fertility in sub-Saharan Africa. Only 15 years ago a range of nations in the region were broadly similar to much of South and Southeast Asia on various socioeconomic indices. Indeed, such African countries as Ghana, the Ivory Coast, Kenya, Nigeria, Senegal, Tanzania and Zambia were considerably richer than their Asian counterparts, as least as measured by per capita income. They were no less urbanized and no more dependent on agriculture. They were only slightly behind in educational levels and rates of mortality decline. Their fertility was higher, but not by much.

Today the picture is quite different. Asian incomes have grown much faster than African ones, even though there has been no equivalent change in the relative levels of urbanization or dependence on agriculture. More important, between the early 1960's and early 1980's Asian fertility fell by more than a third while African fertility remained constant. Even India, where per capita income in 1985 was still lower than in any of the African countries listed, participated in the Asian fertility transition.

Strong governmental family-planning programs in Asia helped to reduce fertility there. Governmental inaction or inefficiency, however, is not at the root of constant or rising fertility in Africa. Kenya and Ghana, for example, entered the family-planning field as early as Indonesia and Thailand did, but roughly six times as many Asian women have actually adopted efficient methods of birth control.

African family-planning programs have failed in large part not for lack of supply but for lack of demand. In 1973, for example, we found that of the entire population of Ibadan City, Nigeria, only one married woman in 80 older than 40 years had deliberately and successfully limited family size to less than six live births. Furthermore, these large familes are by no means considered undesirable. African women want families twice as large as do people in even the poorest Asian or Latin American countries, and African men, commonly polygamous, want much larger families still. Elsewhere in the developing world women are only too happy to cease childbearing with four living children, but not in Africa.

We believe the primary cause of high fertility in sub-Saharan Africa is the social and family patterns that have developed over millennia in response to conditions in the region. The social and family patterns of Europe and Asia, which coincidentally lend themselves more easily to decreased fertility, evolved in response to living conditions that differed sig-

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WOMEN AND CHILDREN furnish the bulk of agricultural labor in sub-Saharan Africa, as shown in this picture from Tanzania. The need for people to work the land has been a determining factor, the authors argue, in the evolution of social structures that resist fertility control.

nificantly from the African pattern.

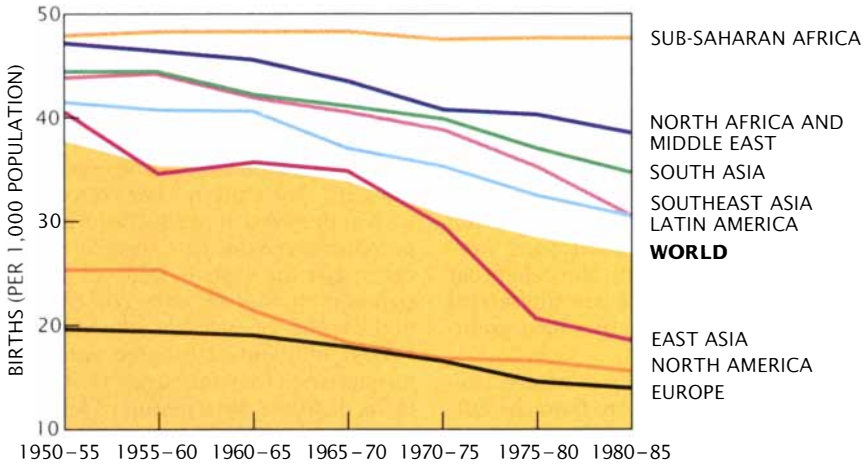
The socioreligious system that accounts for sub-Saharan Africa's persistently high fertility differs greatly from those that pervade Europe, Asia and the Americas. It is not more traditional, primitive or backward; it is simply very different, and the differences have profound implications. The core of African society is its emphasis on ancestry and descent. In religious terms, this is usually reflected by a belief in the intervention of ancestral spirits in the affairs of the living. In social terms, the emphasis is reflected in the strength of ties based on the family of descent—the lineage. A person's true spiritual home, and in some societies the physical home for a lifetime, is the lineage rather than the conjugal family.

It is important to recognize that the African worldview and social structure are part of a seamless whole. The religious belief in the supreme importance of ancestral spirits and in the overriding need for descendants to ensure the survival of that lineage is continuous with the social structure: the centrality of the lineage and the concept of it as an almost eternal institution, for which those now living serve as temporary caretakers. The belief in the power of dead ancestors is continuous with the awe of living ancestors who will soon pass over through death and with the belief that both can effectively curse ungrateful descendants to whom they have granted the boon of life.

The high gods of this structure, who tend to be more remote than the Eurasian gods, are primarily concerned with fertility, both of humans and of crops. Indeed, the two are almost indistinguishable. These gods are the ultimate sanction for the belief that a woman who has borne many children and continues to bear them is virtuous, whereas a woman who does otherwise is at best tainted with sin and is at worst evil.

Christian missionaries, and also to a large extent those who spread Islam, concentrated on displacing the higher gods with their one god, believing this was the essence of conversion. They chose not to regard the ancestral spirits as an issue for religious discussion, even though ancestors impose their morality (particularly that concerned with unfettered reproduction) by supernatural means. Our research indicates that the vast majority of Christian and Muslim Africans still believe in the reality of ancestral intervention.

Most of them also agree with the missionaries that ancestral spirits, the living dead, are not a matter of religion but rather a social and worldly matter. The veneration of ancestral spirits constitutes a kind of prolongation of their lives for a few generations beyond the grave, made possible by having descendants who remember and respect them and carry out the necessary rites. If a son does not properly organize the burial rites and the pouring of libations during the ceremony as nourishment for the ancestors, then the father's spirit does not



BIRTH RATES in regions throughout the world have declined since the end of World War II. The only exception to this trend is in sub-Saharan Africa. As a result, Africa may account for nearly a quarter of the world's population by the late 21st century.

survive. Most men regard this spiritual return from their fertility as outweighing in value all the considerable material benefits their children yield during their lifetime—as being the great bonus at the end that caps the value of a large family.

Women are important in the African social system not only because they bear children but also because they do most of the agricultural work. Both facts are recognized by the payment at marriage not of dowry from the wife's family but of bridewealth from the husband's. In the patrilineal societies that predominate, this transfer of ownership ensures that children belong to the husband's lineage. It does not, however, usually lead to the obsessive concern about premarital and extramarital chastity or to the distinction between legitimate and illegitimate children that is found in Mediterranean and South Asian societies. In Africa the obsession is focused on fertility.

Indeed, the emotional and economic bonds of marriage in sub-Saharan Africa are fairly weak, and in many parts of the continent separation rates are fairly high. Typically from 20 to 50 percent of wives are in polygynous marriages, and most must be prepared for the likelihood that their husbands will acquire extra wives. Levels of polygyny may be 10 times as high as those typical in Asia's "polygynous" societies. It follows both from the emphasis on lineage and from the prevalence of polygyny that the molecular unit of African society is a woman and her children rather than parents and their children. Indeed, the woman is responsible for much of the economic support for herself and her children.

The existence of the lineage and the concomitant relative weakness of emotional and economic conjugal links wreak havoc with the assumptions of Western demographers about the family economic pressures that are generally thought to lead to declining fertility. Those who decide that children should be borne are usually not the ones who bear their major costs, and the children they decide to have do not necessarily impose costs on them.

In most African societies births to an unmarried woman pose no insurmountable economic problem; her lineage usually accepts the children as a recruitment to its strength. Virtue lies in reproducing the lineage rather than in female premarital chastity. Apart from the question of lineage survival, most Africans today still feel that the large lineages and the large families do better economically, and the limited hard evidence seems to support this belief.

Even if larger families did not do better, other forces might still keep fertility high. Married African women usually have a marked degree of control over their own sexuality but practically no control over their reproduction. The payment of bridewealth—even the low, almost symbolic bridewealth of the contemporary Yoruba in southwest Nigeria—secures the children of a marriage for the husband's lineage, and so he and his blood relatives make the reproductive decisions. In Ibadan we found that not one married woman in 100 believed she could decide to have no more children if her husband thought otherwise. This was true even for women in the educated professional group and even for those whose husbands provided no financial support, were rarely around and consorted mostly with other women.

Husbands have little reason to restrict fertility. They usually provide only limited economic support for their children. Nevertheless, they can expect both loyalty and, as the children grow up, material support for the rest of their lives—not to mention the all-important burial and subsequent rites. The loyalty and support are ultimately based on ancestral status and on descendants' deep fear of denying ancestors, whether dead or alive. A living father whose children do not provide for him can curse them with misfortune in reproduction and other aspects of life.

Fathers are likely to receive much more from children than they spend on them. Furthermore, the return is likely to be just as great to fathers who neglect and mistreat their children and the children's mother as to those who spend lavishly on them. Research in Ghana during the 1960's and in Nigeria during the 1970's gives strong support to this rather surprising proposition.

One reason for this anomaly is that there is no simple concept of dependent children. Many men have children by more than one wife, and so Africans commonly have half-siblings as well as full ones. The emphasis laid on descent in traditional rural compounds is such that a patriarch would not allow his children to distinguish between their own offspring and nephews and nieces.

In Nigeria, the Ivory Coast, Sierra Leone and elsewhere, we and other researchers have found up to half of all dependent children living with persons other than their own biological parents. Often they live with uncles and aunts—a situation that foreigners describe as fostering, to the irritation of Africans, who believe that both researchers and children should regard such children simply as living in their own families. The complex web of dependency weakens the relation between the number of children a woman bears and the number she supports, rendering fertility control on economic grounds improbable.

The communal land tenure of the lineage social structure rewards large families. Large Eurasian families end up by fragmenting their landholdings, but large African families are rewarded by a greater share of lineage or clan land. And where there is no ownership of land or expensive farming equipment, the only possible investment in farming is in human beings. The prosperous rural patriarch is the one who

has many wives and children working in the field.

Not only are large families considered good, but small ones are considered bad. Throughout much of sub-Saharan Africa childless women are regarded as evil or as tainted by evil. The Yoruba say, for example, that a barren woman has made a pact with evil spirits before her own birth that she would kill her children and, devoid of descendants, return to join these spirits in some otherworldly sphere. The notion of child killing draws little distinction between barrenness, miscarriage, induced abortion, infanticide and the death of children by illness or accident. (Abortion is regarded with abhorrence, but desperate schoolgirls or young women in training courses may still procure abortions to preserve their economic options.) Barren women were once treated very badly: they were returned to their lineages, often subsequently banished to a hut beyond the village so they could harm no one by association and kept away from children and pregnant women so that their witchlike powers would not kill. Their bodies were thrown to wild animals or mutilated at death. Still in rural southwest Nigeria the body of a barren woman is buried at night in a lonely and forgotten place with only a few of the lineage women present.

Barrenness not only carries an aura of evil but also marks the end of a line of descent. Women are almost as afraid of being rendered functionally infertile by the death of all their children as they are of bearing none. Female sterilization and even contraception are widely feared. Even women with four or five children fear that all of them may suddenly die.

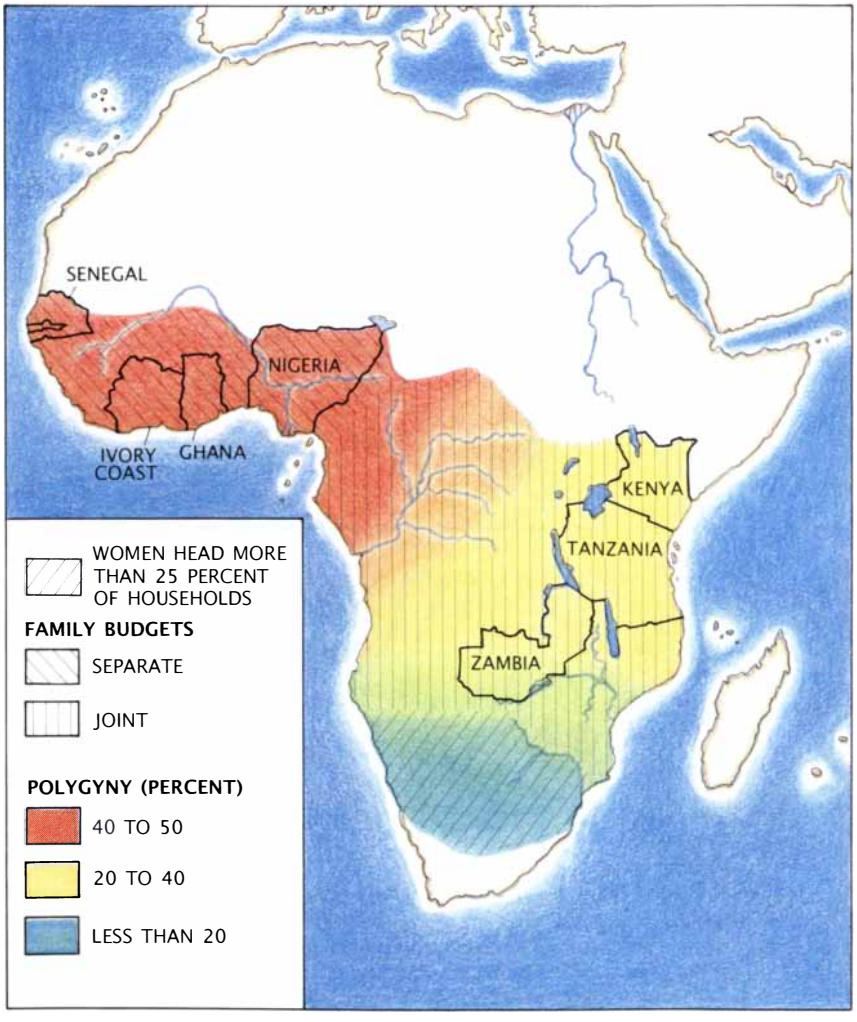
Our research in Ibadan showed that fertility control was in fact associated with improved survival. In very few cases did women who limited their family size subsequently lose all their children. Those few, however, were known throughout the city as having suffered the typical fate of contraceptors. Among middle-aged, sexually active women with large families, only one in 20 was doing anything to avoid further pregnancies. Most did not even like to say that they hoped they would have no more children.

Demographers have frequently looked for a relation between declining mortality and willingness to begin fertility control. If such a relation exists, it varies among societies according to how disastrous it would be to have no surviving children. When fertility decline began in France in the late 18th century, women who had three children (one of them an infant) took a 5 percent chance that they would leave no descendants; late 19th-century American women took a 2 percent chance, but women in Ibadan are not willing to face a 1 percent risk.

Because religion and morality center on fertility, politicians and the state, particularly in fledgling African nations, trespass on this area with trepidation. African governments are often dictatorial, but none of them could impose a family-planning program like China's or even one like India's without being torn asunder. Indeed, African leaders at all levels have until recently been far from certain that they could advocate fertility control without being accused of initiating a direct assault on African society and its belief system.

African society was once typical of most of the world. After the Neolithic revolution, 5,000 or more years ago, however, a society that British anthropologist Jack R. Goody calls "Eurasian" began to develop, with very different characteristics. These included cultivation with the plow, ownership of land by individuals and a social structure based on a strong conjugal family, ostensibly protected by a concern that female sexuality be restricted to marriage; marriages were usually monogamous and, outside the Islamic world, lifelong. This system and its accompanying beliefs have spread through five continents.

Why has the African social structure persisted over millennia during which the Eurasian model could have supplanted it? Danish social scientist Ester Boserup has argued that African men rejected the Eurasian system be-

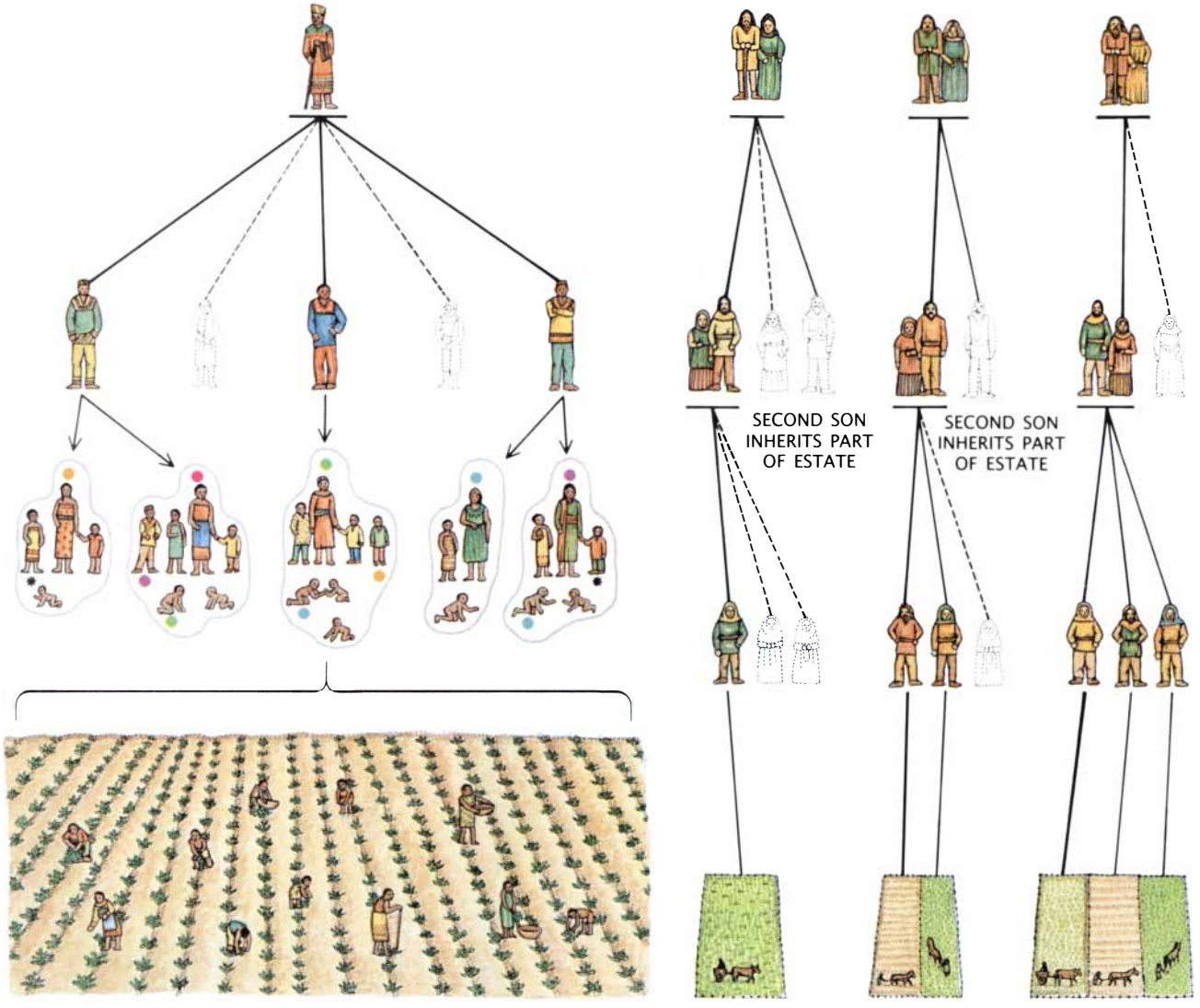


SOCIAL STRUCTURE of sub-Saharan Africa (shown in color) has been shaped by marginal agricultural land and fearful diseases. Distinctive characteristics include polygyny, separate lives for men and women and children, and postpartum sexual abstinence by women. Colonization and development have made only partial changes.

cause it would have required the use of plows and consequently increased male farm work. Canadian sociologist Jean-François Saucier has contended that the old, especially the old men, rejected change because they saw a conjugal society as threatening to the lineage system and the veneration of ancestors that buttressed their gerontocracy. We find both of these theories unconvincing because they portray whole societies acting with foresightful decision about their future and carrying out their intent by controlling social change even at their borders.

The most plausible explanation, put forward by Goody, focuses not on African society but rather on Eurasian society and the unusual circumstances that allowed it to develop. It is necessary to emphasize, for people largely conditioned by the Eurasian social model, what a peculiar structure it really is. Only over millennia has it come to seem natural.

After the Neolithic revolution, ancient people living on alluvial plains and valley bottoms from the Mediterranean to northern India found that these regions could be made to produce surplus grain, and thus wealth, for anyone who could maintain control over enough land. A few people could produce enough food to support many more. The resulting battle for wealth and privilege based on control of land area led to a society stratified by social class and to a determination on the part of each class not to be reduced to the circumstances of the classes below it. This aim was achieved by strict control over land and other property, by the marriage of children to families from the same class and by managing dowry and in-



FAMILY STRUCTURE in sub-Saharan Africa (*left*) differs substantially from the "Eurasian" one familiar throughout the rest of the world (*right*). Women and children do the majority of the work on the land, which is held communally by a lineage or clan rather than by individual families. The more offspring each mother has, the more surplus food the lineage as a whole can produce; this situation contrasts with the Eurasian one, in which a family's landholdings determine the amount of food produced and additional offspring reduce the amount available for each person. From 20 to 50 percent of women in sub-Saharan Africa are in polygamous marriages, conjugal links are relatively weak—separation is not uncommon—and fathers frequently provide little support for children. As a result, a mother and her children (as opposed to two parents and their children) form the basic unit of society. Men may have children by more than one woman, women may have children by more than one man (*asterisks*) and children may be raised by a woman other than their biological mother (*colored dots*). These factors may increase fertility by reducing the direct cost of a man's decision to have more children.

heritance. (Some societies even adopted primogeniture to reduce the fragmentation of inherited property, by passing most of it to the firstborn son.) Fertility took second place to ensuring the right match by the outlawing of women's sexual activities outside marriage and to maintaining indisputable inheritance by identifying and anathematizing illegitimacy.

Africa escaped the gains and losses of the Eurasian system, according to Goody's theory, not by conscious rejection but because it had no great alluvial valleys suited to irrigation or good temperate soils that were moist the year round. Its agriculture was carried out on upland soils unsuited to the plow, which yielded only small surpluses beyond the food needed by the families cultivating them.

Just as the African system of belief in ancestors reinforced its social structure, so the popular religions of Eurasia—Buddhism, Hinduism, Judaism, Christianity and Islam—grew up across Eurasia's agricultural heartland, from the Mediterranean to the Ganges. These religions did not preach sustained inequality; religions must convince not only those who are advantaged but also those who are not. Instead they preached the virtuous life. This virtuous life, however, tended to include strong female sexual restraint, guidance in marriage by one's parents and marriage within one's social class—all factors that acted to sustain inequality.

Bolstered by the wealth generated in their home regions, Eurasian belief systems were exported to many places where the economic conditions that had fostered their growth did not prevail. By diffusion these religions conquered the rest of Europe and by migration, the Americas and Australasia. The diffusion was not complete, of course, and so the lines of power in northern European and North American families were never as absolute as in those of the Mediterranean, Middle East or India.

Meanwhile sub-Saharan Africa was protected from the spread of the Eurasian system by its hoe-based agriculture, by the gulf of the Sahara, by devastating diseases and by a lack of resources attractive to migrants and conquerors. Even when outsiders identified a valuable resource—slaves—in the 17th century, they still made significant settlements only in limited parts of the East African coast and in the extreme south. Eurasian religions penetrated the West African savanna quite slowly over the centuries, and European colonies arrived in West Africa only within the past 100 years. As a result, the original African social structure has largely held its own.

In some ways the African social structure has advantages over the Eurasian one. Fundamentally, Eurasia's society is the product of materialistic, acquisitive and wealthy classes acting to maintain their position and possessions. To achieve this, women and the poor were kept in a relatively debased state for millennia; much of the history of the West has been of the struggle to right that situation.

African women, in contrast, were freer and did not have to fear death or lifelong humiliation if they were caught in sexual indiscretions. Society was relatively classless, and marriages between persons of powerful and powerless families were common. These elements of the African situation are ones toward which many rational reformers have urged the West during the present century.

Only within the past generation has Africa suffered two unexpected by-products of this freedom. Because high fertility receives great social acclaim and its restraint yields smaller economic gains than in the West, government programs aimed at curbing population growth face an uphill struggle. In addition, relative sexual freedom now assists the spread of HIV infection and AIDS, a calamity completely unforeseen.

The second problem in particular should be seen in perspective. The high levels of female independence that arise from the primacy of the lineage, the prevalence of polygyny and various degrees of marital instability often make it advantageous for women to enter new or additional relationships. Sexual freedom, especially female sexual freedom, may be no greater in Africa than it is in the more emancipated countries of the West—it is similar, as one observer has put it, to the situation on American college campuses. Those campuses, however, do not have woefully inadequate health systems. In Africa venereal diseases and other pelvic infections go untreated, and lesions and ulcers may remain for a lifetime to channel HIV infection. Any society that combines a reasonably relaxed attitude toward sexual relations with extreme poverty and rudimentary health services faces the same problem. South Asian or Arab peasants achieve some protection by a degree of female seclusion that few African women have to face.

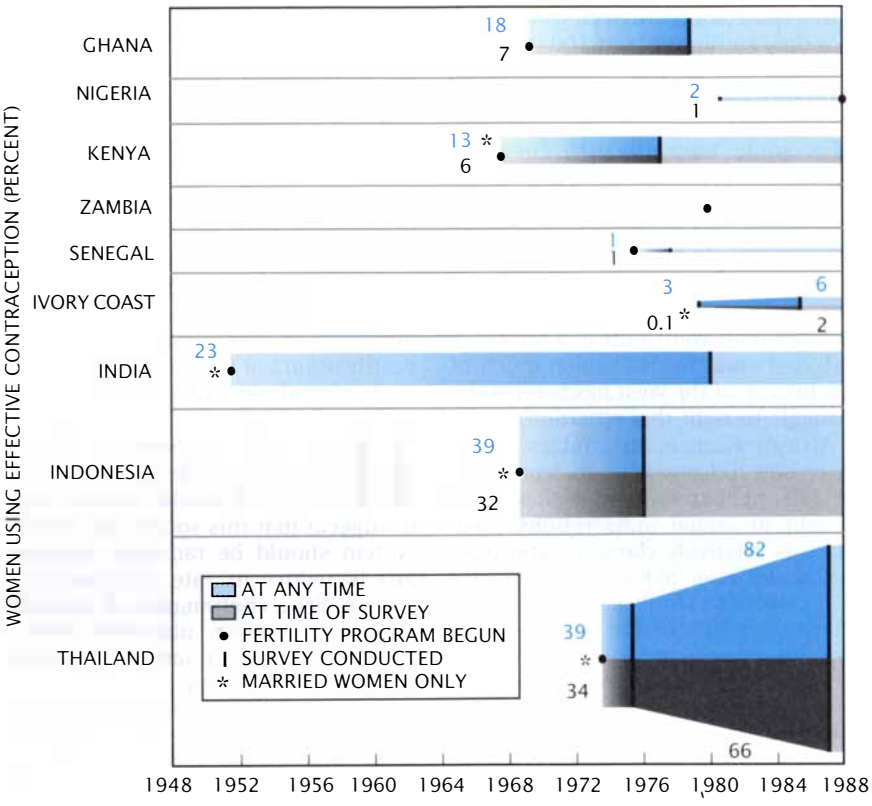
Outside observers have put far too much stress on the role of Western-style prostitution in the spread of AIDS in Africa. In part, prostitution is the kind of health-endangering sexual activity that outsiders understand—and there is a tendency to classify all women who receive support from, and have sexual relationships with, more than one man as prostitutes. In addition, much of the analysis of the situation depends on data from clinics specializing in sexually transmitted diseases, whose clientele is often too hastily assumed to consist almost entirely of professional prostitutes.

How will sub-Saharan Africa cope with its persistently high fertility? It would be imperious to suggest that this society and belief system should be radically changed just to reduce its rate of population growth. Yet a continuation of present rates will probably ultimately prove disastrous, and in any case, some changes are occurring.

At the world population conference in Bucharest in 1974, most African governments were deeply suspicious of national population programs. Only Kenya and Ghana had entered the field. Ten years later, when the conference was held in Mexico City, most African governments supported family planning. Nigeria, with one fourth of independent sub-Saharan Africa's population, is now vigorously urging women to restrict themselves to four children. In general, the number of programs is now growing, although most are not very dynamic and reach only parts of each country.

This policy volte-face by African governments has come about for both good and bad reasons. The good one is a realization that uncontrolled population growth is likely to be economically harmful; the bad one is a misplaced hope that curbing rapid population growth will be a panacea for all of the region's economic problems.

Meanwhile the rural conditions that gave rise to the lineage system are disappearing. The proportion of people living in the countryside is declining, and individual land ownership is becoming more common. Lineages may wither with the rural system that created them, and the power of ancestors may fade. Many parts of the social structure, however, seem to have a life of their own. There is little evidence that polygyny has declined, except in southern Africa where there is a long history of Christianity. And the conjugal link does not appear to be strengthening in emotional or economic terms except among small ur-



FAMILY-PLANNING PROGRAMS have fared significantly better in Asia than in sub-Saharan Africa. The authors contend that the high social and economic value of fertility and a deep-seated fear of dying without descendants work against widespread adoption of contraception in Africa. More recent data from several countries there indicate that fertility may decline as health care improves overall life expectancy.

ban elites. Nor is there evidence of a reduction in fostering.

The most likely source of change in fertility patterns is a growing determination of women to extend their very considerable economic independence into the reproductive domain. This will not necessarily lead to a marked decline in fertility: as the rural social system passes, women will be, if anything, more dependent on their children for company and economic support in old age unless there is a complementary increase in conjugal economic security.

The effects of changing religious beliefs are also unclear. Most Africans are now Christians or Muslims; most probably also believe in the possibility of ancestral intervention. Research in this area is least satisfactory among the new urban elites, who are the harbingers of change. Most members of the elite are not quite sure about their spouses' beliefs and do not discuss such matters. Most do not anticipate ancestral intervention in their own lives, but beliefs can change rapidly if children or spouses sicken or if children die. The vast majority still dread barrenness or the remotest possibility that all their children might die. Yet there is evidence that contraception, abortion and even female sterilization are no longer as closely associated with the evils of barrenness or contrasted as starkly with the virtues of unfettered reproduction as was once the case. One sixth of the women in Ghana, one eighth of those in Kenya and probably even more in Zimbabwe have used modern contraception.

Certain aspects of African society, however, obscure the connections between contraception and fertility levels. Africans have maintained substantial intervals between births not only by long breast-feeding but also by abstention (by the mother) from sexual relations, often for two years or more after birth. Long birth intervals were not inconsistent with fertility levels of from six to eight births per woman only because African societies usually insisted that women of reproductive age should be constantly in the married state; widows remarried very quickly thanks to the world's highest levels of polygamy.

Traditional beliefs about the importance of long birth intervals persist, as does social willingness to pillory parents whose children die after short birth intervals. Nevertheless, the postpartum abstinence period has been shortening everywhere—spectacularly so in parts of East Africa in this century—largely as a result of the contraceptive practice of withdrawal, or coitus interruptus.

Postpartum abstinence has had two effects on fertility control. First, many Africans see no reason for other kinds of control; abstinence can meet any need. Typically women who have become grandmothers or who have four or more surviving children begin terminal abstinence (in southwest Nigeria at about 42 years of age). Second, the level of contraceptive use in Africa is not a measure of attempts to control family size. Contraception serves instead to sustain birth intervals while shortening the abstinence period.

In Asia most couples will practice birth control only when they have attained their desired family size. In contrast, in Nigeria we found that only one ninth of those who adopted contraception did so because they had attained their desired family size. Half of them turned to contraception to shorten postpartum abstinence, and most of the rest did so to prevent premarital or extramarital conception. Usually contraception was given up when these needs passed.

A confluence of factors will almost certainly lead to fertility decline: on the one hand, greater government advocacy of small families and provision of family-planning services; on the other, social change, particularly among women, and a shortening of the postpartum abstinence period to a point where it no longer influences fertility. Even Africa's imperfect demographic statistics should make the trend clear by the end of the century. Yet the decline is unlikely even over two decades to match the 37 percent decline achieved by Indonesia and Thailand in the 1960's and 1970's. It is unlikely to prevent the region's population from reaching 2.5 billion by late in the next century.

In particular, the African desire for guaranteed survival of descendants will almost certainly persist in the years immediately ahead, and it will constrain the success of family planning. There is new evidence, not yet fully proved, that family-planning programs may be beginning to work in Botswana, Zimbabwe and central Kenya. The major factor in these programs appears to be the achievement of low overall mortality: life expectancy exceeds 60 years, and infant mor-

tality is as low as 70 per 1,000 births.

If reduced mortality is in fact the key to lower fertility, then the best investment for population stability is in health services and family planning together. Health services must be expanded to drive mortality down, especially in the face of the AIDS epidemic. By the mid-1990's, 80 percent of deaths in people between the ages of 15 and 50 in Uganda, and probably soon afterward throughout much of eastern, middle and southern Africa as well, will be attributable to AIDS. Overall mortality will be twice what it would be otherwise—a situation that can be compared only to the Black Death in Europe.

Given the present inability of medicine to control AIDS and little evidence of effective behavioral change in Africa, the most practical course is to pour resources into establishing a health system that will quickly detect and treat venereal and other pelvic infection, detect HIV infection and give such care as is possible, and deliver general health treatment, especially to children. Comprehensive family planning could easily be grafted onto such an overall effort. This task is the greatest challenge for international aid in modern times, and posterity will not forgive our generation if we do not meet it.

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MATHEMATICAL RECREATIONS

How to transform flights of fancy into fractal flora or fauna

by A. K. Dewdney

"So, naturalists observe, a flea
Hath smaller fleas that on him prey;
And these have smaller still to bite 'em;
And so proceed *ad infinitum*."
—JONATHAN SWIFT,
On Poetry. A Rhapsody

So, mathematicians observe, if fleas are all the same except for size, then all their hopping and rotations reduce to affine transformations. What exactly is this high-sounding term? It is nothing more than a formula for scaling, turning, displacing and sometimes even distorting an object geometrically. As in the case of fleas, a single affine transformation can be applied repeatedly to produce miniature replicas of the original. People who prefer not to waste their talents on propagating fleas can apply these rather simple geometric formulas to generate images as intricate as the paintings in museums or landscapes in nature.

A small set of affine transformations can create such abstract works as the Sierpinski triangle illustrated on the opposite page. A larger group of transformations can re-create landscapes such as the Monterey coastline shown below. In fact, any image whatsoever can be reproduced from a series of affine transformations. The trick is knowing which ones to choose. Along these lines, Michael F. Barnsley of Iterated Systems, Inc., in Norcross, Ga., has discovered a general procedure for reducing an image into a series of affine transformations. His technique has opened up some exciting possibilities for the transmission of television and computer images. Before I describe his work, let me say a bit more about affine transformations.

When an affine transformation is applied to a figure such as a triangle or a leaf, it moves the points that make up the figure to new locations. In the process, the transformation may translate, scale, rotate and stretch the original figure. If one starts with a triangle, an affine transformation could shrink the triangle and move it to the left somewhat, thus creating a second triangle. If the same transformation is applied to the smaller, displaced triangle, it will produce a third triangle that bears the same relation in size and proximity to the second triangle as the second does to the first. One can apply the transformation repeatedly and watch the triangles trace a path into infinitesimal oblivion.

If one applies an infinite series of affine transformations to an object, the result has the property of being self-similar, that is, a magnified portion of the result looks like the whole. Hence, a series of affine transformations can create a self-similar object, better known as a fractal.

All affine transformations have the same kind of formula for moving the points of a figure around in a plane. The original point can be defined by two coordinates, which I will call x and y. The new point has the coordinates (x', y'). The transformation is then defined by two equations:

$$x' = ax + by + e$$
$$y' = cx + dy + f$$

The symbols a, b, c, d, e and f represent a set of numbers that determine the character of the affine transformation.

What would happen, for example, if b

Photograph of Monterey coastline **(left)** ***and the same image*** **(right)** ***reproduced from a few affine transformations***

were equal to .5, c were –.5 and a, d, e and f were all 0? The two equations that define the affine transformation would become:

$$x' = .5\ y$$
$$y' = -.5\ x$$

To determine its effect on a specific point, say (1, 2), one merely applies the formulas. Thus, x' becomes $(.5 \times 2)$, which equals 1, and similarly y' becomes –.5. If one carries out this operation for a great many points in a triangle, a general pattern emerges. The entire triangle seems to have rotated 90 degrees clockwise and simultaneously to have shrunk to half its former size. If e and f were both equal to 1 instead of 0, then not only would the triangle be reduced and rotated, it would also be shifted one whole unit up and to the right.

This kind of transformation is called contractive because its effect on any collection of points is to shrink the distances between them. The transformation also preserves shapes. Contraction and shape preservation are key properties of the affine transformations employed in the technique that Barnsley calls an iterated-function system.

The fun begins when several transformations of this kind are applied many times to any figure the mind can imagine. The transformations, along with their continued reapplication, make up an iterated-function system. One might think initially that solving the formulas for iterated-function systems involves an extraordinary amount of arithmetic. For instance, if a sequence of transformations were applied to a figure composed of 1,000 points, each transformation would have to operate on 1,000 points at a time. This would yield 8,000 arithmetic operations.

The astute reader will realize that to determine the effect of an iterated-function system on a figure such as a triangle, it is necessary to operate only on the three corner points. (The figure can be completed by simply connecting the points with lines.) In this case the transformation would only have to operate on three points at a time, and yet no savings can be guaranteed for a figure that has an irregular shape whose outline is defined by many points.

Do not despair. Barnsley has come up with a clever idea so that even complicated figures can be efficiently transformed many times. The advantage of his technique is that only one point at a time is transformed. His idea can be appreciated by playing the game I call fractal tennis.

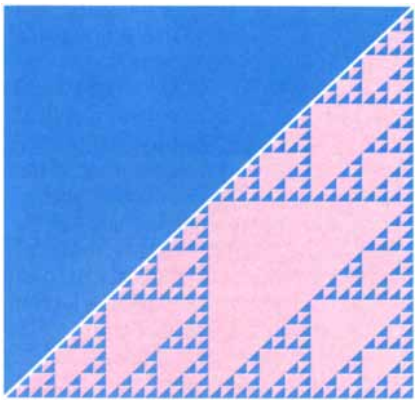
This unusual racket sport requires four mathematically minded players and an umpire. The players—Abby, Bob, Carla and David—stand around a square court, separated by two nets that divide the court into four square quadrants. The umpire assigns each player to a home quadrant. To start the game, the umpire tosses a ball into Abby's home quadrant and shouts "Bob." Abby lets the ball bounce only once, swings her racket and hits the ball over the net so that it lands in Bob's quadrant.

Abby is not allowed to hit the ball to just anywhere in Bob's quadrant, however. To make the perfect shot as prescribed by the rules, she must first judge where the ball landed in her own quadrant. This task is rather simple because the tennis ball, which has been soaked in black ink, leaves a mark on the court. Abby creates a mental map of the ink mark within the entire court. She superposes the map on Bob's home quadrant by shrinking it to half its dimensions. The position of the superposed ink mark on Bob's quadrant is where she must hit the ball. If the ball had landed in the center of the whole court, Abby would have been required to hit the ball to the center of Bob's quadrant. In this case, however, the ball landed two meters north and six meters west of the center of the whole court. Because the dimensions of Bob's quadrant and the others are half those of the court as a whole, Abby should hit the ball one meter north and three meters west of the center of Bob's quadrant.

Abby's great shot represents an affine transformation. She has created a second ink mark, which has been displaced to Bob's quadrant and is closer to its boundaries.

After Abby's return, the umpire calls out "David." Bob rushes to catch the ball on the bounce and makes a perfect shot into David's home quadrant. The umpire, perhaps a bit maddened by the sun, then starts to shout names at random. Yet Abby, Bob, Carla and David, being consummate calculators, play a flawless game. Each player always hits the ball to just the right point. After a while, however, the ink marks left by the tennis ball create a fractal pattern on the court. In fact, the marks eventually blacken the court uniformly. That is when the umpire calls a halt to the play.

The figure on the next page shows the early stages of the game. After Bob made his first shot to David, the umpire called "David" for a second time. This did not present a problem, except for David of course. He hit the ball toward the southeast corner of his own quadrant because his quadrant is in the southeast corner of the whole court. After the ball bounced in David's own quadrant, the umpire called "Carla," and



The Sierpinski triangle

David hit the ball to her quadrant according to the rules. If the umpire had yelled "David" again and again, David would have had to direct the ball ever closer to the southeast corner.

Fractal tennis illustrates a key feature of iterated-function systems. A single point mapped repeatedly by a random sequence of affine transformations will eventually "fill in" a certain region. The umpire's calls, or transformations, are what determine the ultimate image. In practice, the game ends when a satisfactory density of black dots emerges.

Readers who wonder why the game is called "fractal" tennis will see the game come into its own when it is played on the leaf of a black spleenwort fern. The game still involves four players, but unlike the classic smooth square of the practice court, the fern-leaf court has a jagged outline. As the illustration on page 129 shows, when the umpire calls "Abby," one of the players must hit the ball to Abby's leaflet. The point where the ball must land depends on the position of the last bounce relative to the whole leaf. In this way, the call "Abby" corresponds to an affine transformation. The call "Bob" is also an affine transformation that sends the "ball" to the corresponding point in the leaflet at the left side of the leaf near the base. The call "Carla" does the same thing in relation to the leaflet at the right side of the base. Finally, the call "David" sends any point of the leaf as a whole into the straight-line segment representing the stem at the base of the leaf.

When the point is put into play, the umpire begins to call the names of these four players in a random order. The point might start in the middle of the leaf, hop to the middle of Bob's leaflet, then shift to a point in Carla's leaflet and so on. The game goes on for 10,000 hits. As it continues, an image of the fern leaf, delicate and organic-looking, emerges [*see illustration on page 129*].

There is one element of the game that I have yet to describe. The sequence is not quite random: the judge favors certain players as he makes the 10,000 calls. The case of the spleenwort leaf provides a perfect example. Abby's leaflet has the largest area. Therefore, if the umpire is just as likely to shout "Abby" as any of the other three names, Abby's leaflet will fill in more slowly than the others'. To adjust for this, the umpire gives Abby the lion's share of play. In fact, the amount is proportional to Abby's share of the total leaf area.

The umpire calls "Bob" and "Carla" roughly the same number of times, the numbers in both cases being proportional to the areas of their respective leaflets. Because the stem has the least area of all, David will get to play the least.

Perceptive readers may have noticed that the four transformations associated with the spleenwort leaf change the basic outline into four regions that approximately subdivide the outlined area. Barnsley calls this subdivision a collage. He and his colleagues have found a theorem that guarantees good fractal reproduction. The collage theorem says that the more accurately the outline of a fractal shape is approximated by a collage of a certain number of affine transformations of the shape, the more accurately the iterated-function system will reproduce the original fractal.

The collage theorem brings us to a fork in the expository road, that between creation and re-creation. To what purpose will an iterated-function system be put?

Creatively speaking, almost any fractal can be constructed by means of one iterated-function system or another. Take, for example, the Sierpinski triangle shown on the preceding page. This is a triangle from which a central triangular area has been removed, leaving three smaller triangles. Given the fractal nature of our topic, it will surprise no reader to find that each of the three triangles has its own central triangle removed.

Three affine transformations participate in the production of the Sierpinski triangle. They arise from a collage composed of three identical right triangles that all have the same orientation. The triangles in the collage are positioned to form a right triangular hole of the same size as one of the three triangles. Each of the triangles is associated with a particular affine transformation. When the game of fractal tennis is played on this strange surface, the original triangle begins to fill in, except for the hole in its middle. Each of the corner triangles has a hole in its middle, of course, and so do the triangles in their "corners." The final object, insofar as any finite scheme can reproduce it, is literally full of triangular holes at all visible scales of magnitude.

Readers who have computers at their command can reproduce the Sierpinski triangle by following an algorithm for the appropriate iterated-function system. I will describe the algorithm in general terms. It begins by setting the coordinates x and y equal to 0. Then three main operations are repeated 10,000 times: First, one of the affine transformations is chosen at random. Second, the chosen affine transformation is applied to the current coordinates of the point, namely, (x, y). The result is a set of new values that are now deposited in the x and y symbols, so to speak. Third, a test is made to determine whether 10 iterations have been carried out.

The third step ensures that the ball has been in play long enough to be somewhere in the court. In a general scheme such as this, one does not know in advance the best place to start the ball bouncing. Hence, one starts it from the origin and assumes that after 10 iterations it has pretty well "settled into" regular play.

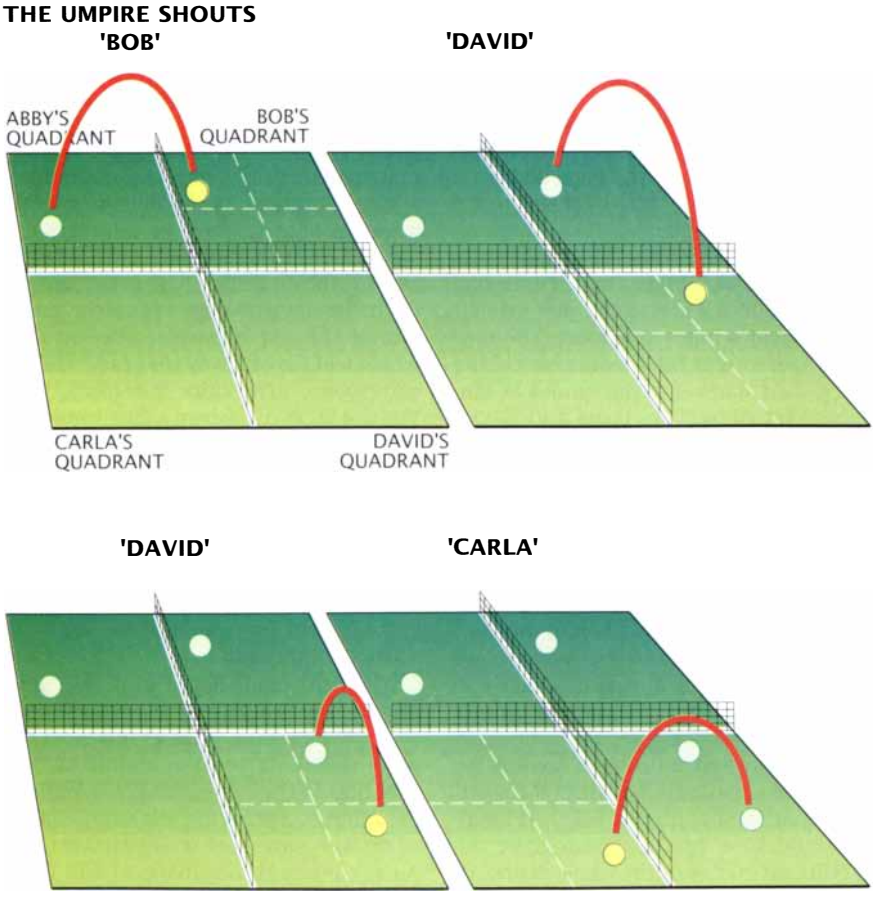
This algorithm will work for any iterated-function system if one adds an extra feature. Because an affine transformation must be chosen at a rate that depends on the area it must cover, the algorithm must select each transformation with a certain probability.

What are the formulas for the affine transformations that produce the Sierpinski triangle? At the beginning of this column, I described the type of formula one needs, and I mentioned that six coefficients determine the transformation's character. The coefficients for the Sierpinski triangle are given below.

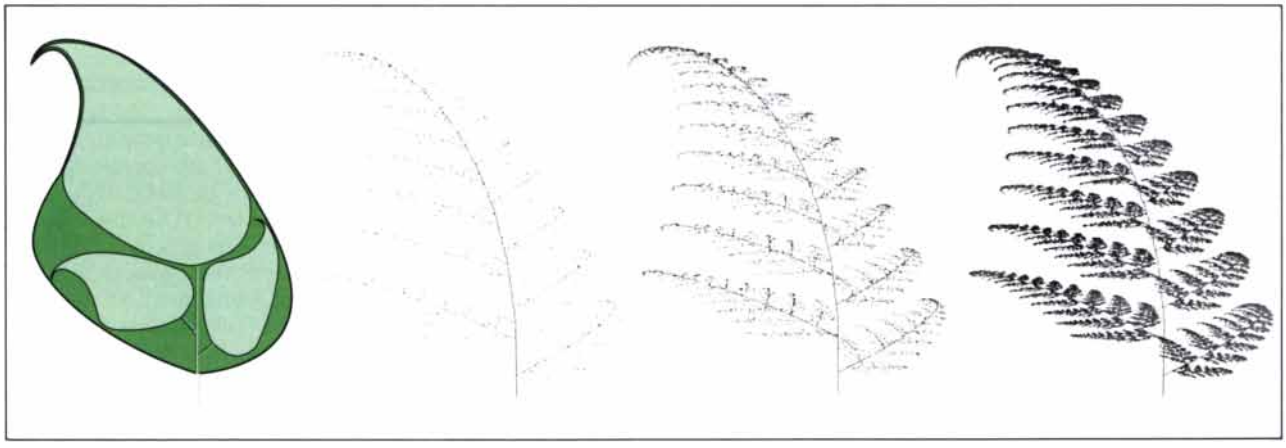
	a	b	c	d	e	f
(1)	.5	0	0	.5	0	0
(2)	.5	0	0	.5	0	1
(3)	.5	0	0	.5	.5	.5

Each row of the table represents one of the three transformations.

One can tell what these particular transformations are up to almost at a glance. All three have the primary effect of shrinking any geometric figure to half its size, but transformation number 1 also shrinks the figure toward the origin, whereas transformations 2 and 3 move the shrunken form one unit to the right and one-half unit up and to the right, respectively. Thus, the original triangle is



Opening shots in a game of fractal tennis



An iterated-function system fills in the leaf of a black spleenwort fern

transformed into three smaller triangles, and the miniature triangles are in turn transformed into minuscule ones.

From these simple ingredients, readers with moderate programming experience should be able to reconstruct the Sierpinski triangle on their display screens. Others may have to consult a more extensive recipe now available in *Algorithm: The Personal Programming Newsletter*. I shall be happy to send a free copy of the recipe to any reader who does not already subscribe.

Up to this point I have addressed the creation of forms. There is not as much recreation in re-creation, but that is the major application of iterated-function systems. Thanks to Barnsley and his colleagues it is now possible to convert any scene into an iterated-function system.

Normally it takes thousands of bits of information to store the image of a natural scene in a computer file. For example, an image might consist of a 300-by-300 grid of pixels, or picture elements, each requiring several bits to specify a gray level or color at that point. Ordinary pixel-by-pixel storage might therefore take up a million bits or more. One can apply standard compression techniques to such pictorial data to store the same information in a smaller space, but iterated-function systems promise compression factors of 500 to 1—or even better! The key: store the iterated-function system rather than the image it produces. A glance at the pictures of the Monterey coastline on page 126 enables one to compare the veracity of the coded image (on the right) with the original photograph (on the left).

The method begins with a computer image drawn directly from a photograph or video camera. The image is analyzed and broken up into connected patches, large and small, in which the gray level (or color) is relatively constant. The pieces in this collage become the basis for a search through a large library of standard affine transformations that map some pieces into others. If it should happen, for example, that one of the transformations maps a droplet of spray into a great many other droplets, then that transformation would make a valuable addition to the iterated-function system under construction. Actual images can then be reconstructed in certain computers at video rates, that is, faster than 30 whole images per second.

The commercial potential of the discovery so impressed Alan D. Sloan, a mathematician formerly at the Georgia Institute of Technology and a close collaborator of Barnsley's, that the two researchers started Iterated Systems. Among the company's current products is a video modem that produces an iterated-function-system code for a 512-by-512 pixel image in just under three seconds. At the receiving end the images can be reconstructed at video rates. In the future Barnsley sees full-color video transmission over telephone lines as a definite possibility. The technology may also be applied to automated pattern recognition and other projects that are as yet a fractal gleam in Barnsley's eye.

The Tinkertoy computer that plays tic-tac-toe drew some telling analyses out of the woodwork last October. For example, Richard Arend of Wolcottville, Ind., attempted to reproduce the reasoning that led the former Massachusetts Institute of Technology students to a memory array of 48 memory spindles. Unsatisfied with the machine's passive play in games where the human fails to take advantage of a winning possibility, Arend added a carefully minimized set of 12 additional memory spindles to bring the game more quickly to a triumphant conclusion.

Although I had mentioned 48 spindles in the article, Charles Kluepfel of Bloomfield, N.J., noticed that the illustration of the machine had only 47. Nevertheless, he translated the spindles into a computer program that, he then discovered, contained a bug. Was the problem in the illustration or in the original machine? If a certain position is reached, Kluepfel claims, the tic-tac-toe computer may try to play an *O* over an *O* instead of over an empty square.

A number of readers had problems getting the HOLE IN ONE program in last November's column to work. The errors in our listing were the cause. Anyone still pondering the problem is advised to change line 10 from CLS to SCREEN 1 and to change lines 160 and 170 by inserting an asterisk to indicate multiplication in both cases.

The most exciting extension of our innocent game of golf came from longtime reader Theodore C. Yapo, an engineering physics major at Rensselaer Polytechnic Institute in Troy, N.Y. Not content with our Euclidean green, Yapo wrote a program that permits the user to define almost any curved surface. Viewed from above, the play is tricky. "One of the more interesting surface features I have explored results from asymptotic functions.... These infinitely deep wells function as black holes on the golf course." Currently Yapo is building a microminiature golf course on the slopes of Mount Mandelbrot, the surface in which altitudes supplant colors.

FURTHER READING

THE FRACTAL GEOMETRY OF NATURE. Benoit B. Mandelbrot. W. H. Freeman and Co., 1983.

FRACTALS EVERYWHERE. Michael Barnsley. Academic Press, Inc., 1988.

BOOKS

Practically autobiographical: the latest look at the father of the H-bomb

by Priscilla Johnson McMillan

EDWARD TELLER: GIANT OF THE GOLDEN AGE OF PHYSICS, by Stanley A. Blumberg and Louis G. Panos. Charles Scribner's Sons, 1990 ($24.95).

From the fall of 1949, when Edward Teller's behind-scenes lobbying helped persuade President Harry S Truman to announce an all-out program to develop a hydrogen bomb, until the fall of 1982, when Teller sold a willing President Ronald Reagan on a dubious concept known as Star Wars, Teller's wizardry in the corridors of power has been legendary. Over the past four decades his advice led the U.S. to spend billions on nuclear weapons and repeatedly foiled arms-control initiatives.

A portrait of this Hungarian-born physicist, who had the ear of presidents, who played a role in shaping years of U.S. weapon policy and who was embroiled in one of the most celebrated cases of the McCarthy era, could be fascinating reading. Born in Budapest in 1908, Teller was trained in Europe by some of the most prominent physicists of the time, including Werner Heisenberg and Niels Bohr. He came to the U.S. in 1935 to accept a professorship at George Washington University and was teaching at Columbia University when, in September, 1941, Enrico Fermi suggested that it might be possible to ignite a fusion reaction in deuterium with a fission weapon. The idea became an obsession that, together with his fear of communism, led Teller into the back corridors of Washington policy-making.

Unfortunately, the most recent offering, *Edward Teller: Giant of the Golden Age of Physics,* is an authorized biography in the fullest sense. It is Teller's version of events from the cold war and the arms race to the recent Strategic Defense Initiative. It attempts to give Teller the last word on issues such as his claim to exclusive authorship of the hydrogen bomb, his contention that the Soviet Union—not the U.S.—tested the first deliverable hydrogen weapon, his positions on nuclear winter and reactor safety, and the charges that he oversold the Reagan administration on the X-ray laser, a technology envisioned as the key to Star Wars defenses.

There is now available to researchers a small but growing amount of declassified material on Teller's role as a physicist and policy adviser. Yet Blumberg and Panos largely ignore this material. Missing is any reference to documents declassified through the Freedom of Information Act, particularly a 1952 interview with Teller by the Federal Bureau of Investigation.

Instead the book draws heavily on a 1976 biography co-authored by Blumberg as well as a series of interviews with Teller conducted during the late 1970's and 1980's by Blumberg and his present co-author, Panos, a columnist for the *Baltimore Sun*. Other exclusive material includes a 20-page statement dictated by Teller in 1979 to his friend George A. Keyworth, a Los Alamos physicist who became science adviser to President Reagan, and correspondence about SDI between Teller and Hans Bethe, the Nobel laureate and emeritus professor of physics at Cornell University.

The portrait that emerges from these sources presents contradictory aspects. There is the private Teller, the enfant terrible, forgiven for many years by colleagues who enjoyed his company and admired his originality. Then there is the public Teller, whose fear of communism and obsession with nuclear weapons drove his political efforts for four decades. Along with the argumentativeness, the thin-skinned defensiveness of this Teller, I thought I heard something else—the voice of a bad conscience.

From the beginning, Teller was an avid proponent of fusion weapons. When the physicist J. Robert Oppenheimer, who would head the Manhattan Project to develop an atomic bomb, called a conference at the University of California at Berkeley in July, 1942, to discuss problems of building a fission weapon, Teller steered the meeting into a discussion of a thermonuclear device instead.

After the atomic bomb project sprang up at Los Alamos in 1943, Teller was afraid he would be left out because he had relatives in Nazi-occupied Hungary. But he won security clearances through the efforts of Oppenheimer. Yet once at Los Alamos, Teller refused to head the group assigned to perform the detailed calculations needed to design a fission weapon. He was removed from this phase of the work by Oppenheimer and Bethe, head of the division. In an essay published in the journal *Los Alamos Science* in 1982, which was written in 1954 but classified for 28 years, Bethe noted that "after two failures to accomplish the necessary work," Teller was "relieved of further responsibility for work on the wartime development of the atomic bomb."

Teller continued to work on thermonuclear reactions, and in April, 1946, he played a key part in a conference held at Los Alamos to summarize research on the Super, as the still conceptual H-bomb was called. Toward the end of the meeting Teller passed around a proposed report that one participant, Berkeley physicist Robert Serber, found so "incredibly optimistic" as to be "completely misleading." Serber sat down with Teller, and together they rewrote the report so that, Serber says, it was "still quite optimistic, but not ridiculously so." Serber was startled when, three months later, a Berkeley librarian showed him the published report: Teller had gone back to his original version.

The publication of Teller's report had far-reaching consequences. Officials in Washington who had read Teller's account were gripped with fear when it was learned that Klaus Fuchs, a participant in the 1946 meeting, was an espionage agent. In fact, participants now say, no data of use to the Soviets could have been revealed at the meeting.

When the Soviets detonated their first atomic bomb in late summer 1949, Senator Brien McMahon, chairman of the congressional Joint Committee on Atomic Energy, Lewis L. Strauss, one of five commissioners of the Atomic Energy Commission, and high officials at the Pentagon lost no time agitating for development of the hydrogen bomb. During four months of intense lobbying behind the scenes they were assured by Teller and Ernest O. Lawrence, director of the Radiation Laboratory in Berkeley, that the Super was a feasible weapon.

The General Advisory Committee, a

PRISCILLA JOHNSON MCMILLAN was a 1988–1989 MacArthur Foundation Fellow in research and writing. She is writing a book on the H-bomb decision and the Oppenheimer affair.

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Grand master: Teller relaxing with his family in the early 1950's

group of highly regarded scientists attached to the AEC, disagreed. At its Halloween meeting in October, 1949, this committee, chaired by Oppenheimer, voted 8–0 against a "crash" program to build the Super. Although its members were later accused of harboring moral compunctions about the weapon, the GAC was primarily moved by practical reservations. It believed the odds were no better than 50–50 that the Super, as then conceived, could be built.

The committee also regarded as irresponsible any effort to divert scarce fissionable materials and physicists away from the fission program to develop a weapon it considered of doubtful feasibility. The members also believed U.S. tests would provide data to the Soviets that could speed up their program. They feared that the U.S., with its large cities concentrated along the two coasts, would be far more vulnerable to the hydrogen bomb than the more sparsely settled Soviet Union.

When they learned of the GAC's negative recommendation, many of the scientists at Los Alamos, including their director, physicist Norris Bradbury, were dismayed. They became more enthusiastic when, after a secret debate, President Truman, on January 31, 1950, publicly announced a U.S. commitment to build the H-bomb. Contrary to reports that have appeared this year, Truman had almost certainly made up his mind before he learned that Fuchs had passed secrets of the Manhattan Project and the report of the 1946 H-bomb meeting to the Soviets. Truman was aware of Fuchs's espionage, however, by the time he issued his second and stronger H-bomb directive of March, 1950.

The bomb still had to be built, and as the GAC had foreseen, this proved to be no easy matter. In 1950 the Polish-born mathematician Stanislaw M. Ulam, working at Los Alamos with an American colleague, Cornelius Everett, found Teller's 1946 calculations to be wrong. Further calculations by Fermi and Ulam cast more doubt on the feasibility of igniting a thermonuclear reaction from liquid deuterium. The work showed, as Bethe wrote in a May 28, 1952, letter to AEC chairman Gordon E. Dean (which was declassified in July, 1987), that "every important point of the 1946 program had been wrong."

In his 1982 article in *Los Alamos Science,* Bethe also said, "[T]hat Ulam's calculations had to be done at all was proof that the H-bomb project was not ready for a crash program when Teller first advocated such a program in the fall of 1949." Bethe added that physicists at Los Alamos blamed Teller "for leading the Laboratory, and indeed the entire country, into an adventurous program on the basis of calculations which he himself must have known to have been very incomplete." Serber puts it more simply: "They felt swindled."

Teller, for his part, was stung by Ulam's "spectacular" (Bethe's word) results. Ulam's wife, Françoise, who was down the hall, recalls hearing a disbelieving Teller loudly demanding more and more figures and trying to find errors in the Ulam-Everett calculations. What should have been the shared examination of a difficult scientific problem had become, in her words, "a Homeric struggle, unpleasantly confrontational." By the end of 1950 Teller's credibility was at a low ebb.

All of that changed a few weeks later when Ulam, who had been thinking about a two-stage fission device, remarked to his wife at lunchtime one day that he had had an idea that might make the Super feasible: compressing the hydrogen core with the shock waves created by a fission device inside the bomb. Françoise Ulam, remembering Teller's anger a few months earlier, suggested to her husband that before seeing Teller he should first test his idea on other members of the lab. After lunch Ulam went first to Carson Mark, head of the theoretical division, and then to Bradbury. Bradbury quickly saw the implications and told Ulam to go to Teller.

Ulam met with Teller the next day. The meeting was at first uncomfortable, but Teller accepted Ulam's ideas and quickly added a new one of his own. Teller proposed using radiation, rather than mechanical force, to compress the core. "In the following days I saw Edward several times," Ulam wrote later. "We discussed the problem for about half an hour each time. I wrote a first sketch of the proposal. Teller made some changes and additions, and we wrote a joint report quickly." That report, "On Heterocatalytic Detonations 1. In Hydrodynamic Lenses and Radiation Mirrors" (LAMS-1225, March 9, 1951), remains classified.

Blumberg and Panos offer a different story in the form of an extensive quote from the statement Teller dictated to Keyworth in 1979:

"Ulam came into my office and said, 'I have a way to make the Super. Let us compress the material.'

"I said, 'Yes.'

"And then he said, 'Well, you know, we could, for instance, have here a nuclear explosion and then put it around some containers to make a starlike structure and put deuterium in here and they will be compressed by the shock and then it will work.'

"I said, 'Stan, [that is] the simplest thing and it might work, but I think I know something better. You should not compress *mechanically.* You should compress by *radiation*.'

"I said, 'Look, I will put down both of these ideas into a paper and we'll both sign it.'

"Now you know the situation," Teller concludes. "Ulam did not have the idea, he did not write the paper."

After this conversation, Teller pushed Ulam aside. They never saw each other or had meaningful communication again. And when Blumberg and Panos asked Teller in 1979 whether Ulam had triggered the breakthrough, Teller snapped, "Ulam triggered nothing."

Ulam was not Teller's only target. He had decided that Bradbury and the Los Alamos laboratory lacked enthusiasm for the H-bomb. "Thermonuclear work at Los Alamos was at an almost com-

plete standstill between the spring of 1946 and 1950," Teller wrote in an August, 1952, memorandum that was declassified two years ago.

On February 8, 1950, with Ulam hard at work at Los Alamos, Teller went to see Marion W. Boyer, general manager of the AEC in Washington. According to the recently published *Diary of Gordon Dean,* Teller suggested that the work be moved away from Los Alamos. The same day, former AEC commissioner Strauss, a Teller ally, paid a visit to Dean. He complained about Los Alamos and gave the impression that he, too, favored a new laboratory.

Two months later, after the breakthrough, Teller himself saw Dean. According to Dean's notes, Teller gave a long, one-sided history of thermonuclear research, apparently without once mentioning Ulam's name. He also complained about Bradbury and apparently threatened to quit the laboratory. In the fall of 1951, after Bradbury had named Marshall G. Holloway, an engineer, rather than Teller, a theoretician, to head the H-bomb program, Teller did leave.

By now, however, Teller had such powerful backers at the Pentagon and the congressional Joint Committee on Atomic Energy (the GAC and Dean's AEC were not among them) that he was given Air Force funds to set up his own research effort at Chicago. After Defense Secretary Robert A. Lovett okayed a second laboratory in March, 1952, the AEC had to go along. That summer Teller, with the help of Lawrence, set up a laboratory in Livermore, Calif. Now known as the Lawrence Livermore National Laboratory, it has been Teller's scientific home ever since.

Among those opposed to creation of the new laboratory was GAC chairman Oppenheimer, whose reappointment to the committee was up for Truman's consideration. At that time, an FBI agent visited Teller to ask about Oppenheimer.

According to the agent's report of May 14, 1952, "Teller states subject has opposed development of H-bomb since 1945 and is of the opinion that H-bomb would have been a reality at least one year ago if it had not been opposed by Oppenheimer." Teller added that he thought Oppenheimer had discouraged scientists from working on the H-bomb, although he could not prove it, but added that he did not consider Oppenheimer's motives "subversive." Rather, he said, Oppenheimer acted out of "personal vanity in not desiring to see his work on A-bomb done better on H-bomb, and...does not feel H-bomb is politically desirable." Finally, "Teller states he would do most anything to see subject separated from GAC."

Two weeks later Teller spoke to the FBI again. To his earlier remarks he added, "In his youth Oppenheimer was troubled with some sort of physical or mental attacks which may have permanently affected him. He has also had great ambitions in science and realizes that he is not as great a physicist as he would like to be." Still insisting that he did not consider Oppenheimer "in any way disloyal," Teller asked that the interview not be disseminated to his fellow scientists because it "could prove very embarrassing to him personally" and, worse, "make his position in H-bomb program untenable."

The FBI interviewer got the point. He noted at the end of the interview that "considerable damage could occur to the program should it become necessary for Teller to sever his connections." The FBI held the interview so tightly that former colleagues of Teller's, including Bethe, to whom I showed it in 1986, said with surprise that they had not known of it before. The FBI did send the interview to the White House. Whether Truman read it is not known. He did not, however, reappoint Oppenheimer to the GAC.

Meanwhile Oppenheimer had harsher concerns. It was the height of the McCarthy era, and he had become a marked man because of his opposition to the second laboratory and the crash program and because he had dared to oppose the Air Force in other matters. Left-wing associations he had had during the 1930's and 1940's rendered him vulnerable. In closed-door hearings ordered by President Dwight D. Eisenhower in 1954, he lost his security clearance, and the country lost the services of its principal scientific counselor.

In their chapter defending Teller's role in the Oppenheimer case, a chapter titled "Dark Duty," Blumberg and Panos emphasize that Teller made his appearance as a prosecution witness only with reluctance. Teller did indeed testify with what appeared to be soul-searching and in the belief that his testimony and that of the other witnesses would remain secret. Asked whether he considered Oppenheimer disloyal, Teller told the prosecutor, "I do not want to suggest anything of the kind."

Teller added, however, that he had often found Oppenheimer's actions "exceedingly hard to understand...confused and complicated...I would like to see the vital interests of this country in hands which I understand better and therefore trust more." Teller concluded, "I would feel personally more secure if public matters would rest in other hands."

For these words, which became known two months later when the government broke its promise and published the hearings, Teller overnight found himself a pariah among his colleagues. Some would not speak to him for many years. Yet his testimony was the least of the damage he did Oppenheimer. Phrases he had used in his 1952 FBI denunciation were lifted by the prosecution and appeared verbatim in the government's formal charges. Of the seven witnesses, besides Teller, who testified against Oppenheimer, William L. Borden, a former Senate aide, and David T. Griggs, former science adviser to the Air Force, were close to Teller. Three others, Luis Alvarez, Kenneth Pitzer and Wendell Latimer, admitted that on key points in their testimony, Teller had been a source of information.

In fact, recently declassified letters and memoranda show that Teller had long speculated about Oppenheimer's motives with Borden, whose letter to the FBI saying that "more probably than not J. Robert Oppenheimer is an agent of the Soviet Union" led to the hearings. Teller also shared his speculations with Strauss, the current AEC chairman whose advice helped to shape President Eisenhower's response to the Borden letter. Although Teller, Borden and Strauss each disliked Oppenheimer for his own reasons, each had been feeding the others' suspicions for years.

Teller acted for years as though his secret 1952 FBI interview did not exist. He had not forgotten, however. On June 19, 1977, aware that Freedom of Information Act requests would soon open government files to the public, he wrote to the FBI asking that the "document be clarified" to show it had been the FBI, not Teller, who initiated the interview. He also requested that the reference that Oppenheimer "be separated from the GAC" either be deleted or an explanation added that the statement had appeared out of context.

Yet Teller's current biographers apparently do not know about the 1952 interview, since they say that "Teller was not involved in the years-long investigation of Oppenheimer" and "was never asked his opinion of Oppenheimer's loyalty until...the hearing." Their book contains other errors and omissions. To cite a few:

- The upstairs neighbor who was kept awake by Teller's nocturnal piano playing at Los Alamos was not Henry DeWolf Smyth, who was in Princeton, N.J., throughout the war, but Cyril S. Smith and his wife, Alice.
- The authors repeat Teller's contention that little theoretical work was done on the H-bomb between 1946 and 1949 and say that "development of the bomb was retarded by Hans Bethe's ultimate

decision to withhold his services." In a 1954 paper, "A Short Account of Los Alamos Theoretical Work on Thermonuclear Weapons, 1946–1950," released in 1974, Mark, head of the theoretical division, lays out step by step the impressive work done on the Super during the years in question, some by Teller himself. Mark also notes that Bethe came to Los Alamos to consult on both fission and thermonuclear problems every year from 1946 to 1951 and to work on the thermonuclear weapon for eight months starting in January, 1952, and again for three months in 1953.

• On another point of contention, that of Teller's insistence that the H-bomb could have been tested sooner had it not been for slowness at Los Alamos, Mark shows that the complex calculations for the first test of the Ulam-Teller concept could not have been done earlier because of the lack of computer capacity. Blumberg and Panos do not appear to be aware of Mark's evidence.

• The authors say that Teller's famous "It's a boy!" telegram signaling thermonuclear success was sent from Eniwetok following the Greenhouse "George" test of May, 1951. It was actually sent from Berkeley after the Mike shot of November 1, 1952.

• Blumberg and Panos repeat Teller's claim that the Soviets tested their first deliverable H-bomb in August, 1953, almost a year before the U.S. Yet both Herbert F. York, in his 1976 book, *Advisors: Oppenheimer, Teller and the Superbomb,* and Andrei D. Sakharov, in his memoirs, to be published later this year, say that the Soviet Union tested its first deliverable H-bomb in November, 1955, a year and a half after the U.S.

• The book states that in October, 1987, Sakharov "publicly acknowledged" Klaus Fuchs's contributions to the Soviet atomic and hydrogen bomb programs. Americans who were close to Sakharov say he never acknowledged any contribution by Fuchs to the Soviet hydrogen bomb and never spoke of Fuchs in public.

For all its omissions and its towering errors, the book has one great virtue: it gives us Teller as he really is. This is a man who is always arguing, whose point of reference is always himself and who insists that on every issue of his contentious career, he has been right and his critics wrong. Since these issues include Teller's belief in the absolute evil of the Evil Empire and the power of nuclear weapons to do good, the book that truly engages Teller will be taking on some of the greatest issues of our time. That book has yet to be written.

The weighty matter of the invisible universe

by Philip Morrison

THE FIFTH ESSENCE: THE SEARCH FOR DARK MATTER IN THE UNIVERSE, by Lawrence M. Krauss. Basic Books, Inc., Publishers, 1989 ($21.95).

The old thinkers on the order of nature were fond of the idea that there was a quintessence, a fifth element beyond earth, air, fire and water that lay within matter and the void. In this smoothly written and disarming survey, a Yale theoretical physicist and cosmologist has undertaken to show the general reader why in our time too we seek another ether—the "dark matter" in the cosmos—that is invisible, intangible and yet ponderable.

The tools of this agreeably intricate search are diverse. Dark pools of water deep underground are unsleepingly watched by computers. Supercomputer simulations mimic the growth of gravitating galaxies. Telescopes peer from mountaintop and orbit in space, and the razor-sharp arguments of quantum field theories test slippery assumptions.

The first clue that there was more to the universe than meets the eye was thermal background radiation. Dominating all other radiation in energy, it is utterly uniform in all directions, everywhere textbook-simple of spectrum. We believe it the redshifted glow of the universal hot plasma from which all our lumpy world of stars and galaxies condensed.

Then there was the check weighing of galaxies, done on large scale by studying the motions of the glowing matter we do see. However dark it is, the new matter must have weight, so it would tug at the ordinary luminous stuff. The astronomers measured even the great clusters of galaxies and declared "short weight" on every scale.

Enter Alan H. Guth, a young particle physicist. He showed in 1981 that one simple if extraordinary process built into the familiar equations of Einstein could explain quite naturally all the puzzles. His idea forecast an excess cosmic density of matter, although five or 10 times more than observations revealed. You would also have to accept a daring idea: everything we see so far is but a small part of a much greater domain, and yet once upon a time all of it had been con-

tained within a very small region, to be "inflated," flung out pell-mell far toward infinity.

Guth's picture holds together, provided that there is enough dark stuff and that it is disdainfully incapable of interaction, except through gravity, with ordinary matter. The density expected is very low, a millionth of the density of gas around us in the Milky Way. So extensive is dark space that so dilute a gas, if only it be universal, can outweigh by tenfold all of our commonplace kind of matter.

The surprise is that there are quite a few candidate particles. Krauss tells of the likeliest. To start with there is the long-known neutrino. But its candidacy is faulted; in spite of many claims, it does not possess the essential property of moving slowly enough, a fact emphasized by the amazing arrival of 19 neutrinos in a dead heat at light speed from the remote explosion of the supernova 1987A. Nearly all the other candidates are not known to exist; they were born of plausible postulates proposed to explain the symmetries—and the failures of symmetry—that appear in the search for a consistent unification of forces.

A skeptic can well hold that the existence of all such particles are long shots, mere consequences of the simplicity of initial explanations. Yet the proposals are entitled to a hearing, although one ought to recall that proton decay just as plausibly predicted by the simplest grand high-energy theory of all did fail the test of experiment, early in this decade.

The author saves his favorite idea—the "axion radio"—for last. An axion is a low-mass particle proposed on quite elaborate theoretical grounds, "a very pretty construct" indeed. It should interact ever so weakly with photons. Through the possibility of coherent buildup of that interaction within a steady magnetic field, some passing axion of the background can convert into a real photon to be caught in a tuned microwave cavity. One initial experiment is now at work searching the range of frequency that matches the best guess for the mass of the axion.

The book spins out a tale in physics so tall that it would have been hard to accept even 20 years ago. By now it has somehow become, if not yet compelling then credible, at least at the margin. The chief arguments are explicitly reviewed in the book, not passed off by mere appeal to mathematical authority, so that a lot of thinking is demanded. There are many helpful diagrams and not one equation. Readers will find plenty to ponder in this readable volume, fuller than any other popular account.

ESSAY

Time to unshackle U.S. competitive strengths

by Richard J. Mahoney

No other country invests more in research than America does. But others have gotten better at applying new knowledge—some of it our own—and at moving it quickly from the laboratory to the global marketplace. In fact, when it comes to global competitiveness, we may have become our own worst enemy.

In 1989 six high-technology industries were among America's leaders in establishing positive balances in foreign trade. These industries—computers, aerospace, agricultural commodities, chemicals, pharmaceuticals and scientific equipment—together generated a net trade surplus of almost $60 billion, up 14 percent from 1988. Without those industries, the U.S. merchandise trade deficit of $109 billion in 1989 would have been 54 percent worse. The common strength of the six industries is their base of high-technology and scientific know-how.

Yet the global competitiveness of these trade-positive industries is hampered by barriers erected right here in the U.S. My own experience at Monsanto, a company that cuts across several of these industries, has made that painfully clear. There are at least four significant obstacles: the liability crisis in our courts, which discourages bringing new products to market; a regulatory system that slows commercialization of technology; the high cost of capital in this country; and high-technology piracy.

Consider first the liability crisis. In recent years the number of successful multimillion-dollar product-liability suits has grown significantly. They have become an unpredictable wild card that dampens innovation. My own company, for example, invented and developed a safe substitute for asbestos. We abandoned it just before commercialization because we were convinced that a whole generation of lawyers trained in asbestos litigation would see our product as their next opportunity.

Our story is not unusual but typical. A 1988 survey of chief executive officers by the Conference Board showed that uncertainty about potential liability had led almost 40 percent of them to withhold new products, including beneficial drugs and lifesaving technology. For the same reason, nearly 50 percent of them had discontinued existing product lines.

Make no mistake. I do not argue that companies should not be responsible for the consequences of injuries caused by negligence or manufacturing defects, including medical expenses and lost income. But many recent product-liability suits have resulted in astronomical judgments that bear no connection to the extent of harm or to a firm's actual responsibility. These judgments make liability insurance extremely costly or even unavailable, interfere with strategic planning and curb R&D spending and innovation. In the end, society suffers. Other countries are not burdened by comparable liability "baggage" in their home market, which is where you build strength for competing in the international arena. New state and federal legislation is needed to correct this situation.

Research and innovation are also hampered by our system for approving new products. U.S. industries must continue to invest in new research if they are to remain competitive in global markets, and to make that research pay off, they must be able to respond promptly to new opportunities. For some of its relative slowness, American industry undoubtedly can blame only itself. Often, though, the U.S. regulatory system has contributed as well.

When, for example, it takes two or three times longer for U.S. government agencies to approve a new drug than it takes agencies in other industrialized countries, our industry is at a disadvantage, as are the consumers who would benefit from the drug.

It is rare for someone in my position to call for an increase in the size of government. But when products languish in regulatory review because of inadequate resources, it is time to budget additional funds for the agencies involved. Those agencies are also weakened by the increasingly emotional public atmosphere surrounding matters that should be decided on their scientific merits by regulatory experts. To market products successfully, industry needs solid, adequately staffed regulatory review agencies that command the public trust.

A third hindrance to research is the high cost of capital for R&D. Industries that market their products successfully need to invest extensively in technology. To do so, U.S. industries pay a heavy price: a cost of capital that can be twice what it is for their major world competitors. The 1988 rate of return required to cover financing for R&D projects here was a staggering 20.3 percent, according to a study by the Federal Reserve Bank of New York. This compares with 8.7 percent for R&D projects in Japan and 14.8 percent in West Germany—and the differential is expected to continue because of relative savings rates and financing practices.

This means $1 spent on R&D in the U.S. must generate over $6 in 10 years, or more than $40 in 20 years, just to break even. For many products, R&D is so expensive today that it cannot be justified without tapping into global markets. The U.S. market is clearly not big enough to provide an adequate return when it can cost up to $125 million or more in R&D alone to create some new products.

When American industry does spend the money to create new products, it faces yet another problem: the danger of high-technology piracy. According to the U.S. International Trade Commission, in 1986 American industries lost between $43 billion and $61 billion in sales from the illicit copying of U.S. inventions. Inadequate protection abroad of our patents, copyrights, trademarks and trade secrets makes possible this piracy of our R&D investments.

In some cases it is not the absence of laws that is responsible for the piracy, it is the laws themselves. In Brazil, for example, Monsanto was forced to license one of its important herbicides to a local competitor who paid virtually nothing for this valuable right. Such laws and regulations are so onerous in India that we have declined to introduce some products there, and some other firms do not market in that country for similar reasons. The General Agreement on Tariffs and Trade offers the opportunity for an answer to the piracy problem: an international code of effective laws and enforcement.

None of these problems is beyond our reach. Solving them will create an environment that encourages even more high-technology research and development. Further, it will strengthen America's competitive advantage. That not only will be good for our trade-positive industries but also will swell the ranks of industries showing a trade surplus. Solving these problems merits a high priority on our national agenda.

RICHARD J. MAHONEY is chairman and chief executive officer of the Monsanto Company.

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