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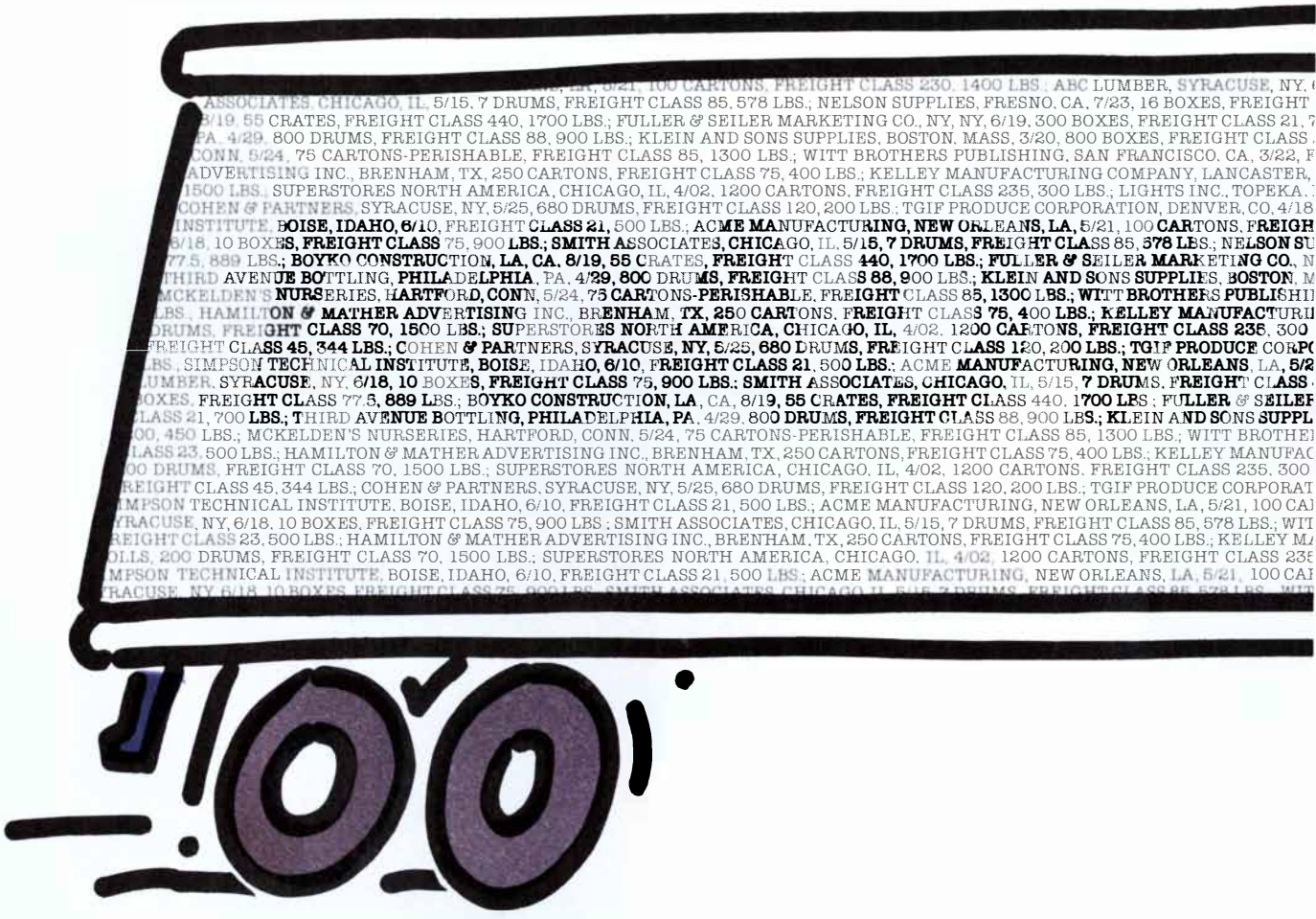

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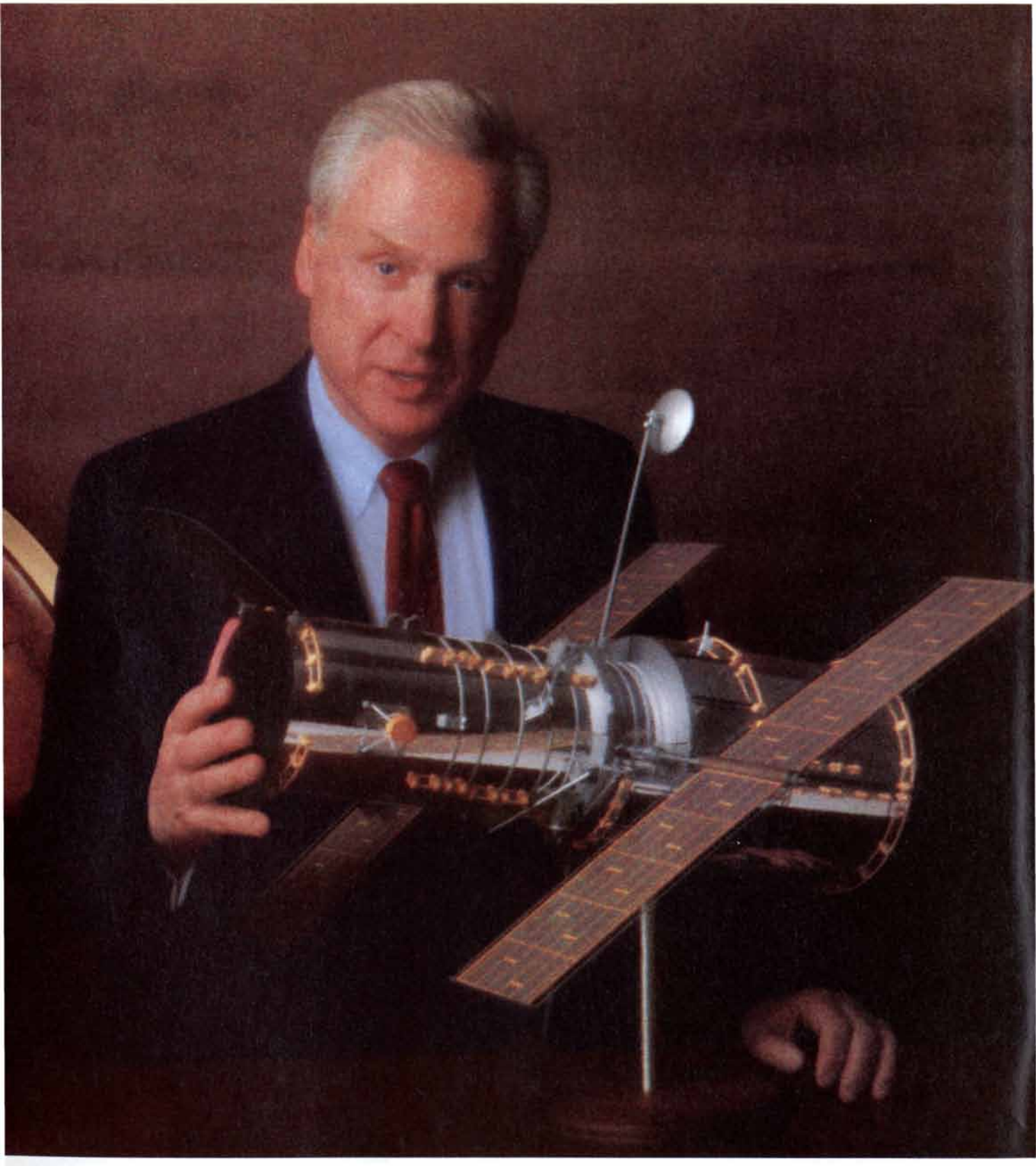

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Not since Columbus sailed to the edge of the world has discovery loomed so close on the horizon. But now, Hughes Aircraft Company has a telescope that's so far-reaching, it could help NASA change the course of history.

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First up is the Hubble Space Telescope, the world's first complete space observatory. It is the greatest leap in astronomy since Galileo first gazed into a telescope in 1609.

No telescope has ever been this precise. Its eight-foot primary mirror is smooth to within a half-a-millionth of an inch. And its fine guidance system can lock onto a hummingbird 1500 miles away.

Both are part of Hubble's Optical Telescope Assembly, designed and developed by Hughes Danbury Optical Systems, formerly part of Perkin-Elmer and now a subsidiary of Hughes Aircraft Company.

Orbiting high above the earth's atmosphere, the Hubble Space Telescope will have a clear view of the universe. Seven times as far as the world's largest telescopes. 50 times as sensitive. And infinitely more revealing.

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Near the beginning of time.

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The Hubble Space Telescope, which will open the window to the universe, is the first of NASA's Great Observatory programs.

Soon NASA will also launch the Advanced X-ray Astrophysical Facility (AXAF). At the heart of this mission is an x-ray telescope system now being developed by Hughes Danbury Optical Systems. It will reveal light patterns in outer space that optical telescopes can't see. And it could help us uncover the secrets of "black holes," perhaps the key to understanding how the universe was formed.

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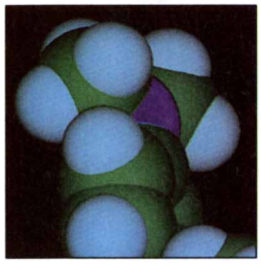
Hughes' Currie with model of Hubble Space Telescope.

SCIENTIFIC AMERICAN

June 1990 Volume 262 Number 6

42 

RU 486
André Ulmann, Georges Teutsch and Daniel Philibert

Most drugmakers stay out of reproductive research. The development of new contraceptives is costly, the reward slight and the risk of controversy great. France's Roussel-Uclaf was no exception. But its work on synthetic steroids turned up an unexpected result: a compound that can safely terminate pregnancy by inhibiting progesterone. Here is the investigators' own story.

50 

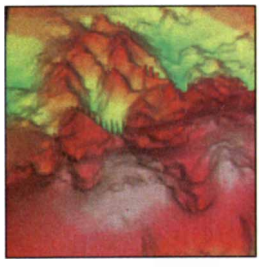
Pluto
Richard Binzel

Astronomers have finally pierced the veil that has surrounded the ninth planet since it was first sighted 60 years ago. They find a frigid, rocky world with bright polar caps, a surface of frozen methane and a huge moon covered with ice. Yet many questions will remain unanswered as long as Pluto continues to be the only planet not visited by a scientific spacecraft.

60 

Biosonar and Neural Computation in Bats
Nobuo Suga

With an ease that would be the envy of any fighter pilot, bats use reflected sound to track and capture prey. An investigation of their complex and highly developed echolocating skill opens the way to a deep understanding of how the central nervous system processes auditory signals—and how it extracts a wealth of information from them.

72 

The Mid-Ocean Ridge
Kenneth C. Macdonald and Paul J. Fox

The Mid-Ocean Ridge girdles the earth like the seam of a baseball. For more than 75,000 kilometers, this submerged range of razorback mountains—many higher than the greatest peaks on land—marks the restless boundary between continental plates. An analysis of this huge structure reveals a fascinating picture of how it is created by magma welling up as the plates pull apart.

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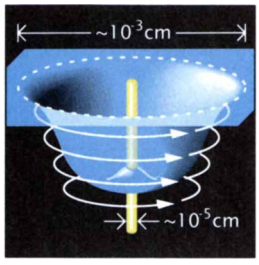
SCIENCE IN PICTURES

Frogfishes
Theodore W. Pietsch and David B. Grobecker

Beautifully camouflaged as rock, coral or some other feature of the aquatic landscape, these sedentary superpredators display a modified fin that acts as a lure. When the prey is within range, they engulf the meal in milliseconds.

Scientific American (ISSN 0036-8733), published monthly by Scientific American, Inc., 415 Madison Avenue, New York, N.Y. 10017. Second-class postage paid at New York, N.Y., and at additional mailing offices. Authorized as second-class mail by the Post Office Department, Ottawa, Canada, and for payment of postage in cash. Subscription rates: one year $27, two years $48, three years $66 (outside U.S. and possessions add $11 per year for postage). Subscription inquiries: U.S. only 800-333-1199; other 515-247-7631. Postmaster: Send address changes to Scientific American, Box 3187, Harlan, Iowa 51593.

104 

The ^{3}He Superfluids
Olli V. Lounasmaa and George Pickett

Physicists despair at re-creating the tremendous temperatures that prevailed at the moment of the big bang. But near the low end of the scale they routinely outdo nature. At temperatures colder than any occurring normally in the universe, matter behaves strangely. Helium 3, for example, becomes superfluid. Its properties may provide insight into conditions at the core of a star.

112 

Sustainable Agriculture
John P. Reganold, Robert I. Papendick and James F. Parr

Chemical-intensive, fossil fuel–dependent farming made U.S. agriculture the most productive in the world. The price: polluted water, barren soil and economic vulnerability. Growing numbers of farmers are now turning to practices that aim for a "sustainable agriculture." They are profitably applying such techniques as crop rotation, biological pest control and natural fertilization.

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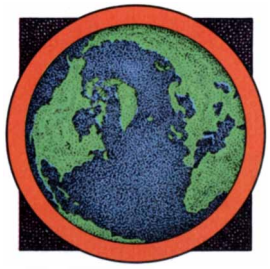
Oliver Heaviside
Paul J. Nahin

Every time you talk on the telephone, you benefit from the work of this forgotten Victorian genius. A brilliant, self-taught mathematician, he held only one job—that of a telegraph operator—and quit at 24. He then clarified Maxwell's electromagnetic theory, invented a device that makes long-distance telephony possible and became the first to use vectors to describe forces.

DEPARTMENTS

17 

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Essay: *Ralph Gomory*
IBM's former technology leader on the right way to look at innovation.

Bill Rice, the bug, the plow, and the Lands' End Interlochen Knit Shirt

Bill Rice, ready to meet the President in his favorite Interlochen Knit Shirt.

There wasn't much moving on that shimmering hot summer day not long ago, on a West Texas ranch. Just a skittish lizard, here and there. And a tractor, plowing the fields, driven by a man named Bill Rice.

Now, summertime and bugs seem to go together like bacon and eggs. So it wasn't surprising that pretty soon, a bug crawled down into the Lands' End Interlochen Knit Shirt that Bill happened to be wearing that day.

(While we have gotten pretty well acquainted with Bill Rice, we can't tell you anything about this bug, whether it was a brave bug or an ornery bug, a wise old bug or a foolish young bug. It disappeared without giving any interviews.)

Anyway, we'll let Bill tell you what happened at this point, in his own words.

"There wasn't room for me and the bug, so I yanked the shirt off and just hung it on the back of my tractor.

"Well, to make a long story short, the shirt fell down and I accidentally plowed it under. After I plowed it back up and threw it in the washing machine, it was still as good as new. Now that's a well-made shirt."

A shirt good enough to meet the President.

At this point in the story, as Bill talked to us, he began to warm to the topic of our Interlochen Knit Shirts.

"I wear them everywhere I go. Working out here on the ranch, and going into town too."

Bill says it's the comfort of the shirt that's got him sold. Along with the way it looks. (He owns six of the shirts he's pictured in here!)

"If I was going to meet the President," says Bill with a twinkle in his blue eyes, "I'd wear this shirt."

What's so special about our Interlochen Knit?

As its name somewhat prosaically implies, it's knit with an "interlocking" stitch to create a fabric that is especially lofty and plush. Of pure combed cotton, no less, for surpassing softness next to the skin.

In one of our more exuberant moments, we once declared that our Interlochen Knit Shirt is absolutely "COTTON BALL SOFT!"

More unusual than the knit fabric itself is the fact that our Interlochen is even tailored with a soft touch. The collar is taped, the shoulder and armhole seams neatly single-needle stitched, the placket smoothly finished inside—all so no rough edges of fabric ever come between you and the softness of our Interlochen.

Why take such pains with a simple knit shirt? For the same reason we add extra features to our Oxford Shirts, our Corduroy Pants, our Canvas Attaches:

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THE COVER painting depicts a cutaway view of a rotating container of superfluid helium. Quantum-mechanical laws prevent the liquid from rotating as a whole; instead an array of miniature whirlpools perforates its surface. The rare isotope ^{3}He, which becomes superfluid only at millikelvin temperatures, forms four distinct types of vortices (see "The ^{3}He Superfluids," by Olli V. Lounasmaa and George Pickett, page 104).

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Cover painting by George V. Kelvin

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98	Allan Hancock Foundation, Hancock Library of Biology and Oceanography, University of Southern California (*top left and middle; bottom middle and right*), Museum of Victoria, Melbourne (*top right*), British Museum of Natural History (*bottom left*)
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New York, NY 10017
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LETTERS

To the Editors:

It was timely to feature an article on the mysterious halo surrounding the shuttle at night. I have reason to believe, however, that "Shuttle Glow," by Donald E. Hunton [SCIENTIFIC AMERICAN, November, 1989], has confused many of your readers.

The greatest harm was done by the title, because much of the article was dedicated to spacecraft surface erosion instead of shuttle glow. Surface erosion is caused by chemical reactions between atmospheric atomic oxygen (O) and the surface materials. Spacecraft glow, in contrast, is a reaction between atmospheric gases in which the surface acts only as a catalyst. Although the article does not explicitly state that the two phenomena are closely related, several passages in the article imply that there is a connection between them.

Perhaps the most outstanding error is the repeated discussion of nitric oxide (NO) as having a spectrum similar to the observed, visible shuttle glow. There are no significant NO emissions in the visible spectrum. According to current understanding, most of the glow emission is produced by excited gaseous nitrogen dioxide (NO_2), and NO is only a precursor for the glow process. NO forms on the outer surfaces of a spacecraft and remains absorbed there until it is bombarded by O. In gas-phase chemistry, NO reacts with O in the presence of a third body to form excited NO_2, which emits a red glow.

NO can readily form on surfaces of the spacecraft in the presence of atmospheric atomic nitrogen (N) and O. N is also available from atom-exchange reactions in the plow cloud surrounding the spacecraft. The surface dissociation of molecular nitrogen, which Hunton mentioned in the article, is not currently believed to be a workable process for forming N.

If the surface of the spacecraft is cold, then the adsorption of NO onto the surface is enhanced, which leads to increased NO_2 production and therefore a brighter glow. The article credits me with having proposed this idea, but it was my colleague at the Lockheed Palo Alto Research Laboratory, Dr. Gary Swenson, who first drew attention to the fact that the surface temperature might be more important than the surface material.

In the discussion of future experiments, Hunton refers to a "NASA experiment to be carried out by Leger's group at the Johnson Space Center." This is presumably the Experimental Investigation of Spacecraft Glow, which is a collaborative program under the sponsorship of Dr. Lubert J. Leger's group at the Johnson Space Center. A large part of the work, however, is to be performed at the Lockheed Palo Alto Research Laboratory by Dr. Swenson, as the principal investigator, and my Atmospheric Emission group.

STEPHEN B. MENDE

Space Sciences Laboratory
Lockheed Missiles
& Space Company, Inc.
Palo Alto, Calif.

The author responds:

I thank Dr. Mende for his comments and corrections. Mende and Dr. Swenson have worked together on shuttle glow and are co-authors of numerous publications. For simplicity, I chose to refer to their work collectively under Mende's name. No slight was intended to Swenson in my discussions of the mechanisms for shuttle glow or of the planned experiment sponsored by NASA. I apologize for any offense.

The focus of my article was interactions between the shuttle and the atmosphere. Glow and erosion are related to each other in that both phenomena are caused by the impact of the reactive atmosphere on shuttle surfaces. For this reason, I feel it is legitimate to discuss them in a single article. The article itself clearly draws distinctions between the two phenomena.

Finally, NO has been suggested in the scientific literature as a possible source of shuttle glow in nonvisible regions of the spectrum, although this idea has not been proved. As Mende asserts, however, it was incorrect to say that NO contributes to the visible glow.

DONALD E. HUNTON

Geophysics Laboratory
Hanscom Air Force Base
Bedford, Mass.

To the Editors:

"The Analytical Economist" states that "'In God We Trust' is imprinted on all U.S. currency" ["Science and Business," SCIENTIFIC AMERICAN, January]. In fact, the phrase is missing from the $500 and $1,000 bills, series 1934, as well as from larger denomination bills. Is it not peculiar that the motto is reserved for those bills that the public handles and is missing from those that the Federal Reserve "handles"? Should we petition Congress to engrave large bills with "In the Fed We Trust"?

EDWARD C. TIPSHUS

Worthington Hills, Ohio

***The Analytical Economist** responds:*

"In God We Trust" has graced new currency since the U.S. Congress authorized the use of the phrase on money in 1955. Precisely why Congress endorsed putting the motto on currency is harder to pin down. Federal Reserve notes once promised to "pay bearer on demand" while also stating: "This note is legal tender for all debts, public and private, and is redeemable in lawful money at the United States Treasury, or at any Federal Reserve Bank."

In 1933 Congress decided that paper money could no longer be redeemed for gold; by 1968 those bills formerly redeemable in silver went out as well. (The government also quit printing denominations larger than $100 in the 1960's.) Now bills only claim to be "legal tender for all debts, public and private." Perhaps Congress has more faith in heaven than in the banks.

ERRATA

In "The Variable Sun," by Peter V. Foukal [SCIENTIFIC AMERICAN, February], the figure on page 40 states that nitrous oxide (N_2O) absorbs extreme ultraviolet radiation in the upper atmosphere. It is actually molecular nitrogen and atomic oxygen that absorb this radiation. N_2O plays almost no role in screening out solar radiation of any wavelength. Also, representatives of the Toronto Stock Exchange report that the failure of the exchange's computer systems during the summer of 1989 was caused by an equipment malfunction and not by solar activity, as asserted in the article.

"Slow Boat to Mars" ["Science and the Citizen," SCIENTIFIC AMERICAN, April] erroneously implied that in the judgment of the National Research Council, NASA's proposal for a manned Mars mission "underestimates engineering and operational challenges." The council found several weaknesses in NASA's plan but reserved the harsher verdict for the separate plan advanced by workers at the Lawrence Livermore National Laboratory.

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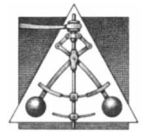


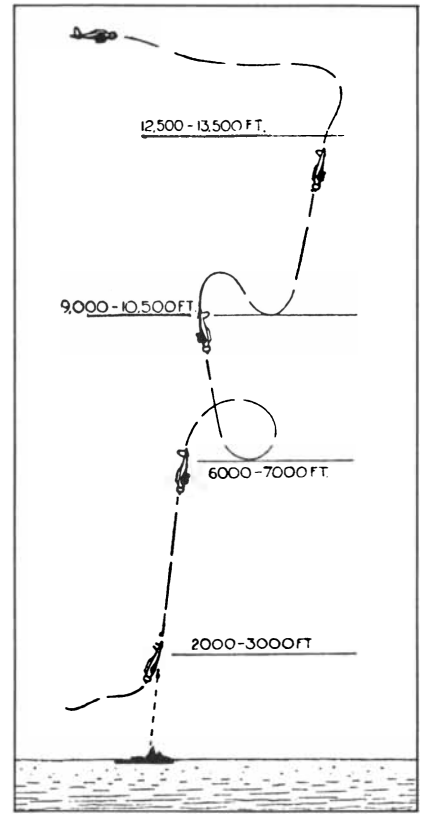
JUNE, 1940: "One day there is a majestic forest of whispering pines, a wealth of scenic beauty as well as of timber. An infestation of bark beetles moves in, and in a few weeks many of the trees are dead; in some areas a whole forest of pines will become white, lifeless ghosts. Pine bark beetles are not alien enemies that have slipped into our forests, unchecked by natural enemies. They are a native menace. For centuries bark beetles have periodically laid waste to pine forests, and in about 150 years a new forest would take the place of dead trees. Such is Nature's deliberate and protracted plan. The destruction of great trees in their prime may suit Nature's plan, but it is disastrous to men; they cannot wait 150 years for the natural replacement of the bark beetles' undoing."

"The average person thinks of the X-ray as a medical tool. During the last four years this tool has made another important place for itself, this time in the food industry. The processors and packers of many types of food products have developed in recent years screens, sieves, magnetic separators, and have applied photoelectric cells to the job of removing foreign objects from all kinds of foods, but fluoroscopic inspection has proved to be superior to them all in some respects. The X-ray does more than detect impurities; in one case, three fluoroscopes, costing a total of $10,000, gave a saving of $60,000 when a large quantity of oranges scheduled for destruction were found to be undamaged by freezing."

"Pollen analysis is still new, relatively unknown, and not as well substantiated as tree-ring analysis. However, it does hold promise of adding to our knowledge of changing climatic conditions. Analysis of a vertical series of samples from pollen-containing peat makes it possible to trace the history of the succession of different kinds of trees composing the neighboring forests from the time when the bog was established. Though seemingly a fragile substance, pollen possesses an exceptionally durable outer coat. This outer coat, or wall, is characteristically marked; sculptured, punctured, crossed with bands or spined like a sea urchin. The pollen of forests is readily separable down to genera, and occasionally even to species."

"In these parlous times we must perforce be interested in such gentle arts as dive bombing. The German attack on Poland showed the value of the method in attacking tanks, and generally in support of infantry. The speed of the dive increases the vertical velocity of the bomb so that its penetration is equal to that of a projectile released in level flight at a great altitude. Therefore, in spite of the fact that the dive bomber is peculiarly vulnerable to shell fire at low altitudes, dive bombing must remain a powerful aerial tactic."

JUNE, 1890: "Professor S. P. Langley has been investigating the nature of light emitted by the fire fly, using the spectroscope. He finds the light is substantially from the green side of the spectrum. It is of exceedingly narrow range of refrangibility, extending only from the F line to the C line, and culminating in the green, so that it contains no appreciable heat. The amount of heat yielded, as measured with Professor Langley's wonderfully delicate 'boloscope,' is less than one-half of one per cent of that given out with an equal amount of light from the candle and other common illuminants."



The gentle art of dive bombing

"Visitors to the British Museum frequently have a hard time getting 'acclimated' to the place. An hour spent in the rooms invariably gives the first-time visitor a headache. This curious malady is said to arise from the peculiar odor created by the storage of so many books. You can get some idea of what this odor is by going to your bookcase, that has been closed for twenty-four hours, and opening one of the doors; immediately your olfactories will be greeted by the mustiest fragrance imaginable. Bibliomaniacs profess to love this odor, and many declare that they cannot value a book unless it has about it that unmistakable and ineradicable smell which infects a volume when once it has crossed the sea in the hold of a vessel."

"The wonders of production are not confined alone to minerals dug from the earth's bosom, or to the organic life which flourishes upon its surface. Man's inventive skill has perfected the art of utilizing waste materials, so that the residue of former arts furnishes the substance upon which new workers expend their labor. The slag of furnaces for many years was dumped into ravines and piled upon vacant fields, but now it is being mined again, resmelted in some instances, made into asbestos or used in ballasting roads. Shutters and doors are made from wood pulp, blood is manufactured into door knobs, dust and dirt are transformed into multitudinous building materials, while the waste products of the gas house are more valuable, if possible, than the original substance."

"The *Building News* thinks there won't be any Channel tunnel ready for the holiday exodus of architects and students to the Continent this summer; but there seems some reason to believe that in days that have grown yet more evil, the tunnel will be commenced with serious intentions, be it ultimately finished or left incomplete. Of ideas and schemes there are plenty, not to mention the marvelous designs for blowing up or flooding a tunnel at a moment's notice—a fascinating subject to reflect upon, one would think, when in the bowels of the earth, midway between Calais and Dover!"

You can do business in Japan without shelling out a fortune.

For many companies, the biggest barrier to new markets has been the cost of business trips. Restaurants can be expensive, and even the smallest accommodations may carry oversized bills. Yet those willing to be a little adventurous will find that traveling comfortably in Japan doesn't require packing a suitcase full of yen.

Hop on the bus.

A $20 bus ride from Narita Airport may not strike you as a bargain, but compared to a $150 taxi, it is. The buses marked "Airport Limousine" stop at all the major hotels in Tokyo.

Sleep cheap.

Business hotels are a fairly new phenomenon. Catering primarily to Japanese businessmen, they're clean, functional, and conveniently located. Although vending machines replace amenities like room service, at $40 to $50 a night these hotels are a sound investment. Two major chains are the Tokyu Inn (tel. 03/406-0109) and the Washington (tel. 03/434-5211).

Food for naught.

It should come as no surprise that you'll save money eating where the locals eat. Good and reasonably priced restaurants can be found in department stores and the basements of office buildings. At lunch, ask for *teishoku*. It means special of the day, and includes rice, miso soup, salad, meat or fish, and dessert—all for around five dollars. *Ramenya* and *sobaya* (noodle shops) are perfect places for a quick and tasty meal.

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SCIENCE AND THE CITIZEN

Blood Feud

Researchers begin fighting back against animal-rights activists

This is not the treatment you expect at an academic conference. An armed guard exchanges nervous laughter with police watching the back entrance of this building at Texas Tech University in Lubbock. We are led briskly to a checkpoint where more guards and police stand by, and jumpy administrators scrutinize photo ID's.

But the topic at this March meeting is "The Siege by Animal-Rights Activists," and the scientists and administrators gathered here are frightened. Some members of the well-organized and well-funded animal-rights movement—now estimated to number a few hundred thousand—break into laboratories, destroy equipment and steal research data and animals. They threaten physical harm to individuals who conduct or condone animal research—and their families. They have made several recent attempts to carry out their threats.

Since 1981 animal activists have committed 71 illegal acts against research facilities, including the Texas Tech Health Sciences Center. Last July members of a group known as the Animal Liberation Front broke into the laboratory of physiologist John M. Orem. They vandalized equipment and personal records and "liberated" five cats. The damage was estimated at $50,000 to $70,000. Nationwide, estimates run as high as $10 million.

Enough is enough. Angry researchers are beginning the counterattack. Universities are stepping up security and putting in place crisis-management plans. Pro-research advertising campaigns are being launched. And scientists who once felt that debating the activists was beneath their dignity are taking media-training courses. It is time science confronted "the sleaziness of people who play on the public's lack of understanding," declares Frederick K. Goodwin, a psychiatrist who heads the Alcohol, Drug Abuse and Mental Health Administration.

Their adversary is no pushover. Animal activists know how to get media attention, how to pressure government officials and how to use laws to entangle their targets in paper webs. By some estimates, they will spend $50 million to oppose animal research this year. The movement took off in the U.S. in 1981, when Alex Pacheco, co-founder of People for the Ethical Treatment of Animals (PETA), gained employment in a monkey laboratory in Silver Spring, Md. Photographs he took there became the centerpiece of protests that led to a full NIH investigation and withdrawal of a researcher's grant. The events paved the way for a new Animal Welfare Act in 1985. Because the law tightened controls on animal use and heightened accountability, many researchers believed it would defuse the movement.

Peary revisited, an atomic fountain, a better boomerang, schizophrenia's mysteries

Instead the Animal Welfare Act was taken as an admission of guilt. Activists wielded it as a wedge, saying in a *Wall Street Journal* advertisement, "We've won the battle, now let's win the war." Today PETA is the largest animal-rights group in the country, with 250,000 members, a $7-million annual budget and a Washington headquarters staffed by 60 full-time employees. Its tactics have shifted with the audience and the times.

These days the kind and gentle approach is in. "Maybe animals are not inferior, just different," suggests Ingrid L. Newkirk, the organization's national director. "Perhaps we don't have the right to capture animals, take them from their homelands and slaughter them, just because we might get something out of it." PETA's goal is still the same as it was several years ago when a more strident Newkirk used such slogans as "A rat is a pig is a dog is a boy!" The mission is to stop all use of animals by society—not only as biomedical-research subjects but as food, clothing, sport and pets.

Most scientists concede that animal rightists brought beneficial changes early on, by encouraging more efficient use of animals and development of alternatives. But cultured cells and computers cannot substitute for the complexity of organ and immune systems. Animals are still needed for some kinds of research. "The vanguard of antivivisectionism has surrounded itself with right-minded people who wish to be kind and who have

***CHIMPANZEE** is fed by a researcher at the New York University Medical Center.*

Preying on Animal Research

Recent assaults by animal activists:

Jan. 15, 1990	University of Pennsylvania	Office break-in. Computer disks, personal files and a manuscript stolen
July 14, 1989	Texas Tech Health Sciences Center	Caused $50,000 to $70,000 in damage breaking into a researcher's lab and office. Stole five cats and research data; vandalized equipment
June 5, 1989	Avon	Two bomb threats caused evacuation of sales and distribution center
April 24, 1989	National Institutes of Health	Around 200 activists protest; 58 are arrested. Three await trial for assaulting an NIH guard
April 2, 1989	University of Arizona, Tucson	Break-ins at four buildings and fires set at two. More than 1,000 animals stolen. Damage estimated at $100,000
Feb. 21, 1989	University of California, Berkeley	Demonstrators attempt to halt construction of new animal research facility

Data: Foundation for Biomedical Research

been lured into supporting a movement against even careful use of rats and mice," notes Franklin Loew, dean of Tufts University School of Veterinary Medicine. Indeed, the focus of animal rightists' complaints has shifted, says John Miller, a veterinarian who is director of animal welfare at the National Institutes of Health's Office for Protection from Research Risks (OPRR). "Instead of filing allegations of filthy housing conditions or about some supposedly crazy investigator doing unmonitored, painful experiments," he says, "the activists now disagree over the scientific merits of research."

The OPRR investigates all claims of research abuse, from inside institutions and outside. Most, in fact, come from the institutions themselves. "We lose in any event," Miller says. "If we find substance, they take credit for doing our job—overseeing research. If we don't find substance, our reports are inevitably labeled as whitewash." For example, OPRR found no basis for any of PETA's charges of violations in Orem's Texas Tech laboratory. Now PETA is considering calling for a General Accounting Office investigation of the OPRR investigation.

The Animal Welfare Act enhanced institutional and public scrutiny as well as governmental. It requires institutions to establish Institutional Animal Care and Use Committees. These groups, which must include members of the public, consider the merit of every proposed experiment on animals and the validity of the protocols for carrying it out. Increasingly, the meetings themselves are open to public hearing. Newkirk and other animal activists claim these are nothing but rubber-stamp committees. Yet the activists make full use of the public's right to know, asking for and receiving copies of all research grants given federal funds.

Some of the federal agencies that fund biomedical research are toughening up on grantees, so that research is not abandoned out of fear of protest. Goodwin raised this issue at the Texas meeting. "Any university that returns a grant to our agency for reasons not related to science will have all its grants from the agency reviewed," announced the straight-backed, silver-haired psychiatrist. "If universities want to give in to pressure groups, they may no longer be eligible for funding from our agency." In addition, Goodwin's agency has put aside money for fellowships so that several selected scientists can travel around the country to explain how animals are useful in research.

The scientific backlash may also get some help from Congress. A bill that would make it a federal crime to steal, destroy or make unauthorized use of animals in federally funded laboratories has already passed the Senate. Another seeks to impose stiff penalties for breaking into research and agricultural facilities even if they are not federally funded. A third bill, which would protect primate and health facilities, should come to vote with the others this summer.

Scientists are also turning to the public for support. The Foundation for Biomedical Research (FBR), a public-education organization, has prepared a series of advertisements for television. One features former Surgeon General C. Everett Koop explaining what the *Physicians' Desk Reference* encyclopedia of pharmaceuticals is, as he rips out its pages. "Without animal research, this book would make very light reading," he says, holding up the tome's shell.

Around the country, researchers are staging counterdemonstrations against animal-rights protesters. The pro-research picket lines include not only faculty and students but often members of the Incurably Ill for Animal Research (IIFAR), a national organization headquartered in Chicago. "The debate will be won or lost at the local level," says Mary Brennan, the FBR's program director, who reports that 31 states have their own biomedical-research educational organizations in development.

All these moves, however, confront the carefully organized activities of the animal rightists, who are taking full advantage of the crumbling infrastructure of science education. PETA publishes *PETA Kids*, a magazine for elementary school children, and teaches "PETA 101" courses in large halls around the country. Other groups sponsor art and essay contests. Nine bills supported by animal-rights activists are pending; the bills would limit biomedical research to varying degrees.

So researchers are hoping that their efforts to expose the public to how and why science is done will not come as too little, too late. Animal rightists pleading for helpless animals and biomedical researchers trying to advance human health are both playing the same game. It's called the politics of compassion, says Larry Horton, associate vice president of Stanford University. Ultimately, the public will decide who wins. —*Deborah Erickson*

Hubble's Legacy

The space telescope launches a new era in astronomy

The most complex and expensive scientific instrument ever built is finally orbiting the earth and undergoing initial tests. The *Hubble Space Telescope*, which was carried into space by the shuttle on April 24, is "Big Science" epitomized. Built for more than $1.5 billion for the National Aeronautics and Space Administration, the telescope requires 290 technicians at the Goddard Space Flight Center just to monitor and control its operations. The telescope pushes technology to new limits. The 94.5-inch primary mirror has the smoothest surface of any mirror ever made, and its pointing system could center it on a dime 400 miles away.

Named after Edwin P. Hubble, the American astronomer who inferred the expansion of the universe from the redshifts of distant galaxies, the telescope had a difficult birth. Launch was originally scheduled for 1983 but was repeatedly delayed. In some ways the delays were fortunate: workers

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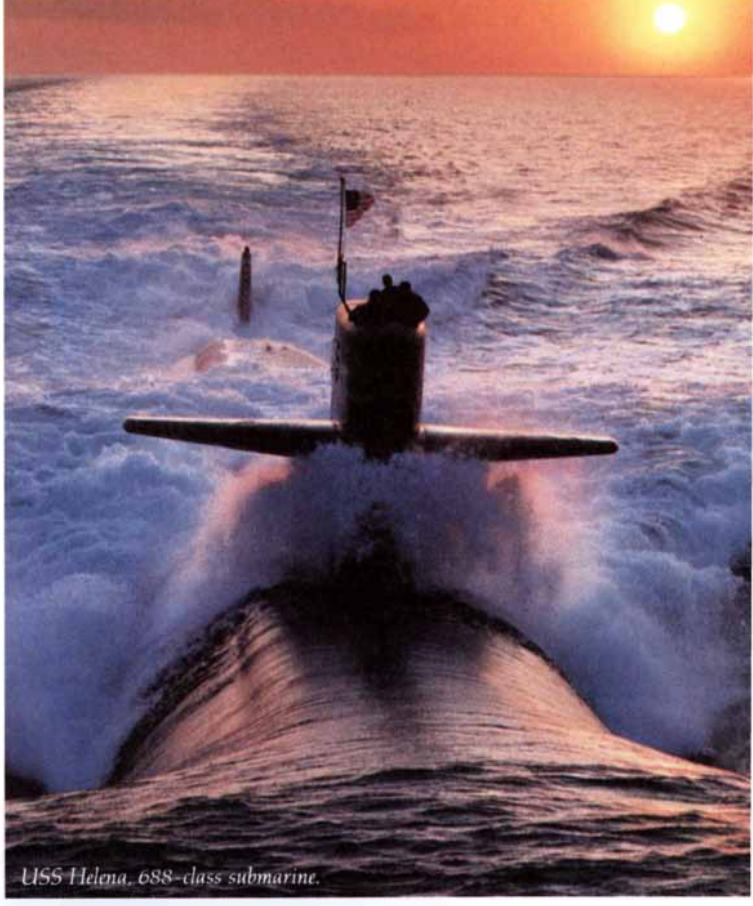

USS Helena, 688-class submarine.

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. In an astonishing adventure, she also became the first submarine to sail under the North Pole.

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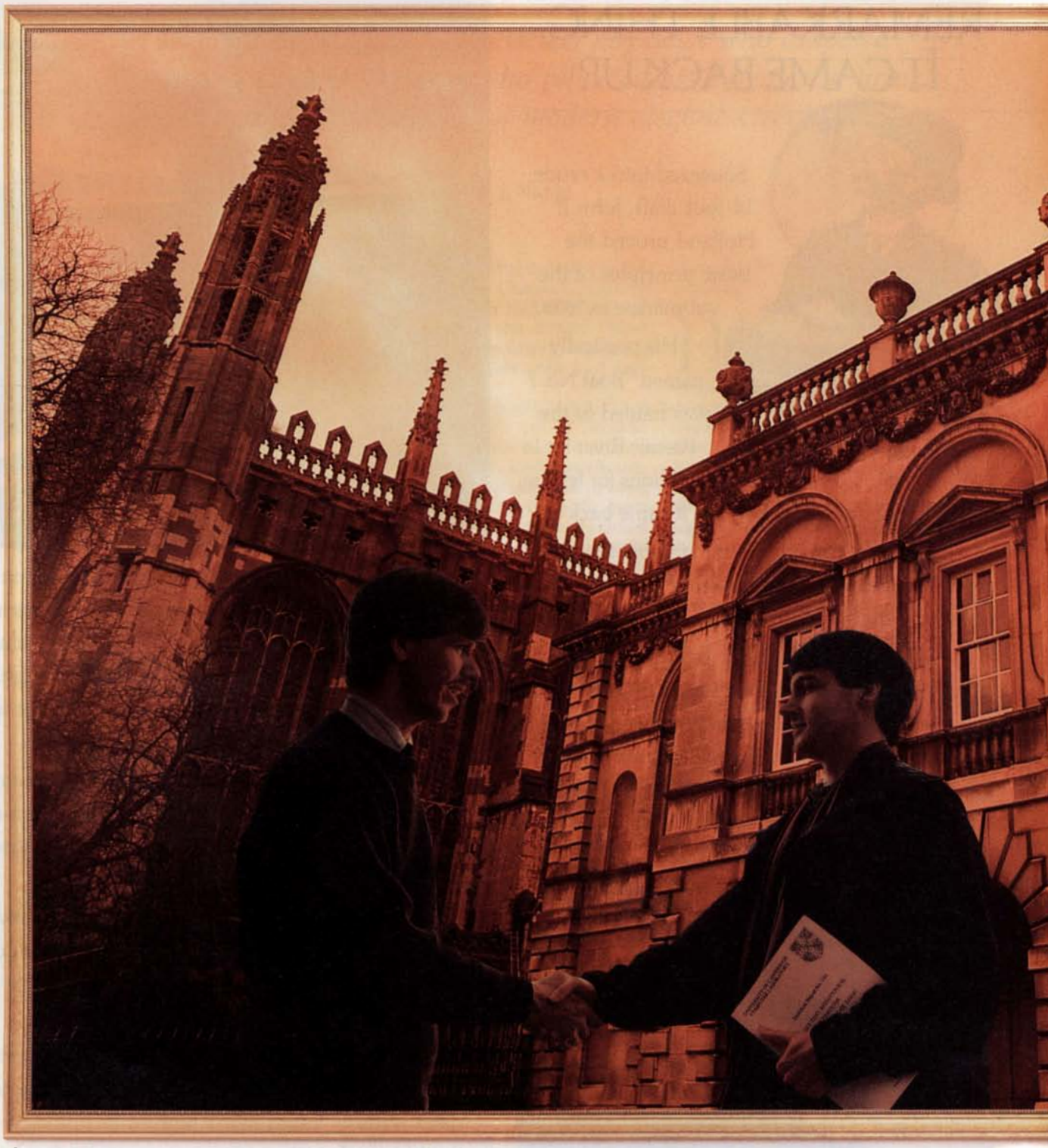

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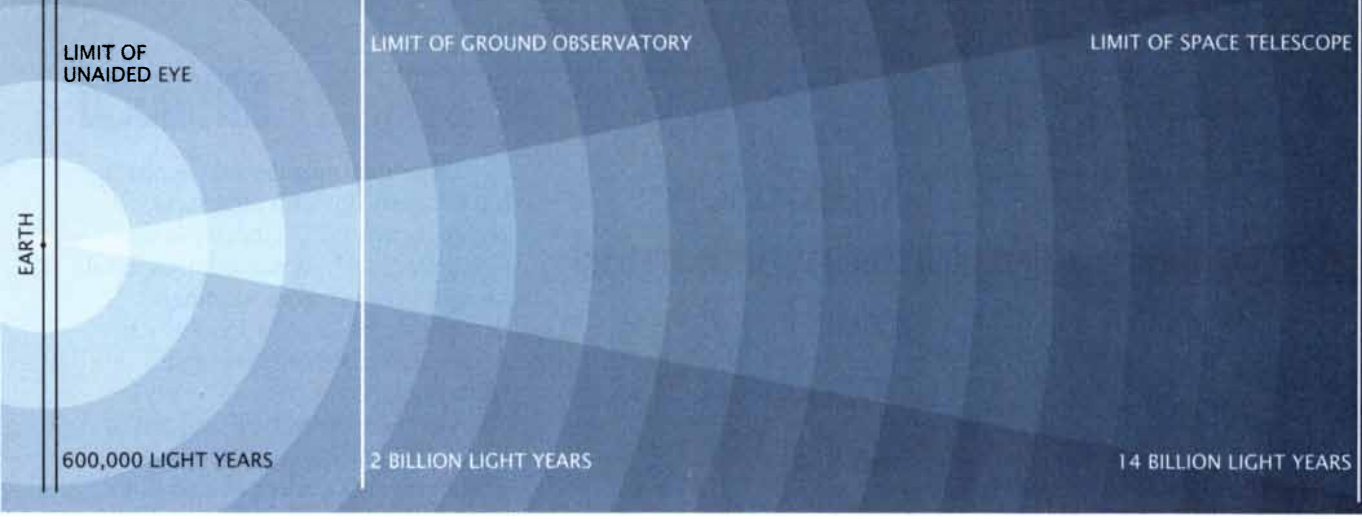


HUBBLE SPACE TELESCOPE *will allow astronomers to peer much farther into the universe than any ground-based observatories.*

used the time to make engineering improvements and to rewrite the software for pointing the telescope, which had been found to be faulty.

The technology of ground-based telescopes has certainly advanced since the space telescope was designed. The best telescopes today routinely achieve resolutions of about one arc second. Flexible, computer-controlled mirrors that compensate for atmospheric distortion can sometimes improve that figure to about .3 to .4 arc second. Nevertheless, the space telescope's principal camera, operating in the clear void of space, should be able routinely to reach a resolution of .05 arc second.

Moreover, the telescope will observe not only visible light but also ultraviolet emissions, which are blocked by the atmosphere. "To me the ultraviolet is the real gain," says Christopher Blades of the Space Telescope Science Institute in Baltimore, where astronomers will plan observations and process data from the telescope's five scientific instruments.

If the telescope performs as designed when normal observations begin this fall, it should shed light on some long-standing cosmic questions. One fundamental task is to measure the distances of galaxies more accurately by scanning them for the distinctive flicker of Cepheid variable stars. Because the intrinsic brightness of these stars is known, their apparent brightness provides a measure of their distance—and that of their parent galaxy.

These data should help narrow the range of values for the Hubble constant—the rate at which the universe expands. The number is now known only to within a factor of two, but Hubble's namesake telescope should fix the value to within 10 percent. A more precise value will indicate the age of the universe, now thought to be between 10 and 20 billion years.

In addition, observations of stars and of distant—and therefore young—galaxies should clarify how such celestial objects evolve. The data might reveal the role of black holes in the formation of galaxies and the nature of the very distant and energetic objects known as quasars. The telescope will also look for evidence of planets around nearby stars.

By measuring the velocity of very distant objects, the telescope may also determine how quickly the universe's expansion is slowing down. If the expansion is slowing sharply enough, then the universe will eventually collapse back into a "big crunch"; if not, it may go on expanding forever. "It could be part of Hubble's legacy to determine the fate of the universe," says Eric Chaisson of the telescope institute. "That's pretty spectacular." —*Tim Beardsley*

Death Watch

Updates on four dubious but enduring theories

Remember Generalissimo Francisco Franco, who ruled Spain from 1936 until his death in 1975? For months before he died, the media reported every downturn in his health. For weeks after that, a mock newscaster on the comedy television show *Saturday Night Live* kept the deathwatch alive, solemnly informing viewers that "Franco is still dead." In that spirit, SCIENTIFIC AMERICAN updates the following scientific theories.

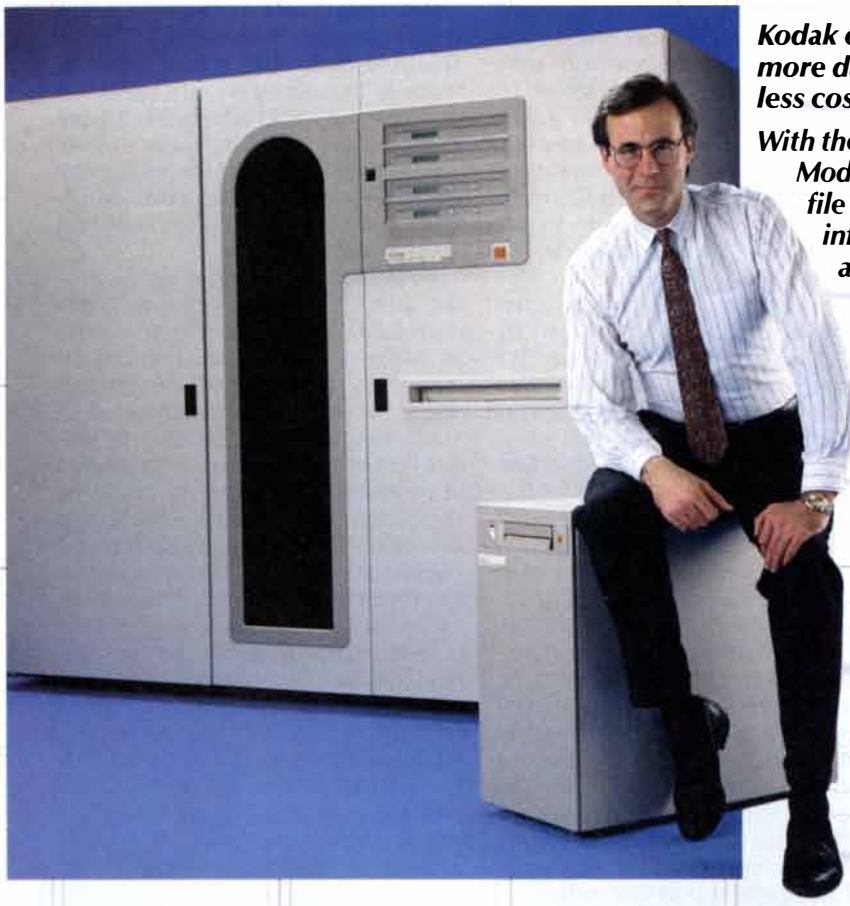
• *Cold fusion*. It has been more than a year now since B. Stanley Pons and Martin Fleischmann announced they had achieved nuclear fusion by running electricity through a coil of palladium immersed in a beaker of heavy water. Virtually every laboratory in the world, it seems, has tried to confirm the report. Although a few investigators have reported observing fleeting excesses of heat or radiation, the vast majority have found nothing to support the cold-fusion claim.

The latest nail in the coffin was hammered home by researchers from Pons and Fleischmann's very haven, the University of Utah. A team led by physicist Michael H. Salamon reported in *Nature* that after five weeks of monitoring Pons and Fleischmann's *own apparatus*, they had observed no signs of fusion.

Pons and Fleischmann have called the report erroneous but have offered no counterevidence. Then again, why should they bother? Although their claims have been rejected by most of the scientific community, in the past year they have received $5 million from the state of Utah, $400,000 from the U.S. Office of Naval Research and a "substantial" amount from an anonymous benefactor to continue their research, according to a spokesperson.

• *Nonbiological petroleum*. This theory, promulgated for more than a decade by Thomas Gold of Cornell University, shares with cold fusion the promise of an almost limitless source of energy. Gold believes that oil and gas derive primarily not from decayed organic matter (the accepted wisdom) but from the earth's primordial brew of materials. Vast quantities of these precious fuels, he contends, are harbored in the earth's mantle.

In 1986 Gold convinced the Swedish State Power Authority and numerous private investors to back a drilling project that would test his theory. The experiment took place in Sweden's Sil-



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jan ring district, which was struck by an asteroid more than 300 million years ago and is dotted with oil and gas seeps. Other geologists think the hydrocarbons come from sedimentary deposits near the surface, but Gold argued that they had risen from the mantle after the asteroid shattered the earth's crust. A shaft sunk into the granite floor of the ancient impact crater, he predicted, would tap a huge reservoir of gas or oil.

Four years, $33 million and 6.8 kilometers of solid rock later, the project has stalled without producing the promised gusher. Casings have jammed the borehole, preventing further drilling. Gold claims to have found traces of gas or oil seeping up from below, but independent scientists ascribe this "evidence" to the diesel fuel Gold used as a drilling lubricant. The Swedish power authority has backed out of the project.

Undaunted, Gold insists that drilling a new shaft—or better yet, two shafts—7.5 kilometers deep will prove him right. He and his remaining private investors are now trying to raise the necessary funds. He says that "if all goes well" the new boreholes should cost only $12 million each.

• *Small comets.* In the time it takes to read this paragraph, several house-size chunks of ice will have slammed into the earth's atmosphere and vaporized. These oversize snowballs have bombarded the earth at a rate of 10 million a year for billions of years, filling up the oceans in the process. Louis A. Frank of the University of Iowa proposed this startling theory in 1986 after finding dark specks in satellite images of the earth made by the *Dynamics Explorer I* satellite.

Other astronomers—doubtful that the hordes of comets envisioned by Frank could have been overlooked for so long—dismissed his satellite data as spurious signals, or noise. Support dwindled to the vanishing point when follow-up investigations failed to find corroborating data.

Like cold fusion, however, small comets have received just enough support from other scientists to keep them from being pegged as hallucinations. Clayne M. Yeates of the Jet Propulsion Laboratory in Pasadena, Calif., has concluded that faint streaks he recorded at the Kitt Peak National Observatory in 1987 were caused by small comets. More recently John J. Olivero of Pennsylvania State University has suggested that the 111 microwave bursts he has detected in the upper atmosphere over the past five years could represent vaporizing iceballs.

Meanwhile Frank and science writer Patrick Huyghe have written *The Big Splash,* a book that tells the tale of Frank's "revolutionary discovery." A draft of the book, which Birch Lane Press in New York City plans to publish in September, links the small comets to the origin of life, mass extinctions, UFO's, the "canals" of Mars and other cosmic mysteries.

• *The fifth force.* This theory, unlike the previous three, has no single champion, but it has shown a similar ability to garner funding and attention in spite of a lack of substantive evidence. The story unfolded in 1986, when Ephraim Fischbach of Purdue University found subtle anomalies in measurements of gravity made by the Hungarian physicist Roland von Eötvös near the turn of the century. Fischbach suggested that the anomalies resulted from a fifth force of nature (the first four being gravity, electromagnetism and the strong and weak nuclear forces) that counteracted gravity over distances of several hundred meters.

Physicists began testing Fischbach's proposal by measuring gravity in various exotic settings—atop radio towers, in mines and below the Arctic ice cap—selected to minimize the distortion from unknown geologic fea-

tures. Some groups reported finding evidence of Fischbach's proposed repulsive force, but others discerned something (inevitably dubbed the sixth force) that worked the other way, augmenting the pull of gravity. Theorists began busily concocting explanations for the data, some of which solved some nagging problems in particle theory rather nicely.

Since last fall, however, negative reports have been piling up. One of the most recent comes from a team at the Air Force Geophysics Laboratory in Bedford, Mass., which had previously discerned signs of "non-Newtonian" forces in a radio-tower experiment. They acknowledged in *Physical Review Letters* that their original data probably derived from variations in the density of the local terrain. That is what skeptics had said all along.

Other investigators are nonetheless still pursuing the phantom forces. One group hopes to track them down in the Pacific Ocean. Another, which last year detected gravitational anomalies in the Greenland ice cap, is planning a follow-up experiment in Antarctica. A third intends to observe antiprotons in a vacuum. It appears that this theory—like the others, and like old Generalissimo Franco—will enjoy a long afterlife. —*John Horgan*

Peary Redux

Are the facts (if any) getting lost?

Did Robert E. Peary reach the North Pole? Round 12: Retired Rear Admiral Thomas D. Davies of the Navigation Foundation compiled a report last December for the National Geographic Society that was intended to settle the matter once and for all. Instead of proving Peary's claim, the report only fanned new controversy ["Science and the Citizen," SCIENTIFIC AMERICAN, March].

At issue is the claimed accuracy of the technique Davies used to analyze photographs ostensibly taken by Peary near the pole in 1909. James R. Williamson, a photogrammetrist who was approached by Davies in 1989 to analyze the Peary photographs, said in a letter to SCIENTIFIC AMERICAN: "It is unfortunate that close-range photogrammetry receives the black eye of 'useless in practice' because of the actions of a nonprofessional." Among the problems he cites: Davies analyzed the pictures using a perspective technique that is permissible only when a camera faces a flat subject head-on. If the camera is tilted, different equations must be used. (Correspondence between Williamson and Davies shows them differing over how much error analysis should be done; Williamson wanted more, Davies less. When Davies decided to do the work himself, Williamson asked that his name not be cited.)

Davies, meanwhile, complains that his claims of accuracy were misrepresented. His foundation only claimed to have established Peary's position (with 65 percent probability) within 20 miles of the pole, he says, not five or six. "There's no scientific evidence that's *very* strong" in the case, he comments. Yet he wrote in the January, 1990, *National Geographic:* "We were able to analyze several pictures in the vicinity of Camp Jesup and concluded that Peary was probably within four or five miles of his reported position and certainly no more than 15 miles away."

Then, in mid-February, the Navigation Foundation apparently discovered two additional Peary photographs (one was published in the May issue of the *National Geographic*). The sun is directly visible in both pictures, and so, according to photogrammetrist William G. Hyzer, they permit a determination with less than a sixth the error of the shadow method. Hyzer's calculations place Peary some-

where along a line—although no one can know where—that runs within three miles of the pole.

Dennis Rawlins, an astronomer and outspoken Peary skeptic, did his own photogrammetric analysis of two other Peary pictures (using the proper equations) and came up with a position 100 miles from the pole. In addition, according to Rawlins, the two new photographs that show the sun were in fact found in the National Archives last August. He suggests that the foundation omitted them from its earlier analysis because they could be used to support a contention that Peary deliberately timed his pictures so that they would show a line of position passing through the pole.

Rawlins also takes extensive issue with the suspiciously good statistics of the foundation's photographic analysis and the lack of detailed support for its error estimates; he called on the National Geographic Society to make the photographs widely available for independent analysis.

As this issue went to press, the Navigation Foundation had just released a supplemental report containing the two new pictures and other data. And yet a third new photograph—still to be analyzed—has turned up. The Naval Institute is considering holding a forum in April, 1991, to let Rawlins, Davies and others air their views. Stay tuned. —*Paul Wallich*

Science Writ Small

A microscope builds an atomic-scale billboard

It was a rare advance that combined both advertising and science. Donald M. Eigler and Erhard K. Schweizer of IBM's Almaden Research Center spelled out their employer's three-letter acronym—using 35 atoms of xenon, an inert gas, meticulously arranged on the surface of a supercooled nickel crystal. The entire array of atoms is only 16 billionths of a meter across. A report on this bit of atomic calligraphy appeared in the April 5 issue of *Nature*.

Eigler and Schweizer accomplished the feat with the help of a scanning tunneling microscope (STM)—a device developed in the early 1980's to observe atoms and molecules, not rearrange them. The STM operates by passing an ultrafine tungsten needle over the surface of a sample to be studied. A low voltage is applied to the needle, creating a tiny electric potential between the tip of the needle and the atoms on the surface. Although the needle and the sample never touch in the classical sense, quantum fluctuations enable electrons to "tunnel" through the intervening distance, hence the microscope's name.

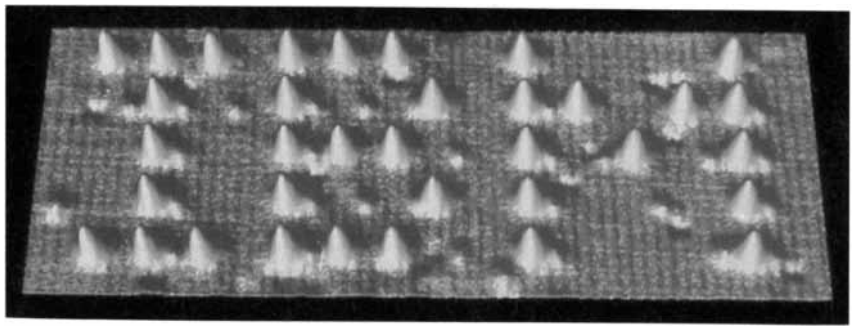
The current passing between surface and tip depends on the distance between them. A feedback mechanism continuously repositions the needle as it scans over the surface to maintain a constant voltage; the undulations of the needle are studied to reconstruct the sample's contours.

At least that is how STM's normally operate. Other researchers have already shown that an STM can be more than a passive observer. The voltage on the tip is kept very low when scanning so as to avoid disturbing the surface, but the voltage can be increased to manipulate atoms and molecules near the tip in specific ways. The electric charge on the stylus exerts a slight pull on the atoms of the surface, both as a result of electrostatic attraction and of van der Waals interaction, wherein the nucleus of an atom is weakly drawn toward electrons around other atoms. The IBM workers set out to exploit this effect.

Eigler and Schweizer began by spraying xenon atoms onto a nickel surface that had been cleaned and cooled to four kelvins. (The low temperature slows the atoms and so increases the stability of the surface.) They first made an STM image of the sample, maintaining a low voltage on the tip; they then increased the voltage, causing the attraction between the tip and the xenon atoms to increase and the distance between them to decrease.

In this way, the investigators were able to grab individual atoms and slide them across the nickel surface. Once the atoms were in their desired locations, Eigler and Schweizer reduced the voltage back to the normal value used for creating images. The xenon atoms remained fixed because they weakly bond with nickel atoms on the surface.

The ability to place individual atoms precisely raises several intriguing possibilities. Custom molecules might be assembled or modified atom by atom. More ambitious goals include atomic-scale data storage (though probably not spelled out in letters) and ultrasmall electrical logic circuits. Eigler and Schweizer admit they do not yet know whether these applications will prove feasible. But the researchers are understandably excited that the STM may permit "the ultimate in device miniaturization." —*Corey S. Powell*



XENON ATOMS spell out the name of the researchers' corporate benefactor.

Atomic Fountain

Laser light slows atom beam to a trickle

Steven Chu's sodium atoms are as slow as molasses in January and, at 30 microkelvins—30 millionths of a degree above absolute zero—considerably colder. To atomic physicists, they are certainly as sweet.

The Stanford physicist bathes an atomic beam with laser light in such a way that the atoms slow to a crawl, as though entrapped in viscous goo. In one of the highlights of the April American Physical Society meeting in Washington, D.C., Chu described a new technique for aiming these supercooled atoms in a fountain. The atomic fountain, he said, can be used for atomic clocks more precise than the present standard and to investigate quantum-mechanical phenomena.

The idea for an atomic fountain was first conceived some 40 years ago by the late Jerrold R. Zacharias of the Massachusetts Institute of Technology. He proposed aiming an atomic beam upward so that the slowest atoms would be turned around by gravity and fall back down. Over the second or so that it would take for the atoms to rise and fall, it would be possible

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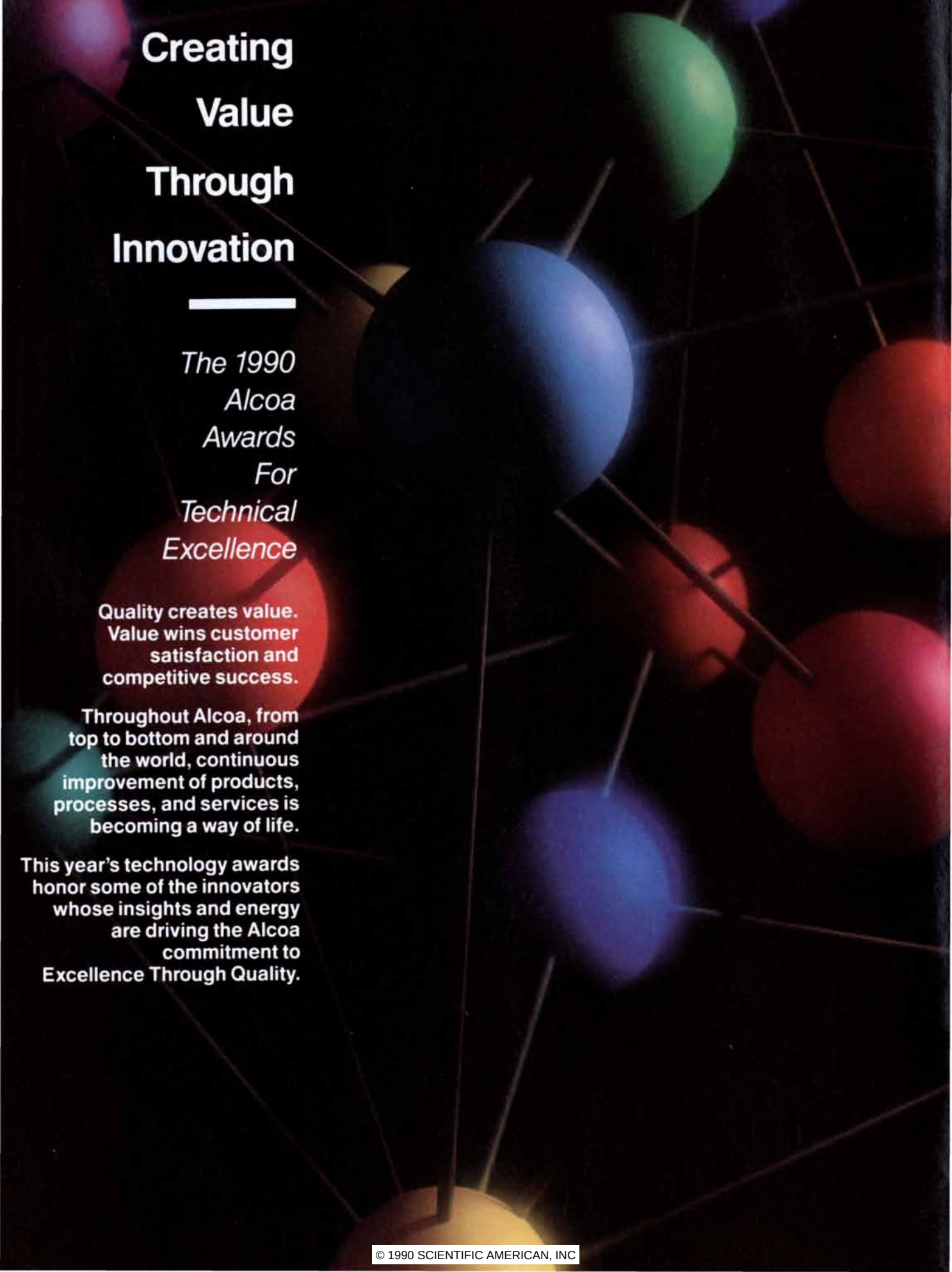

Creating Value Through Innovation

The 1990 Alcoa Awards For Technical Excellence

Quality creates value. Value wins customer satisfaction and competitive success.

Throughout Alcoa, from top to bottom and around the world, continuous improvement of products, processes, and services is becoming a way of life.

This year's technology awards honor some of the innovators whose insights and energy are driving the Alcoa commitment to Excellence Through Quality.

The 1990 Francis C. Frary Award

for a career of outstanding individual contribution to technology

Stanley C. Jacobs
Director–Primary Processing and Services, Alcoa Laboratories

Stan Jacobs has earned 22 patents and two national R&D 100 Awards as inventor or coinventor of improvements for Alcoa's primary smelting system, including molten metal treatment, purification of aluminum and alumina, and fluoride emission control. He is recognized worldwide as an authority on aluminum smelting technology.

The 1990 Chairman's Award

for significant individual contributions to the development and implementation of materials, processing and systems technologies

Charles E. Johnson
An international authority on power conversion and distribution technology, Charles Johnson has developed innovative, cost-effective programs to optimize equipment design and power systems at many Alcoa smelters. His work has created value through improvements in quality, efficiency, and capacity.

Charles K. Matocha, Sr.
Chuck Matocha has specialized in the technology for measuring and monitoring primary production processes streams. His pioneering work in process analysis has had a major impact on Alcoa's refining and smelting, and some of the analytical instruments he developed have become standard tools.

Duncan D. McGregor
The high quality of carbon anodes used in Alcoa's smelting operations owes much to the work of Duncan McGregor. His leadership in advancing the technology of carbon anode baking ring furnaces also produced major gains in fuel efficiency and productivity of the anode baking process.

The 1990 Arthur Vining Davis Award

for outstanding group achievement in Alcoa technology

At its best, the pursuit of Excellence through Quality is a team achievement, as demonstrated by the two groups of Alcoans who have earned the Arthur Vining Davis Award for 1990.

This award goes to the Caster Technology Development team of 92 technical and operating Alcoans at Massena (New York) Operations and Alcoa Laboratories. Their joint initiative raised the standards of technology and established practices for Massena's new production continuous rod caster.

Alcoa Laboratories engineers deduced the metal flow, heat transfer and solidification mechanisms that occur with various alloys. Team members at Massena developed controls and practices to produce cast rod in a wide range of alloys and with improved drawing and forming characteristics which reduce fabricating costs of high-speed wire drawing.

One result of this combined effort: Alcoa has significantly expanded market share in the highly competitive markets for aluminum used in window and door screens.

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Donald W. Brown
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Jacques J. Chenaille
Roy A. Christini
Robert J. Claffey
Donald J. Clements
Herbert E. Clements
Larry J. Colbert
William J. Curtin
Dale J. Dalton
L. Duane Dunlap
Joseph F. Durant
Wayne R. Duso
John L. Fadden
Dennis M. Falls
S. Reed Fennell
Roger J. Fish
Richard Foretek
Robert M. Fournier
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Zebulon T. Gibson, Jr.
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Robert L. Green
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William D. Spagnolo
Judith G. Stevens
S. Paul Supernault
Cloudiou L. Thomas
Phillip R. Trimm
Chester Whitehead
Jack L. Zydonik

A team of 40 employees from Alcoa Laboratories earned the Davis Award for accomplishments in reducing the weight of beverage can bodies to 25 pounds per 1,000 cans—compared with 44 pounds per 1,000 bodies for early generations of aluminum cans.

By adding statistical design and analysis and finite element modeling techniques to the traditional tools of experience and intuition, they reduced wall thickness by 15 percent while retaining the can's desirable structural and processing characteristics.

Result: added value for customers and added strength for Alcoa in this vital market.

Arthur Benson
Scott C. Biondich
George H. Blake
John C. Brem
Dennis V. Cochran
Robert E. Dick
Hans H. Diekhoff
Robert C. Eby
Daniel E. Festa
John R. Greenwald
Thomas L. Hartman
Robert E. Heffner
Jeff F. Hersh
William F. Hill
John A. Lake
Daniel J. Lege
John K. McBride
Janel M. Miller
Ronald A. Peck
Jocelyn I. Petit
James E. Premick
Douglas D. Roeber
Charles J. Ross
Robert E. Sanders, Jr.
Freddy R. Schultz
Samuel L. Shelby
David A. Smith
George L. Smith, Jr.
Milton L. Stineman
James M. Story
Kenneth J. Swanberg
Andrew B. Trageser
Kathleen M. Vincent
Peter A. Vranka
John S. Ward
Robert E. Welsh
Joseph E. White
Allan Wienecke
Robert F. Young
Robert J. Zappa

ALCOA

to take ultraprecise measurements of the energy levels of the atoms.

Zacharias's quest ended in failure because the slow atoms were jostled and kicked out of the way by faster atoms, which charged past like youth gangs through a crowd. His idea has now become a reality, however, because of recent breakthroughs that enable electrically neutral atoms to be cooled and manipulated with laser light.

To create a fountain, sodium is vaporized in a hot chamber. Individual atoms escape through a hole at an average speed of 60,000 centimeters per second. Laser beams are aimed in the opposing direction, barraging the speeding atoms with photons (particles of light). "It's like they're being pummeled by BB's," Chu says.

When they have been slowed to 1,000 centimeters per second, the atoms—up to 100 million of them—are caught in a magneto-optical trap. After the atoms have accumulated for half a second, the magnetic field is switched off. The atoms are then cooled further in "optical molasses," a laser-cooling system demonstrated by Chu and his co-workers in 1985. In optical molasses, six lasers slow the atoms' motion in the three spatial dimensions. Finally, a laser lofts the atoms upward, forming a fountain.

The fountain makes possible a new type of atomic clock. This timekeeping strategy is based on measuring the energy states of the atom with the "separated field" technique, which helped win Norman F. Ramsey his Nobel prize last year. As the atom flies up through a cavity, oscillating microwave radiation jiggles the atom from its lowest-energy state and creates a superposition of two higher-energy states. Like a spinning top wobbling on its axis, an atom in this state precesses at a particular frequency.

After some time the atom falls back down through the cavity. If the microwave oscillator has kept in step with the atomic precession, the microwaves will excite the atom into the higher of the two energy states. In this way, the frequency of the oscillator can be locked to an atomic standard. The atomic fountain, Chu says, could lead to a time standard 100 times more precise than the present standard based on the cesium atom.

To build such a clock, however, the fountain must contain many more atoms. To that end, the Stanford group recently devised an atomic "funnel." It collects atoms in a two-dimensional version of the magneto-optical trap. In the third dimension, the lasers' frequency is shifted to create a standing wave of light that moves in that direction, herding the atoms with it. The setup is like "a tilted trough filled with molasses," Chu says. "The atoms fall to the bottom and then ooze down the center of the trough."

The funnel collects atoms moving "every which way" at speeds of 2,000 centimeters per second and channels them into a paper-thin stream flowing at a relatively glacial 20 centimeters a second—equivalent to a temperature of 30 microkelvins. The Stanford group plans to employ the funnel to launch atoms upward to form a continuous fountain. In this way, they hope to have tens of billions of atoms available for making precise clock measurements.

The atomic fountain can also be used to probe some bizarre quantum phenomena. One of these is quantum reflection. According to classical theory, all particles should cross from a region of higher energy to one of lower energy. But according to quantum mechanics, such a boundary acts like a half-silvered mirror: particles are

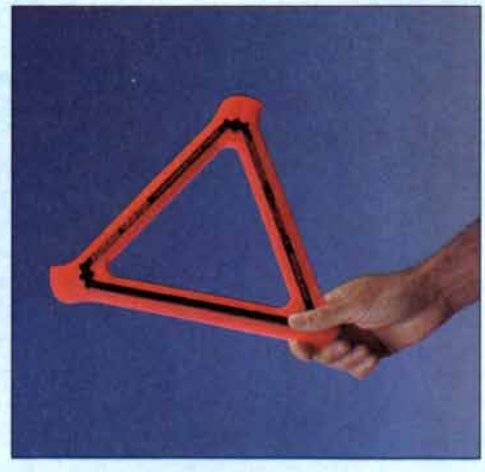
"Flying ring" inventor revamps the boomerang

Alan Adler likes to make far-flung things. Five years ago he created the Aerobie, a rubbery ring that holds the world's record for thrown flight: 1,257 feet. Now Adler, an engineering instructor at Stanford University and the founder of Superflight, Inc., which markets the Aerobie, has produced a new version of what may be the oldest aerodynamically designed object—the boomerang.

The traditional boomerang, believed to have been invented by Australian aborigines some 10,000 years ago, is an L-shaped wing, flat on one side and curved on the other. Because air must go farther and faster to traverse the curved side of the wing, the pressure there is reduced, and so lift is generated in that direction. The net effect is that when the boomerang is thrown at an angle tilted slightly to the right of the vertical position and with its curved side facing left, it swoops counterclockwise and returns.

The Orbiter, Adler's new and improved boomerang, is an equilateral triangle. Three-sided boomerangs, he notes, can be made thinner and lighter than L-shaped ones, thereby reducing drag without sacrificing stability or lift. Other designers have built triangular boomerangs, but only the Orbiter has "wing flaps" at each vertex, according to Adler. Because the flaps generate most of the lift needed to make the Orbiter rise and return, the rest of the triangle could be made even flatter to reduce drag.

Indeed, the Orbiter's cross section is almost as sleek as the Aerobie's. Materials are crucial to the design. Both toys consist of a stiff plastic frame imbedded in soft rubber; the plastic keeps them from deforming during a flight, and the rubber softens the impact on a hand (or head).



And just as the Aerobie slices through the air more easily than a Frisbee, so does the Orbiter fly more effortlessly than the traditional boomerang. At least that was this neophyte's experience during a recent field trial. Getting the Orbiter to return every time, however—or even one time in 10—may take more than a few hours' practice. —*J.H.*

partly reflected and partly transmitted. If the de Broglie wavelength of a particle is infinitely long, the particle will be reflected totally, a situation that seems counterintuitive. The atoms in a fountain are so slow that their de Broglie wavelength is sufficiently long to be, for the purposes of the experiment, infinite. Chu plans to spray fountains of atoms against an energy barrier to see how well the predictions of quantum mechanics are fulfilled. —*June Kinoshita*

Man Bites Shark

Food fads put sea wolf at risk —and under federal protection

A growing taste for shark steaks and shark-fin soup has for the first time in 400 million years put the scourge of the sea at the wrong end of the food chain. Commercial landings of this toothsome fish have doubled every year since 1986, and shark populations are plunging.

It is hardly a case of good riddance. Sharks do for gentler fish what lions do for the wildebeest: they check populations by feeding on the weak. Also, sharks apparently do not get cancer and may therefore harbor clues to the nature of that disease.

Finally, there is the issue of motherhood. Sharks are viviparous. That is, they bear their young alive and swimming (not sealed in eggs) after gestation periods lasting from nine months to two years. Shark mothers generally give birth to litters of from eight to 12 pups and bear only one litter every other year.

That is why sharks have one of the lowest fecundity rates in the ocean. The female cod, for example, spawns annually and lays a few million eggs at a time. If three quarters of the cod were to be fished this year, they could be back in full force in a few years. But if humans took that big a bite out of the sharks, the population would not recover for 15 years.

So, late this summer, if all goes according to plan, the shark will join the bald eagle and the buffalo on the list of managed species. The federal government will cap the U.S. commercial catch at 5,800 metric tons, about half of the 1989 level, and limit sportsmen to two sharks per boat. Another provision discourages finning, the harvesting of shark fins alone, by limiting the weight of fins to 7 percent of that of all the carcasses.

Finning got under the skin of environmentalists, and the resulting anger helped to mobilize support for the new regulations. Finning itself is a fairly recent innovation. Shark fins contain noodlelike cartilaginous tissues that Chinese chefs have traditionally used to thicken and flavor soup. Over the past few years rising demand in Hong Kong has made the fins as valuable as the rest of the fish. Long strands are prized, so unusually large fins can be worth considerably more to the fisherman than the average price of about $10 a pound.

But can U.S. quotas save shark species that wander the whole Atlantic? The blue shark, for example, migrates into the waters of something like 23 countries. John G. Casey, a biologist with the National Marine Fisheries Service Research Center in Narragansett, R.I., admits that international coordination will eventually be necessary. But he supports U.S. quotas as a first step in mobilizing other nations. Meanwhile the commercial fishermen are not waiting for the new rules to take effect. "There's a prequota rush on sharks," Casey says, "and it's going on as we speak." —*Philip E. Ross*

Old Green Genes

An ancient magnolia's DNA reveals its evolutionary roots

On a blustery autumn day about 20 million years ago, at a dying lake in what is now northern Idaho, a leaf dropped from a magnolia tree and sank beneath stagnant, chilly waters. Sandwiched between layers of mud and shale, the leaf lay unchanged even after the lake dried up. Then, last year, it was found by a team of scientists. "When we first cracked open the layer of sediment, the leaf was still dark green," recalls David E. Giannasi of the University of Georgia. "It was also still wet."

The prehistoric leaf's appearance was not all that survived: so, too, did fragile DNA molecules bearing some of its genes. Giannasi and his colleagues Edward M. Golenberg and Michael T. Clegg of the University of California at Riverside and others recently described in *Nature* how they isolated and analyzed that DNA. Their work could be the first of many studies in which molecular biology and paleontology join forces to map the evolutionary history of plants.

Most fossils do not contain DNA, because they are thoroughly mineralized. Petrified wood, for example, is a stony cast of old plant matter in which inorganic materials have replaced organic ones. The magnolia leaf that Golenberg and his co-workers found, like millions of other ancient plant, fish and insect remnants in the Clarkia shale deposit near Moscow, Idaho, belongs to a type called a compression fossil. Cold, oxygen-free sediments in the lake bottom squeezed the leaf and prevented its decomposition.

During the late 1970's Giannasi and Karl J. Niklas, now at Cornell University, showed that fossils from Clarkia still contained biomolecules and subcellular structures like those of modern plants. Giannasi and Clegg speculated that some of the fossils' DNA might also be intact, but at the time it was not technically feasible to isolate and study that DNA.

SHARKS bear their young alive and in small numbers, making them vulnerable to overfishing. This sandbar shark was carrying eight pups when she was captured.

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Over the past decade, however, technology took great strides. The discovery of the DNA-copying technique called the polymerase chain reaction made it possible to duplicate minute traces of fossil DNA in the quantities necessary for experimentation. Faster computers also made it easier to analyze DNA sequences.

Last July the scientists collected fragments of 55 fossil leaves from assorted plants at Clarkia. The samples had to be prepared for analysis immediately after their discovery, Clegg says; within minutes of their exposure to air, long-delayed decomposition would make them blacken and curl.

Working with the magnolia-leaf sample, Golenberg succeeded in isolating and analyzing a piece of a gene called *rbc*L, which is involved in photosynthesis. He then compared the DNA sequence for the prehistoric magnolia's *rbc*L with that of a modern magnolia and found that the gene had changed little over time—only 17 out of 820 base pairs were different. The number of differences increased when the gene was compared with those of more distantly related plants.

According to Giannasi, genetic comparisons between fossil and living plants can clarify the evolutionary lineages of plant species and their features. Many unrelated plants look alike because they evolved under the same environmental conditions; similarities between genes are better evidence for actual relatedness. The next step is to derive gene sequences for a dozen or more fossil species: Golenberg has already sequenced genes in a fossil sycamore and has begun work on a member of an extinct fossil group called *Pseudophagus*.

Other researchers have extracted DNA from animal fossils that are only a few tens of thousands of years old; could multimillion-year-old animal fossils at Clarkia also yield DNA? "It seems possible," Giannasi says. "Someone should take a look at those fish." —*John Rennie*

Skullduggery

Pundits ponder perforated prehistoric pates from Peru

Some ancient people apparently thought there were worse things than having a hole in the head. The archaeological record suggests that humans in northern Africa practiced trephination—the medical term for breaching a skull—as early as 12,000 years ago. Neolithic Europeans apparently trephined at least 5,000 years ago.

People in the New World started relatively late: the oldest trephined skulls found there are only about 2,400 years old. Yet the South Americans—and proto-Peruvians in particular—trephined as no people had before. The Peruvians were "head and shoulders above all other ancient people who developed the use of trephination," according to J. Michael Williams of Hahnemann University in Philadelphia.

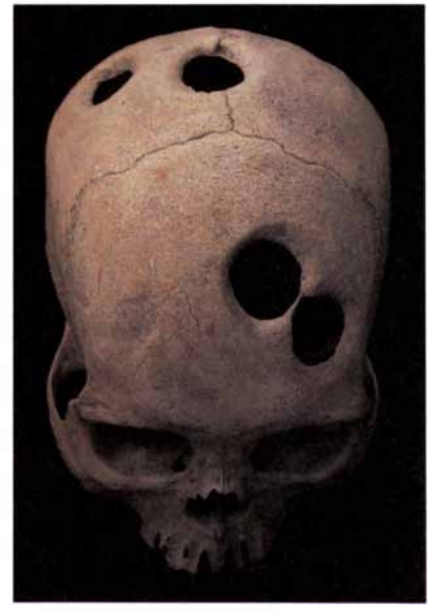
Indeed, Peru has yielded about two thirds of the 1,500 or so prehistoric skulls identified by archaeologists as having undergone trephination. Extensive analysis of the Peruvian skulls has been difficult, since they are divided among museums and private collections in the Americas and Europe. But Williams and John W. Verano of the Smithsonian Institution hope to create a computerized data base describing the holey skulls to promote research on this prehistoric surgery.

Previous studies show that Peruvians trephined by drilling, scraping or gouging the bone—usually in a circular pattern but sometimes in a rectangular one—with stone or metal instruments. Skulls with multiple holes are not uncommon; indeed, one Peruvian specimen has seven holes. "It looks like a whiffle ball," Verano says.

The Peruvians almost certainly employed trephination to relieve cranial pressure caused by a blow to the head; many of the craniums are fractured or show other signs of trauma. "These people were constantly hitting each other in the head with clubs and slingstones," Verano observes. Yet the absence of any evidence of an injury on other skulls, he adds, suggests that the procedure may also have been prescribed for migraine headaches, epilepsy and other brain disorders.

Williams and Verano plan to test this thesis. They also hope to determine whether the Peruvian surgeons knew that they should avoid cutting into certain parts of the skull, such as those covered with large arteries or muscle tissue.

The Peruvians apparently stopped trephining by the time of the Spanish conquest. At least, none of the invaders' accounts mentions the practice. Verano suggests that the Europeans would have profited from observing the "primitive" surgeons. More than half of the perforated Peruvian skulls show signs of healing; European physicians, he notes, did not equal that survival rate for cranial surgery until late in the 19th century. —*J.H.*



***SMOOTH-EDGED HOLES** suggest that this Inca citizen survived five trephinations (another hole faces rear). John W. Verano photographed the skull, which is from Peru's National Museum of Anthropology and Archaeology.*

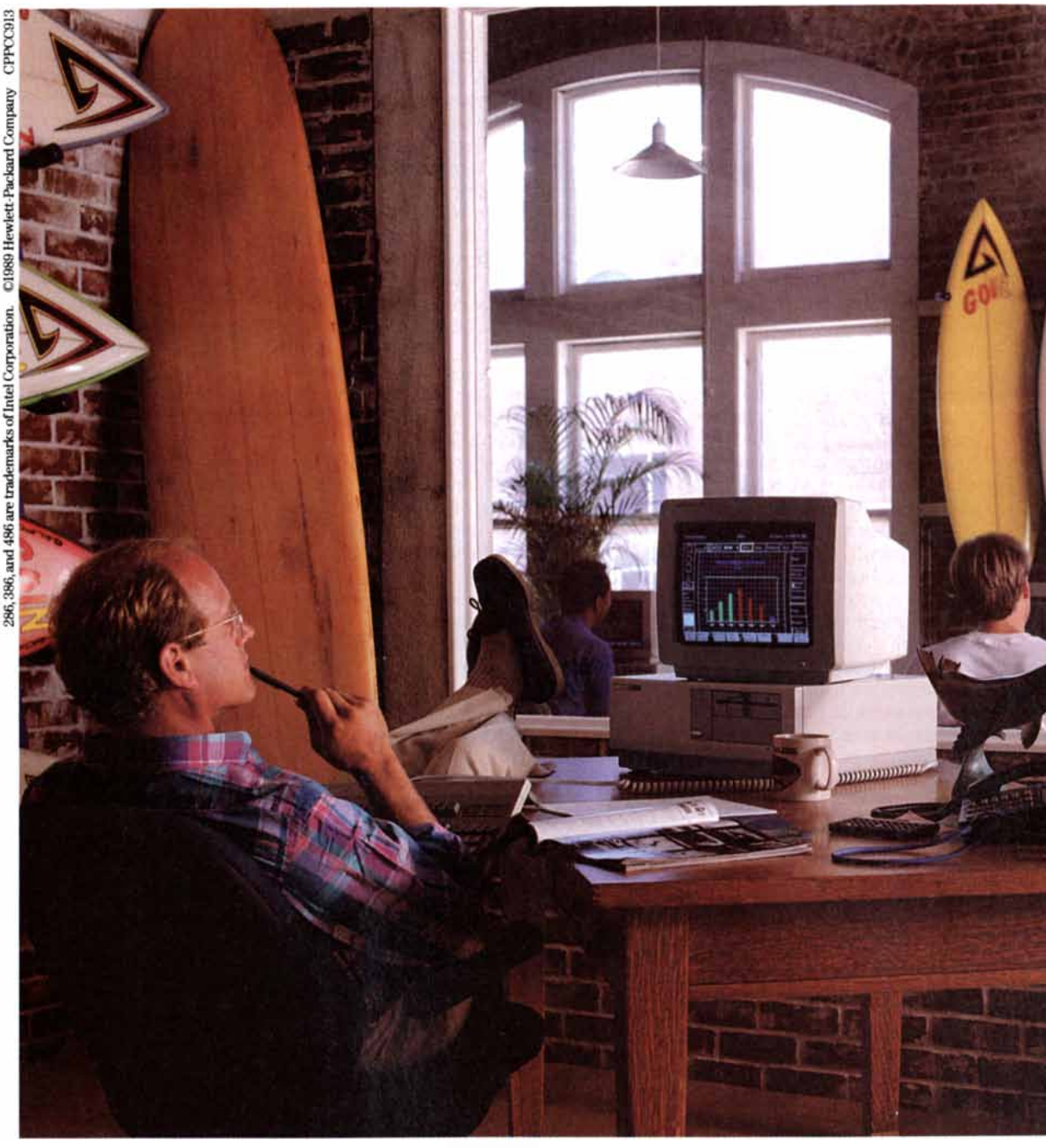
Easing the Trauma

Finally, a way to limit damage from spinal injuries

Until recently physicians had no way to preserve sensation or motion in patients with severe spinal-cord injuries. Now they have at least one drug that works, and it may prove to be a harbinger of even more effective treatments. Indeed, many investigators predict that eventually it will be possible to choose one or a combination of drugs to match the specific needs of an acutely injured patient.

"That's what I expect to see 10 years from now," says Alan I. Faden of the University of California at San Francisco, who has studied the effects of several drugs on injury to the brain and spine. He anticipates that doctors will be able to choose treatments on the basis of the site and severity of the trauma and the time elapsed between injury and the arrival of medical aid.

Faith that patients could be helped has not always run high. In the past several years some researchers became convinced that paralysis results not only from the immediate trauma but also from the body's biochemical response to it. They thought this secondary response spread from the gray



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matter (at the core of the cord) to the surrounding white matter, erasing any residual nerve function in the region within about 24 hours. Yet, in spite of good results in animals, they lacked the clinical proof to convince others this secondary damage was important and treatable in humans. "All we had to offer," Faden says, "was a song and a promise."

Then, this past March, the National Acute Spinal Cord Injury Study (NASCIS), a multicenter study sponsored by the National Institutes of Health, found success with an old and readily accessible drug: the steroid methylprednisolone. The same drug had failed in an earlier NASCIS trial. This time it was given in a huge dose (about 10 grams spread over 24 hours), and it worked if delivery began within eight hours of the injury.

"Most patients will not get up and walk normally," says Howard Eisenberg of the University of Texas, one of the NASCIS investigators. Still, he says, the treatment might make the crucial difference between total paralysis below the site of injury and some self-sufficiency, such as the ability to move an arm to control a wheelchair.

There is some evidence that treatment within the first four hours might be best, which suggests that emergency medical technicians should perhaps give the drug in the field. The NIH plans to study that approach, which may not be advisable for every patient. Subjects in the NASCIS trial suffered no major side effects, but there is concern that as a steroid, methylprednisolone can be risky for some people. For instance, it can counteract the activity of insulin and so can potentially harm diabetics, who would require prompt monitoring by physicians.

The drug's value in spinal injury is thought to be unrelated to its steroidal nature. Wise Young, who headed New York University's participation in NASCIS, says the substance probably works by inhibiting the damaging effects of free radicals (highly reactive oxygen molecules), which are released by injured cells and are toxic to the outer membranes of neighboring cells.

The risk of undesirable effects may eventually be sidestepped altogether by other drugs, one or two of which will be compared with methylprednisolone in a new NASCIS protocol. The drugs for the trial have not yet been selected, but one may well be a lazaroid. These are steroid analogues that counteract the damaging effects of free radicals but have no steroidal activity. One version is now being tested for toxicity in patients with spinal damage, according to Young.

Other promising drugs block the activity of endorphins, the body's natural opioid painkillers. Endorphins secreted in the wake of spinal trauma induce a sharp drop in blood flow in the damaged area and thus deprive neurons of crucial nutrients and oxygen. Naloxone, one such endorphin antagonist, was evaluated along with methylprednisolone in the NASCIS trial but did not show a statistically significant effect at the dose given. A second-generation version is under study in several laboratories, and another opioid antagonist—thyrotropin-releasing hormone (TRH)—is in clinical trials. Natural TRH can help animals if given up to 24 hours after the injury, which suggests that it or possibly a synthetic analogue may serve even after a patient misses the eight-hour deadline for methylprednisolone.

Also promising, according to Faden, are compounds that antagonize the activity of neurotransmitters such as glutamate. The transmitters pour out of injured or dying cells and bind en masse to surrounding cells. These substances then markedly accelerate the uptake of ions and water, which causes cells to swell and can lead to damage to their membranes. The antagonists have preserved the

OPENING CEREMONIES,
THE CANADIAN MUSEUM OF CIVILIZATION, HULL

ability to walk in injured animals.

Eisenberg is hopeful that continued research will lead to better therapies. "Methylprednisolone may not be the best or the ultimate drug. But it gives us confidence we are on a fruitful trail." —*Ricki Rusting*

Overview: Schizophrenia

This devastating illness remains profoundly mysterious

During a recent symposium on schizophrenia held in New York City, E. Fuller Torrey of the National Institute of Mental Health summed up the state of the field as "the best of times and the worst of times." Psychiatrists now have powerful drugs for treating schizophrenia—which is thought to afflict one in 100 people throughout the world—and powerful tools for investigating its nature. Yet the legions of homeless schizophrenics wandering the streets of New York and other cities testify that "we have failed miserably in treating this disease," he said.

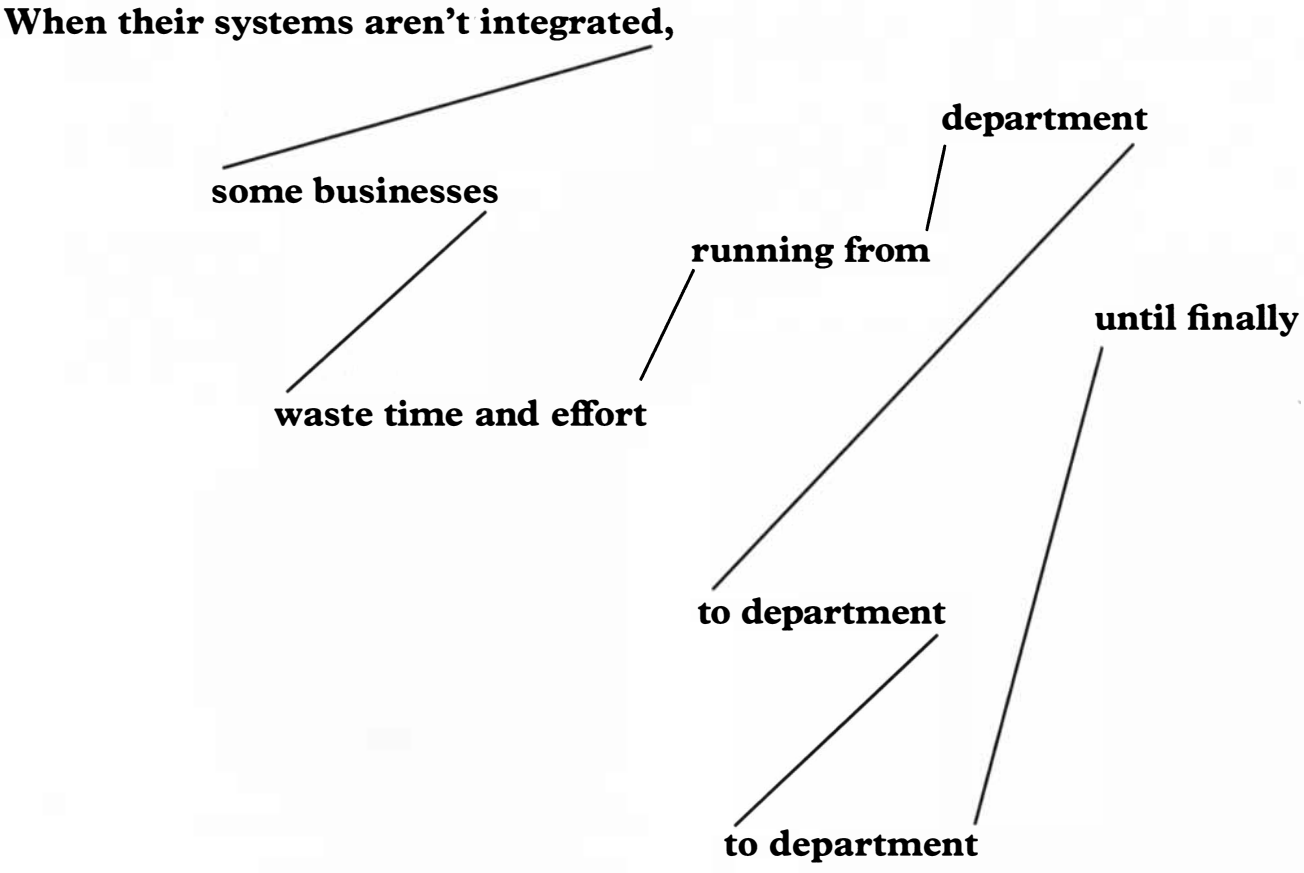
Virtually all mental health experts agree that the field has advanced since the 1960's, when schizophrenia was still widely considered a purely psychological condition. If nothing else, the shift toward biological models has helped to dispel the notion that schizophrenia springs solely from "a combination of personal weakness and poor family life," says Laurie M. Flynn, executive director of the National Alliance for the Mentally Ill, an organization for families of people with psychiatric disorders. Yet, in spite of recent reports of progress, the disease remains profoundly resistant to understanding or treatment.

Part of the problem is that schizophrenia comes in so many guises. According to the American Psychiatric Association's diagnostic manual, the disease induces delusions, hallucinations (particularly the hearing of voices) and, more generally, fragmentation of perceptions, thoughts and emotions. The schizophrenic's behavior may range from "grossly inappropriate" to catatonic. Similar symptoms may result from mania, depression, dementia and other disorders.

Recently the association tried to sharpen its definition by making the diagnostic criteria more exclusive: symptoms must appear before the age of 45 and persist for at least six months. Nevertheless, many researchers still think the diagnosis embraces not a single disease but many. That may be why schizophrenics vary so widely in their response to drug therapy. The discovery that so-called neuroleptic—"neuron-seizing"—drugs can treat schizophrenia is often described as a great medical success story. Yet neuroleptics, which block receptors for the neurotransmitter dopamine, suppress rather than eliminate symptoms and do so in varying degrees. The drugs also produce a feeling of stupefaction and what is known as blunted affect: a dulled personality. Over time they often lead to a nervous disorder known as tardive dyskinesia, which causes spasmodic twitching of the muscles.

These side effects may explain why so many schizophrenics—at least 36 percent over a one-year period, according to a recent study by John M. Kane of the Long Island Jewish Medical Center—stop taking the drugs, even though a relapse almost certainly follows. Lowering the dosage reduces the side effects but also increases the chance of relapse.

Researchers are seeking drugs with fewer side effects, as well as treatments for those severely ill patients—about three out of 10 of all schizophrenics, according to Kane—who do not respond at all to conventional neuroleptics. A drug called clozapine



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has shown some promise in treating this group, but it can induce seizures and a potentially fatal blood disorder called agranulocytosis.

Advances in genetics have raised hopes that schizophrenia may someday be cured through gene therapy. The statistical evidence that the disease is at least partially inherited is "overwhelming," says Kenneth S. Kendler of the Medical College of Virginia. Although 1 percent of the general population develops schizophrenia, it strikes from 3 to 7 percent of the first-degree relatives of schizophrenics (siblings, parents or offspring), even when they are adopted by families with no history of the disease, according to numerous studies.

The effort to pinpoint the "schizophrenia gene" seemed to take a big step forward in late 1988. A group headed by Hugh Gurling of the University of London announced in *Nature* that it had found an association between genetic markers in chromosome 5 and the incidence of schizophrenia in Icelandic and British families. In the same issue, however, a group from Yale University, headed by Kenneth E. Kidd, said it had found no such linkage in its analysis of a large Swedish family. Subsequent studies have also come up negative.

Kidd thinks the effort to identify genes underlying schizophrenia is now at "square one minus five." He notes that it is possible that numerous genes, which individually have little or no effect, work together to create a predisposition to the disease, which is then triggered by environmental factors. If that is the case, he says, investigators may never identify the genes.

Barring the discovery of a genetic marker, investigators are searching for traits that could serve both as diagnostic aids and clues to the etiology of the disease. Physicians have known for decades, for example, that many schizophrenics have difficulty tracking a moving object with a smooth eye motion. This disorder, which occurs in only 8 percent of the general population, is found in 65 percent of schizophrenics and 45 percent of their first-degree relatives, according to a study by Philip S. Holzman of Harvard University. But this finding, while intriguing, has no real diagnostic payoff.

Researchers have also scrutinized the brains of schizophrenics for signs of abnormality. The fact that neuroleptics affect dopamine transmission and that overdoses of amphetamines, which stimulate the production of dopamine, cause symptoms resembling those of schizophrenia has led to speculation that schizophrenics have an excess of a certain type of dopamine receptor, called the D_2 receptor. However, Göran Sedvall of the Karolinska Institute in Stockholm recently reported that brain scans with positron emission tomography found no evidence for this theory.

An article published in the *New England Journal of Medicine* in March claims to confirm the presence of another long-suspected neuroanatomical trait. The study, done by a group at the NIMH, compared magnetic resonance images of the brains of 15 schizophrenics with the brains of their nonschizophrenic identical twins. All but one of the schizophrenics appeared to have slightly larger ventricles (fluid-filled cavities in the center of the brain) and so less gray matter than their normal twins.

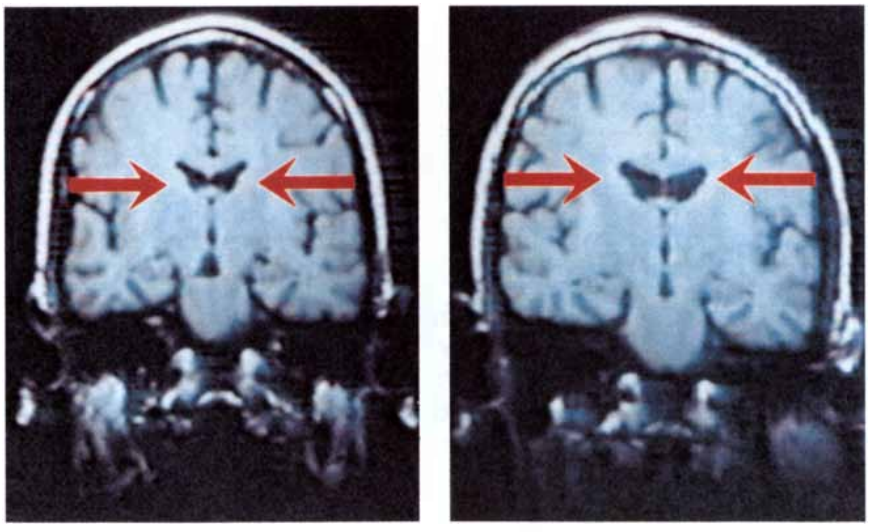
Since the twins are genetically identical, the finding suggests that the ventricle enlargement—and, by implication, schizophrenia—is caused by some environmental factor, according to the NIMH group. Torrey, one of the authors, says "factor X" could be a physical trauma, a toxin or an infectious agent. "My own delusional system revolves around a virus," he says. Noting that the parents of schizophrenics often describe them as being "different" even from birth, Torrey suggests that factor X may do its damage early—even in utero. Other statistics also suggest a prenatal factor: schizophrenics are two to three times more likely than average to have undergone complications in utero or during delivery and slightly more likely to be born in the winter or early spring, when viral infections run high.

Other researchers have questioned the value of the twin study. Kidd says it is unclear whether the apparent abnormalities in the brains of the schizophrenic twins represent a cause of the disease, an effect (perhaps of drug therapy or stress) or neither. Others point out that the abnormalities are too subtle to help in the diagnosis of the general population.

Of course, all this effort would be unnecessary if schizophrenia would simply go away. In a recent article in *Lancet*, three researchers from the Institute of Psychiatry in London ask, "Is schizophrenia disappearing?" and answer with a tentative "yes." Hospital admissions for schizophrenia in England and Wales, they report, have decreased by as much as 50 percent since the mid-1960's.

But in the U.S. there are no signs of decline, according to Ronald W. Manderscheid of the NIMH. The British findings, he contends, reflect not a genuine decline but a narrowing of diagnostic guidelines and a greater reliance on out-patient treatment—and perhaps a touch of the wishful thinking so prevalent in this field.

Someday, Manderscheid says, science may truly eradicate schizophrenia, but that day may come only after 50 or 100 more years of frustration and false starts. After all, he adds, "we probably know less about the brain than we do about deep space." —*John Horgan*



MALE SCHIZOPHRENIC* (right) *has larger ventricles* (between arrows) *and thus a smaller brain than his nonschizophrenic identical twin, as seen in this magnetic resonance image by workers at the National Institute of Mental Health. Because ventricle size also varies widely in the general population, however, it cannot be used to diagnose schizophrenia, according to other researchers.

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RU 486

This controversial drug is now used widely in France to terminate unwanted pregnancies. Yet the compound was not invented for that purpose and actually has many possible applications

by André Ulmann, Georges Teutsch and Daniel Philibert

In 1980 one of our colleagues synthesized a molecule with an unexpected property. Chemically it resembled the hormone progesterone, and like progesterone, it bound tightly to the progesterone receptor in cells. Yet instead of evoking the hormone's usual effects, this chemical blocked them. Because progesterone is crucial to the maintenance of pregnancy, the emergence of this unusual property raised the possibility that the new chemical might serve as a means of interrupting pregnancy.

The substance, designated RU 486 (after the maker, Roussel-Uclaf), is now on the market in France and the subject of worldwide controversy. International attention—both favorable and, in the case of antiabortion activists, unfavorable—has focused on the drug's role in the voluntary termination of early pregnancy.

Under the name mifepristone, RU 486 is administered as a tablet in conjunction with a small dose of a prostaglandin, which increases the frequency and strength of the uterine contractions needed to expel an embryo. In France the drug combination is approved for ending pregnancies of up to 49 days' duration (counting from the first day of the last menstrual period). There, between a quarter and a third of women who decide to interrupt an early pregnancy now choose this chemical approach over standard surgical procedures.

In the next few years RU 486 may also become available elsewhere for the same purpose. The manufacturer is considering distributing it in such countries as Great Britain, the Netherlands and Sweden, where the data required for licensing have already been amassed. The drug may also ultimately serve other functions as well; it has a number of possible therapeutic applications that are not limited to birth control and that include the treatment of certain cancers.

RU 486 was not invented with the goal of pregnancy interruption in mind. Nevertheless, by the time it was synthesized, social concerns and scientific events had already helped set the stage for that use. International agencies were calling for the introduction of a variety of new birth-control technologies. It was hoped that simplified or otherwise improved methods would help stem global population growth, which is accounted for by overwhelming growth in developing nations. The world's population expansion threatens the future availability of food, water and other resources and thus threatens the well-being and the survival of the human species.

Among the desired technologies were new approaches to the termination of pregnancy. Many women in developing nations and, to a lesser extent, in industrialized countries rely on pregnancy interruption for birth control. Although legal surgical methods are safe and effective, they have well-known drawbacks. In the first three months of pregnancy, vacuum aspiration (sometimes preceded by dilation of the cervix) is the usual method of choice. In this approach, suction is applied to remove the embryo and the endometrial tissue in which it is embedded. After about three months of pregnancy, the required procedures generally become more complex. As pregnancy progresses, the risks of infection, hemorrhage, scarring and impaired fertility increase. In developing nations, where surgical facilities are often inadequate, the danger is greater. What is worse, where legally operated facilities are not readily accessible, many women die from having unsafe abortions, typically because of uncontrolled bleeding or infection.

Analyses of steroid hormones (of which progesterone is one) pointed to the possibility of a noninvasive and potentially safer means of interrupting pregnancy. Research suggested that if an agent with RU 486's particular antiprogesterone action could be identified and delivered as a tablet or by injection, it might offer a medical alternative to surgery.

This suggestion was informed by independent work done in the late 1960's and the 1970's by Elwood V. Jensen of the University of Chicago,

ANDRÉ ULMANN, GEORGES TEUTSCH and DANIEL PHILIBERT are colleagues at Roussel-Uclaf in Romainville, France. Ulmann, a nephrologist and endocrinologist, is medical director; he headed the clinical testing of RU 486 by the company. Teutsch, a chemist who is director of endocrine research, focuses on the synthesis of steroids and peptides and on the production of new antibiotics. Philibert, a physicist and pharmacologist, supervised the research into how RU 486 acts in cells and in animals and is responsible for similar analyses of other steroid analogues synthesized at Roussel-Uclaf.

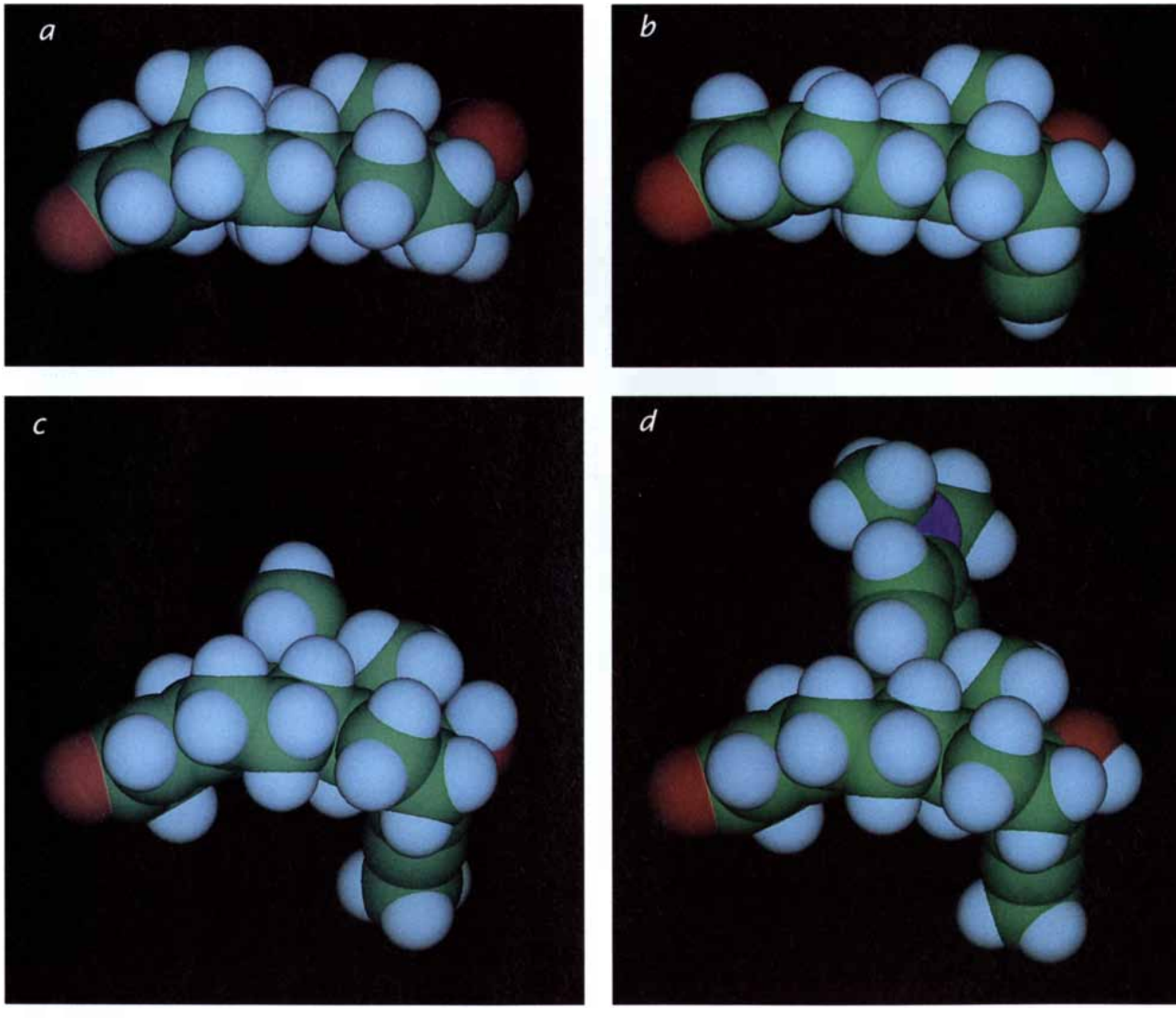
Etienne-Emile Baulieu of INSERM (the French institute for medical research) and Bert W. O'Malley of the Baylor College of Medicine in Houston, Tex. These investigators uncovered the basic mechanism by which steroid hormones induce cells to synthesize proteins. The steroids, which are derived from cholesterol, include not only progestins (progesterone and similar molecules) but also estrogens (such as estradiol), androgens (such as testosterone), glucocorticoids (such as cortisone) and mineralocorticoids (such as aldosterone).

The investigators showed that steroids, unlike polypeptide hormones, actually enter target cells. Inside a cell, they bind to receptors in the nucleus. The resulting unit—consisting of the bound steroid (the ligand) and its activated receptor—then binds to the chromatin in the nucleus (the complex of DNA and its associated proteins). That event then triggers the transcription of a selected gene from DNA into messenger RNA. Because the progesterone-stimulated synthesis of proteins in the uterus is essential to the maintenance of pregnancy, it was evident that the day scientists discovered a compound able to occupy progesterone receptors without inducing progesterone's effects, they would have an efficient and selective method for interrupting pregnancy.

It was expected that a progesterone antagonist would, depending on when it was administered, either prevent implantation of a fertilized egg or cause a more developed embryo to detach from the uterine wall. The details of how such effects might be induced were inferred from a long-held understanding of the menstrual cycle and pregnancy in mammals.

In the first half of the menstrual cycle—the follicular phase—estrogen and other hormones direct the development of a single ovarian follicle (an ovum and the cells that envelop it) and also induce the cells of the endometrium to proliferate. After the mid-cycle release of the egg at ovulation, the remnant of the follicle in the ovary becomes the corpus luteum, a transitory gland that secretes a continuous stream of progesterone.

The progesterone converts the proliferating endometrium into a tissue capable of accepting and nourishing a developing embryo. In particular, the



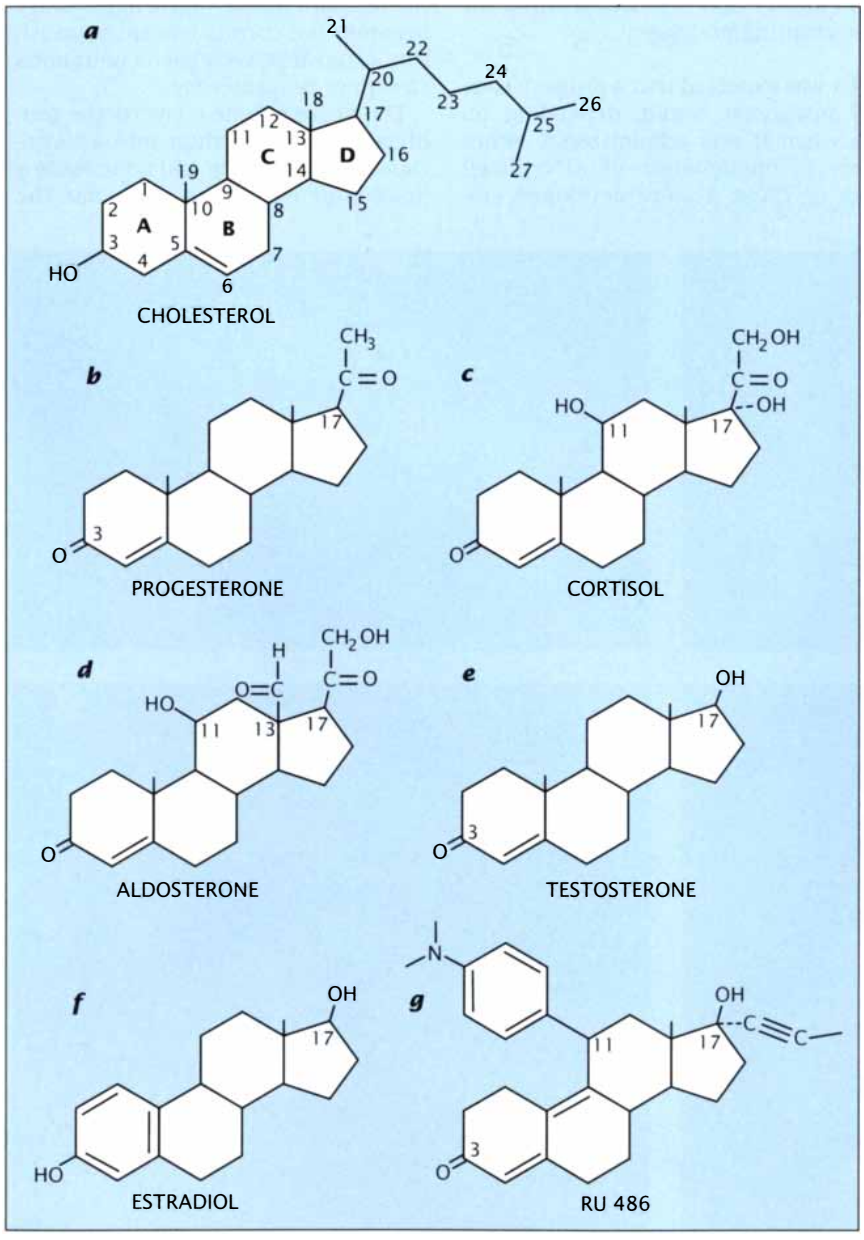
SHAPE of progesterone molecule (*a*) and three of its synthetic relatives was deduced by computer. Two of the molecules, norethindrone (*b*) and RU 42764 (*c*), mimic the hormone's activities, which are crucial to the maintenance of pregnancy. RU 486 (*d*) counteracts progesterone's effects, an antagonism that seems to stem from the bulky projection rising above the plane of the molecule. The green, blue, red and purple spheres represent carbon, hydrogen, oxygen and nitrogen, respectively.

hormone causes the endometrial cells to synthesize and store the sugar glycogen, promotes the growth of blood vessels in the expanded endometrium and increases the secretory activity of that tissue. Progesterone also relaxes the uterine muscle to forestall the contractions that might expel an embryo, and it further prevents expulsion by firming the cervix and inhibiting its dilation. These last effects derive in part from the ability of progesterone to inhibit the uterine secretion of prostaglandins.

If the egg is fertilized, it will begin to implant by about the sixth day after fertilization. Soon after, the trophoblast, or developing placenta, signals the corpus luteum to continue secreting progesterone until the placenta becomes fully functional in about the eighth week of pregnancy. If the egg is not fertilized, the corpus luteum begins to degrade after some 12 days, so that by about the 28th day of the cycle, the decline in progesterone results in the shedding of all but the basal (permanent) layer of the endometrium. Uterine bleeding follows, and the cycle begins anew.

The delivery of a progesterone antagonist before implantation, then, was expected to prevent the endometrium from undergoing the changes required for it to accept a new embryo. Given after implantation, the drug was expected to initiate a chain of events leading to the expulsion of the embryo. Blocking the secretory activity of the uterine lining would initiate endometrial erosion. That erosion would cause the developing placenta and the embryo to detach from the uterine lining. Then the corpus luteum would decay, resulting in a sharp decline in progesterone secretion. This decline would further erode the endometrium. At the same time, the decline in progesterone would lead to increased contractility of the uterine muscle and would facilitate the softening and dilation of the cervix, leading finally to the expulsion of the embryo.

In spite of such insight—and years of research, conducted primarily by the U.S. National Institutes of Health—no reasonable candidate for an antiprogesterone agent emerged until RU 486 was synthesized in 1980. It is ironic that, at the time, no one at Roussel-Uclaf was actively seeking a progesterone antagonist.



STEROIDS are derived from cholesterol (*a*), in which carbons are numbered according to a standard scheme. There is a structural similarity between representatives of each class: the progestins (*b*), glucocorticoids (*c*), mineralocorticoids (*d*), androgens (*e*) and estrogens (*f*). Because of this resemblance, synthetic steroids can sometimes bind to more than one kind of steroid receptor. For instance, RU 486 (*g*), which is a derivative of progesterone, binds strongly to both progestin and glucocorticoid receptors. RU 486 is known as an 11-substituted 19-norsteroid because an atomic grouping not found in progesterone is bound to the 11th carbon and because the methyl group (CH_3) that normally accounts for the 19th carbon has been removed.

The story of the compound's discovery actually begins a few years earlier, in 1975. One of us (Teutsch) was studying how small chemical alterations affect the ability of steroids to bind and activate their receptors. As part of his work, he developed a method of synthesizing versions of steroids that do not exist in nature. A young postdoctoral fellow, Alain Belanger, then produced the novel molecules.

As a matter of routine, each new steroidlike molecule made at Roussel-Uclaf is screened by the company's pharmacologists as a first step toward determining its possible effects in the body. On the assumption that a molecule capable of binding to a receptor might activate the receptor or block its activities, the pharmacologists determine the affinity of each new synthetic molecule for receptors representative of each of the five classes of steroids. The pharmacologists, led by Roger Deraedt, found that certain of the molecules made by Teutsch's

method bound extremely strongly to the progesterone receptor, some bound tightly to the glucocorticoid receptor and some bound well to both.

In many cases a molecule that binds tightly to a receptor is an agonist: it will produce the same effects as the natural ligand. Teutsch therefore decided to see if the same were true for the new creations. Because his responsibilities included research into glucocorticoids, he asked the pharmacologists to examine the activity of a molecule called RU 25055, which had a very high affinity for the glucocorticoid receptor.

RU 25055 did not behave as expected. When the molecule was mixed with cells that normally respond to glucocorticoids, it induced no detectable glucocorticoid activity, such as the shrinkage of thymic cells. That finding suggested the compound was actually a glucocorticoid antagonist. By binding strongly to the glucocorticoid receptor but failing to induce the usual effects, the molecule could presumably prevent such effects from occurring or from occurring with their usual intensity.

After this discovery was made, Teutsch and his colleagues gradually reversed their previous thinking about the relation between binding affinity and activity in this molecular series. They suspected that the molecules having the greatest affinity for the glucocorticoid receptor would actually have the strongest antagonistic, not agonistic, effect. This was an exciting notion because interesting therapeutic applications could be envisioned for an antagonist. For instance, a topically applied glucocorticoid antagonist might hasten the closure of burns or other skin lesions by counteracting the tendency of glucocorticoids to impair wound healing.

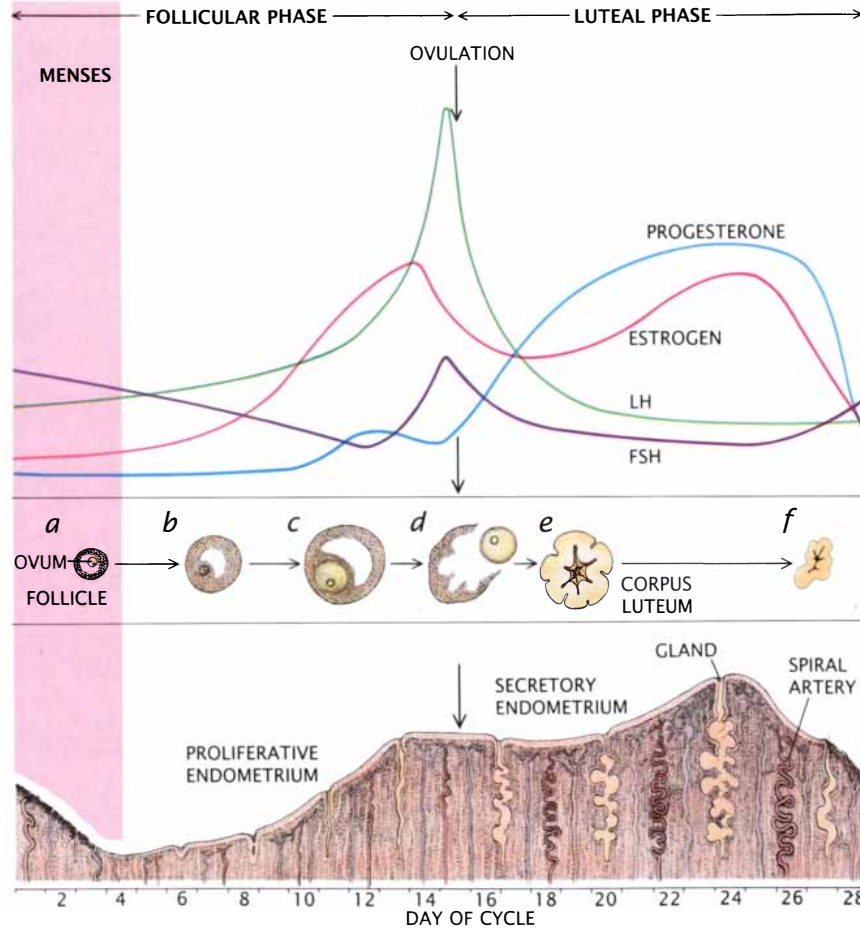
Toward the end of 1979 Edouard Sakiz, a company executive, created a formal research project for the development of glucocorticoid antagonists. Two of us (Teutsch and Philibert) participated in the project, as did other company employees and two scientific advisers from the outside: Sir Derek H. R. Barton, a 1969 winner of the Nobel prize for chemistry, and Baulieu, who by then was an established authority on steroid activity. One of us (Philibert) coordinated the project and supervised the studies of biological activity.

In April of 1980 three molecules synthesized as part of the new project were produced in succession and handed over to Philibert: RU 38140, RU 38473 and RU 38486—later shortened to RU 486. All bound strongly to the glucocorticoid receptor, and all interfered with certain activities of glucocorticoids in cell cultures. Of the three molecules, the last was the most potent; it was best able to block the actions of a powerful synthetic glucocorticoid (dexamethasone).

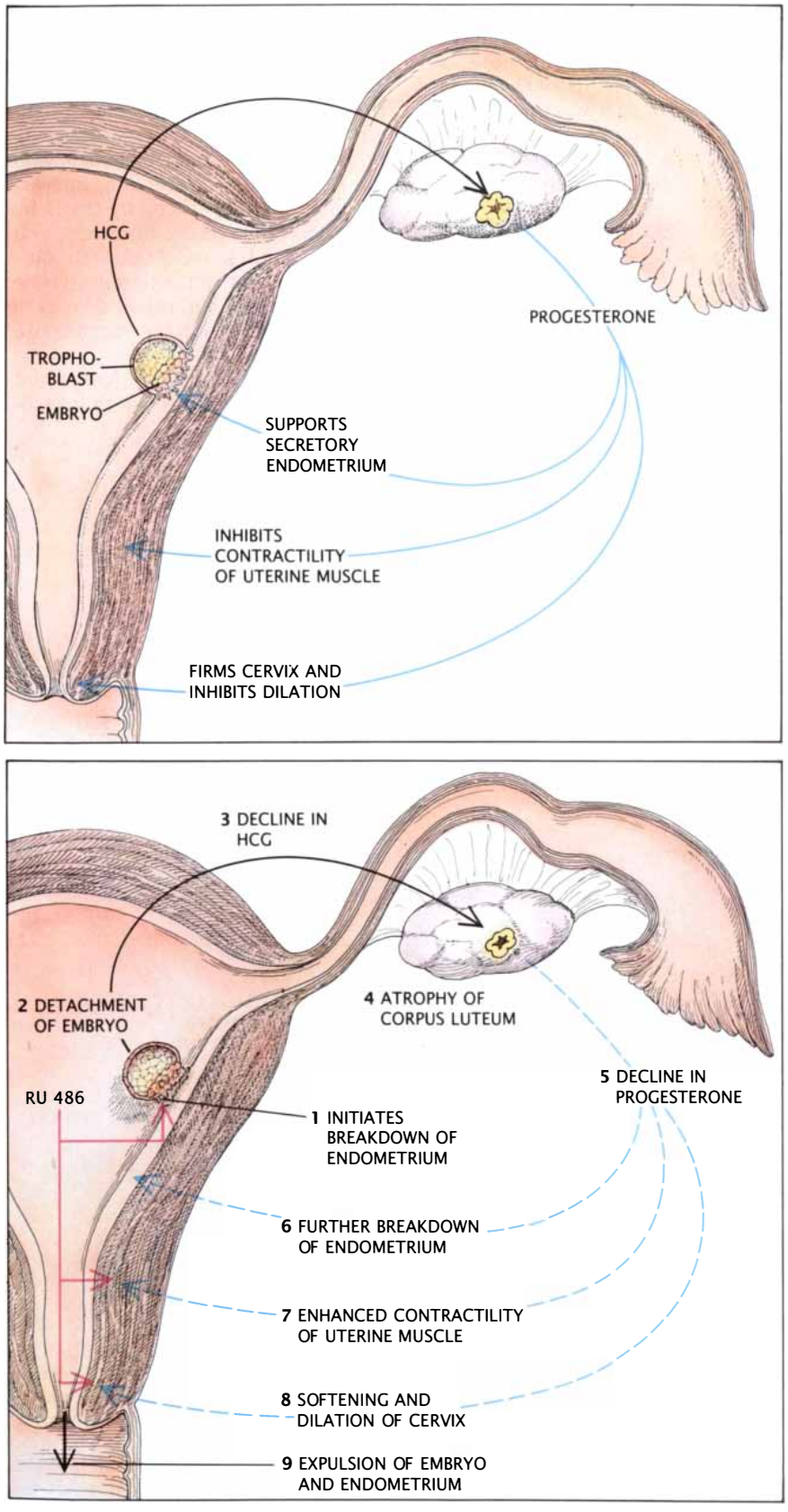
Yet the antiglucocorticoid activity of RU 486 was not the compound's only outstanding feature. Philibert's studies of its affinity for the five classes of steroid receptors indicated that the molecule also bound very strongly to the progesterone receptor. Initial tests in several animal species soon revealed that RU 486 was a progesterone antagonist.

Thus, the research group had inadvertently managed to produce the progesterone antagonist long awaited by investigators and clinicians interested in birth control. Baulieu, who himself had a long-standing interest in that area, was particularly struck by the importance of the discovery, and he convinced Roussel-Uclaf to pursue research into an antiprogesterone drug for fertility control. And so, serious testing of RU 486 for that purpose began.

Among the findings that convinced the company to proceed with investi-



MENSTRUAL CYCLE is regulated by several hormones (*top*). At the end of one cycle, the pituitary gland steps up secretion of follicle-stimulating hormone (FSH), which acts on the ovary (*middle*) to stimulate growth of an immature follicle (*a*). In the first half of the new cycle, the maturing follicle (*b* and *c*) secretes estrogen, which maintains follicle growth and both stimulates proliferation of the uterine lining (*bottom left*) and sensitizes the lining to progesterone. At midcycle, a surge of another pituitary factor, luteinizing hormone (LH), triggers ovulation (*d*). In the second half of the cycle, the remnant of the follicle in the ovary becomes the corpus luteum (*e*), which secretes progesterone and estrogen. The progesterone causes the endometrium to develop into a secretory, highly vascularized tissue (*bottom right*) that can receive and nourish a fertilized egg. If the egg is not fertilized, the corpus luteum eventually decays (*f*), and the resulting loss of progesterone leads to erosion of the endometrial lining. Bleeding then ensues, and the cycle begins once more.



RU 486 interrupts pregnancy by opposing the action of progesterone at several sites in the uterus. In a normal pregnancy (*top*), the trophoblast (the future placenta) secretes human chorionic gonadotropin (HCG), which maintains the corpus luteum. Progesterone secreted by the corpus luteum has several effects that support the pregnancy. When that progesterone is blocked by RU 486 (*bottom*), the endometrium erodes and the embryo is detached and expelled along with the endometrial tissue.

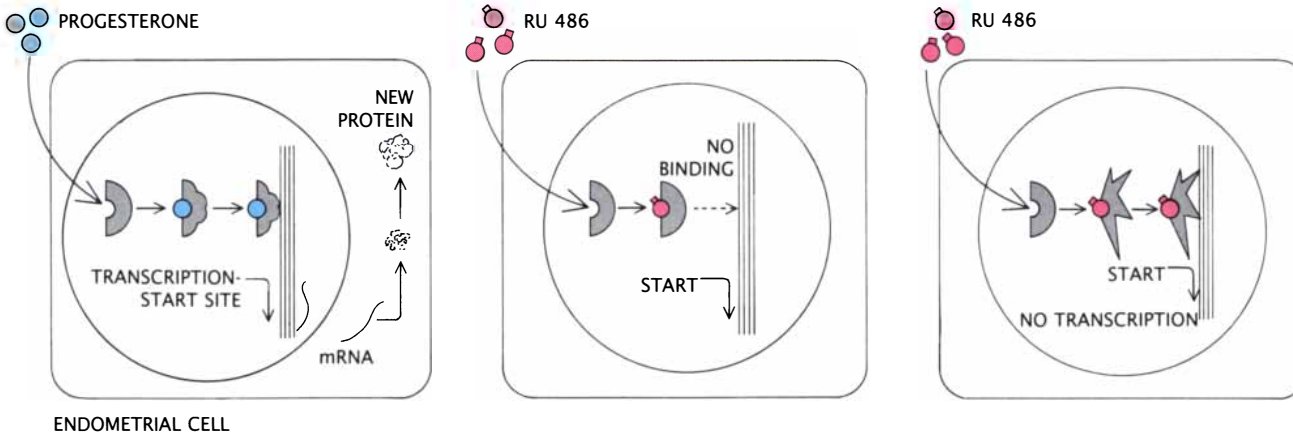
gations into the progesterone-antagonizing activity of RU 486 was the discovery that the in vitro binding affinity of RU 486 for the progesterone receptor was three times higher than that of progesterone. This activity suggested that the synthetic molecule would successfully compete with progesterone in the body and "win" occupancy of the receptor much of the time. Studies of cultured cells supported the idea, demonstrating that the effects of progesterone could be blocked in target cells that were exposed to a small amount of RU 486.

The true test of a compound's potential as a drug is its activity in vivo, and the results of the early animal studies had been encouraging as well. Some of these examined the effects of the compound on the endometrium of immature female rabbits. The rabbits were first injected with estradiol, an estrogen that both stimulates the growth of the endometrium and induces the cells to produce progesterone receptors. Next some of the animals were exposed to progesterone, which transformed the proliferating endometrium into a secretory tissue. Other rabbits were given RU 486 orally. The exposure to RU 486 alone did not induce the same transformation. Furthermore, when RU 486 was administered together with progesterone, the new compound actually blocked progesterone's ability to induce the change from a proliferative to a secretory state—as would be expected of a progesterone antagonist.

The findings of antagonism in vivo were important, but a crucial question still remained unanswered at the time Roussel-Uclaf decided to examine the potential of RU 486 to serve as an antiprogesterone drug: Could the antagonism that had been demonstrated thus far translate into the interruption of pregnancy? Studies of female rats, which do not have a menstrual cycle, confirmed that it could, and experiments with female monkeys (*Macaca fascicularis*), which do have such a cycle, offered further proof.

The first studies of monkeys were done with nonpregnant animals and revealed that a single oral or injected dose of RU 486 given in the second half of the cycle induced a premature menstrual period 48 hours after administration. Subsequently, Gary D. Hodgen and his colleagues at the Eastern Virginia University Medical School showed that the drug could also terminate pregnancy in monkeys. Other animal work established that RU 486, even at high doses, was nontoxic.

Such studies justified the initia-



PROGESTERONE acts within the cell (*left*). By occupying the progesterone receptor in the nucleus, the hormone modifies the receptor's shape, enabling it to bind to chromatin (DNA and associated proteins). Such binding leads to gene transcription and protein synthesis. RU 486 antagonizes these effects by occupying the receptor without stimulating gene transcription. It may block transcription by failing to induce the change in receptor shape required for chromatin binding (*center*). Or it may induce a change in shape that permits such binding but then prevents binding by critical transcription factors (*right*).

tion of clinical trials, and in October, 1981, Baulieu suggested to one of his colleagues, Walter Herrmann of the University Hospital of Geneva, that RU 486 be tested on human volunteers. The results were promising: RU 486 triggered expulsion of the embryo from the uterus in nine out of 11 women.

A number of clinical investigations soon followed under the auspices of Roussel-Uclaf, the World Health Organization and the Population Council, a nonprofit organization based in New York City. One of us (Ulmann) directed the clinical testing undertaken by Roussel-Uclaf.

The first large-scale studies were conducted in 1985 to determine the most effective administration schedule. It turned out that a single dose of 600 milligrams of RU 486 produced the best results. In the course of these studies, a consensus was reached as to exactly what constituted successful use of the drug. In short, RU 486 succeeded if no surgery was needed, that is, if the embryo and all but the deepest layer of the endometrium were expelled. (Incomplete expulsion calls for surgical removal, usually by vacuum aspiration, because the retained material can cause infection.)

By that standard, administration of RU 486 alone at best yielded an 80 percent success rate. The studies also found that the method worked only in early pregnancy, up to a week after menstruation would have been expected to begin. Considering that many women have a pregnancy test done only after that time, it became all too clear that RU 486 alone had limited applicability.

What accounted for the 20 percent failure rate? One reasonable hypothesis was that antagonism of progesterone could not by itself induce the frequent, strong uterine contractions required for complete expulsion of the embryo and the endometrial lining. To help correct that problem, Mark A. Bygdeman of the Karolinska Institute in Stockholm, who was overseeing a clinical trial, proposed adding a small dose of a prostaglandin to the protocol. He had earlier demonstrated that RU 486 increases the responsiveness of the uterine muscle to the contractile effects of prostaglandins.

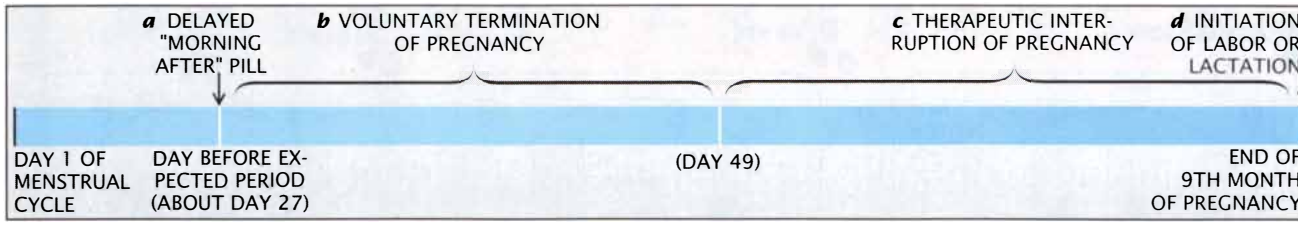
In accordance with Bygdeman's suggestion, new clinical trials were begun in France, Great Britain, Sweden and China to evaluate a new protocol: 600 milligrams of RU 486 delivered in a single dose, followed some 36 to 48 hours later by a prostaglandin. The interval cannot be shortened, because RU 486 takes time to sensitize the uterine muscle to prostaglandins.

The results improved dramatically. The success rate became 96 percent, close to the rate achieved with surgery, which itself is not foolproof. The studies also looked at the effects of the drug combination on somewhat more advanced pregnancies—those persisting up to three weeks past the missed period—and showed that the same 96 percent success rate could be achieved. In most cases the embryo and all endometrial fragments were expelled within 24 hours after the prostaglandin was administered.

As is true of miscarriages, in which a pregnancy is spontaneously arrested, the expulsion of the developing embryo and the endometrial lining was inevitably accompanied by uterine bleeding. In 4 to 5 percent of participants in these studies, the bleeding was heavy, as it can be during a normal miscarriage. Sometimes surgical intervention was needed to stop the bleeding, and in exceptional cases, a transfusion was needed. The results indicated that because of the risk of hemorrhage, the prostaglandin must be given in a medical facility where women can be monitored for several hours and, if necessary, treated.

The clinical studies further showed that abdominal pain, caused primarily by the contractile effects of the prostaglandin, is common. They also demonstrated that the 600-milligram dose of RU 486 needed to terminate a pregnancy did not cause clinically relevant antagonism of glucocorticoids. There was therefore no need to be concerned that RU 486 might produce undesirable antiglucocorticoid effects, such as profound fatigue and disturbances of electrolyte and glucose levels in the blood.

Once these studies were completed and reviewed, Roussel-Uclaf asked the French health authorities for permission to market the drug. This was duly granted on September 23, 1988. RU 486 is regulated by French law covering the termination of pregnancy, which stipulates that such terminations be performed only in authorized centers. There is one added restriction in the case of RU 486. Although the law permits voluntary termination of pregnancy through the 12th week, use of



APPLICATIONS OF RU 486 in fertility control and obstetrics are broad. The drug could serve as a delayed "morning after" pill (*a*) to be taken the day before menstruation is expected, for instance, in cases of rape. In France the compound is given along with another drug, a prostaglandin, to terminate pregnancies of up to 49 days' duration (*b*). The combination of drugs is also able to interrupt pregnancy later and might be used when the mother's life is in danger or when the fetus is severely deformed or has died in utero (*c*). Studies of monkeys show that RU 486 can facilitate labor at term by sensitizing the uterus to the labor-inducing agent oxytocin; they also indicate that the compound can stimulate lactation (*d*).

RU 486 is limited to the seventh week of pregnancy because that is the outer limit examined in formal studies.

Since the autumn of 1988 more than 40,000 voluntary terminations have been performed with the combination of RU 486 and a prostaglandin. A recent study, published in March, of 2,115 of the women has confirmed the 96 percent success rate and the 4 to 5 percent rate of heavy bleeding. The study also showed that in 86 percent of the successful terminations, expulsion occurred within 24 hours of prostaglandin administration.

The average duration of bleeding in the subjects was nine days. Nevertheless, the time to expulsion, the duration of bleeding and the intensity of pain varied, depending on the dose of prostaglandin. A high dose was associated with faster expulsion but also with more prolonged bleeding and more intense pain.

Outside the study, physicians in the field have reported that two out of all the French women who received RU 486 have had severe disturbances in heart function after receiving the prostaglandin. The occurrence is rare and both women survived, but their difficulties suggest that prostaglandins should be administered cautiously in a woman who has heart disease or is at high risk for it, as in the case of heavy smokers.

It is now a decade since RU 486 was synthesized. The compound has begun to fulfill its potential as a nonsurgical method for interrupting early pregnancies, but that is only one of its many applications related to fertility control and obstetrics.

In theory, RU 486 might be taken as a delayed "morning after" pill, say, on the 27th day of a typical 28-day menstrual cycle. Because the drug is not always effective in this role, the woman must be tested some 10 to 15 days later to confirm she is not pregnant. For the same reason, the drug is not suitable as a routine postcoital birth-control agent.

The drug may have a place when a woman decides to end an early pregnancy by vacuum aspiration. Several clinical studies have found that the procedure is facilitated by taking RU 486 some 36 to 48 hours before the surgery. The compound helps by softening and dilating the cervix.

Still later in pregnancy, up through the third trimester, the combination of RU 486 and a prostaglandin might offer an alternative to surgery when a pregnancy must be ended because the fetus is seriously malformed or the health of the mother is endangered. Investigators have found that the approach can be effective in late pregnancy and is, in fact, less risky than the kinds of surgery usually required after the first trimester. The drug combination may also be helpful when the fetus dies in utero. In such cases the fetus is usually delivered vaginally, and so contractions are induced, often with much difficulty. Administration of RU 486 followed by a prostaglandin seems to facilitate expulsion of the fetus.

Studies of monkeys indicate that RU 486 may also help to induce labor at term. In the animals the drug has been shown to augment the labor-promoting effect of oxytocin, a pituitary hormone often infused in high doses in cases of stalled labor to stimulate uterine contractions. Hodgen has found that after RU 486 is administered, the frequency of uterine contractions can be increased with just a small amount of oxytocin. Thus, RU 486 may well help to avoid some cesarean deliveries. Hodgen's experiments also suggest yet another role for RU 486: in monkeys, at least, it triggers lactation and increases the volume of milk that is produced in the breasts.

Outside the realm of pregnancy, RU 486 may one day help to treat cancers that bear progesterone receptors, including certain breast cancers. In test-tube studies, RU 486 has slowed the growth of tumors displaying such receptors. Certain noncancerous tumors that synthesize progesterone receptors might also be controlled or reduced with RU 486, among them meningiomas (tumors of the meninges, the membranes surrounding the brain). Clinical trials examining applications in cancerous and noncancerous tumors are now in progress.

Finally, RU 486 may yet find application as a glucocorticoid antagonist. For instance, it is being studied as a treatment of Cushing's syndrome, a disorder that results from the overproduction of cortisone and leads to such symptoms as hypertension, rapid fat storage in the upper body and osteoporosis.

Clearly, RU 486, the first progesterone antagonist ever brought to market, has potential beyond its value in terminating pregnancy. Its application in that area is but the first stage in the history of the compound.

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Pluto

The ninth planet has a huge moon, a surface covered with frozen methane and a wispy atmosphere that may fall as snow periodically. It may be a relic from the formation of the solar system

by Richard P. Binzel

Although February 18 of this year marked the 60th anniversary of the discovery of Pluto, the ninth planet in the solar system has guarded its secrets well. This frigid world is so small and distant that it appears as a featureless blob even through the largest earth-based telescopes. It is also the only planet that has not yet been visited by a scientific spacecraft.

Despite these difficulties, a new picture of Pluto has begun to emerge during the past decade. Dedicated observational efforts using a variety of modern instruments, aided by some fortuitous celestial alignments, have produced a number of surprises. Pluto has a satellite, Charon, so large that the two objects can virtually be considered a double planet. The planet has bright polar caps and a darker, mottled equatorial region. A layer of methane ice covers most of its surface. Pluto even possesses a thin atmosphere; when the planet is farthest from the sun, all or part of the atmosphere may freeze and fall to the surface as snow. Charon's surface, which appears to be quite different from Pluto's, may be a great expanse of water ice.

Pluto's size and density are much like those of Triton, the large satellite of Neptune that was recently visited by the *Voyager 2* probe. These and other similarities suggest that both bodies may be leftover planetesimals, relics from the early days of the solar system that managed not to be swept up by the giant outer planets. In this scenario, Triton was captured by Neptune, whereas Pluto was able to survive as a bona fide planet in an independent orbit about the sun.

Clyde W. Tombaugh first glimpsed Pluto in 1930 as part of a methodical photographic survey inspired by Percival Lowell, a wealthy Bostonian with a passionate interest in finding a possible trans-Neptunian planet. It was immediately evident that Pluto is an oddball in many ways. The other outer planets orbit the sun in roughly circular paths, but Pluto's highly elliptical orbit carries it from 30 to 50 times the earth's distance from the sun and, at times, brings it closer to the sun than Neptune. This has been the case since 1979; Pluto will regain its status as the most distant planet in 1999. Pluto's orbit also is inclined 17 degrees to the plane in which the earth revolves around the sun, far more than that of any other planet.

Apart from its orbit, few of Pluto's characteristics could be determined with any degree of certainty in the 50 years following its discovery. Lowell and others had postulated the existence of a ninth planet based on perceived gravitational perturbations of the motions of Uranus and Neptune and guessed that this planet must be about 10 times as massive as the earth. Pluto turned out to be far fainter than expected, which implied it must also be much smaller; assuming that Pluto had a reasonable planetary density caused estimates of its mass to drop by about a factor of 10. In the 1960's astronomers refined their measurements of the orbits of Uranus and Neptune, and Pluto's estimated mass shrank by another factor of 10.

Determining Pluto's diameter also proved to be a frustrating task. The shifting layers of the earth's atmosphere distort incoming light. Atmospheric turbulence limits the resolution of earth-based optical telescopes to about one arc second (1/3,600 degree). Viewed from the earth, Pluto's disk is considerably less than one arc second wide, so estimates of its diameter were highly subjective. Over the years, these ranged between .5 and .2 arc second, corresponding to diameters of between 14,000 and 6,000 kilometers. The latter value, about one half of the earth's diameter, became the most widely accepted estimate.

These mass and diameter estimates implied that Pluto's density was similar to that of the rocky terrestrial planets in the inner solar system and significantly greater than that of the gaseous outer planets. In the mid-1970's it became evident that Pluto is a highly reflective icy body that is probably smaller and less dense than previously had been thought.

A revolution in the understanding of Pluto began in 1978 when James W. Christy of the U.S. Naval Observatory discovered that Pluto has a large satellite. Christy was making precise positional measurements of Pluto to produce a refined knowledge of its orbit. Such measurements are of fundamental importance to astronomy, but the work is usually tedious and seldom glamorous. Christy was examining photographic plates of

RICHARD P. BINZEL is assistant professor of earth, atmospheric and planetary sciences at the Massachusetts Institute of Technology. He received a Ph.D. in astronomy at the University of Texas at Austin in 1986. He published his first scientific paper at the age of 15 and has avidly pursued astronomical research ever since. Binzel's other work includes observational and theoretical studies of the structure, behavior and evolution of asteroids. He served as an author and the principal editor of *Asteriods II,* recently published by the University of Arizona Press.

PLUTO AND CHARON appear surprisingly dissimilar. Frozen methane on Pluto's surface has been turned ruddy by solar radiation. Charon's weaker gravity allowed methane to escape, exposing a layer of water ice. Both bodies have large rocky cores; some process evidently favored the formation of rocklike compounds relative to ices in the outer solar system. A star occulted by Pluto in 1988 flickered before it vanished, revealing that the planet has a thin, hazy atmosphere. Since 1985 Charon has appeared to pass in front of and behind Pluto, permitting the first accurate measurements of Pluto.

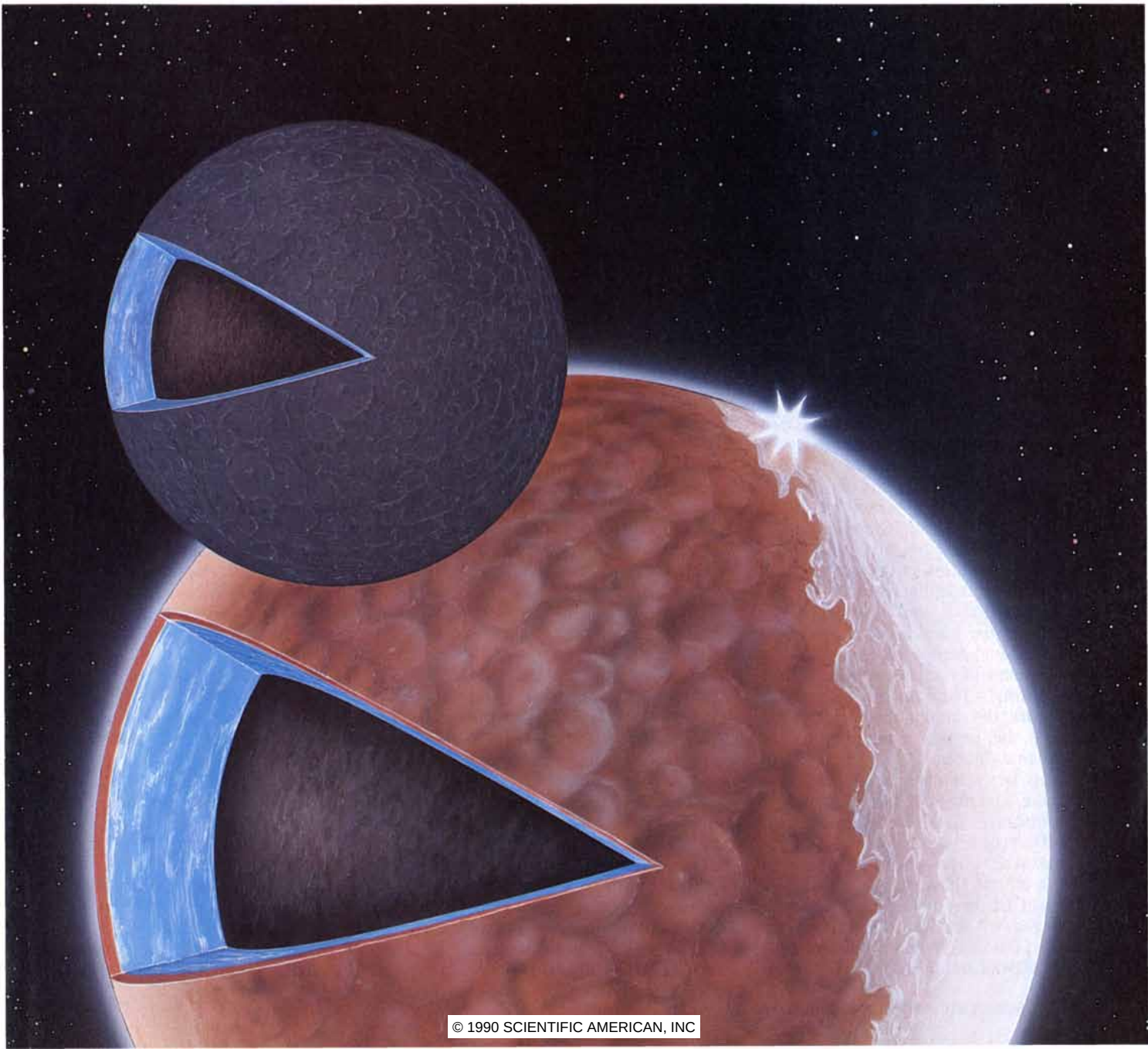
Pluto taken with the Naval Observatory's 1.5-meter telescope in Flagstaff, Ariz., only a few kilometers away from the site where Tombaugh first spotted Pluto.

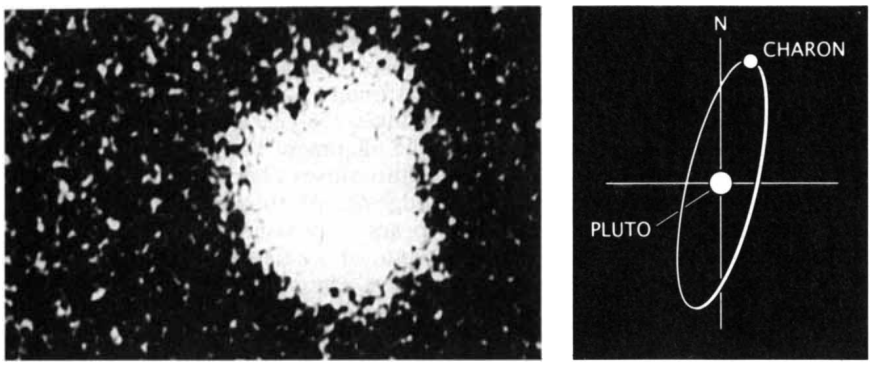
On one plate, Christy found that the images of Pluto showed a slight bump toward the top. Yet images of stars on the plate appeared round. Other plates taken on different nights showed that the bump moved around the planet over a 6.4-day period, the same as Pluto's known period of rotation. Christy and his co-worker Robert S. Harrington realized that the "bump" was actually a satellite in an orbit gravitationally synchronized with the planet's rotation. As a result of this orbit, Pluto and Charon permanently keep the same hemispheres facing toward each other, just as one side of the moon always faces the earth. Christy proposed naming the satellite Charon, both to honor his wife, Charlene, and to reflect Greek mythology: Charon ferried souls across the river Styx to the lower world, which was ruled by the god Pluto.

Planetary scientists heralded the discovery of Charon because at last it was possible to calculate an accurate value for Pluto's mass. For two objects orbiting each other, the period of the orbit is determined by the distance between the bodies, their combined mass and the well-understood laws of gravitation. Measurements of Charon's orbit revealed that the total mass of the Pluto-Charon system is about 1/400 the mass of the earth, another factor of 10 lower than most previous estimates. Subsequent measurements have refined this value only slightly.

Shortly after Charon was discovered, astronomers realized that twice during Pluto's 248-year circuit about the sun, the alignment between the earth and Pluto causes Charon's orbit to be seen edge-on. At those times, Charon appears to pass in front of and behind Pluto at 3.2-day intervals (every half-orbit). These mutual events are commonly referred to as eclipses even though Charon's disk is smaller than Pluto's; strictly speaking, the events are labeled transits (when Charon is in front) and occultations (when Charon is behind).

Contrary to what is usually the case for once-in-a-century opportunities, astronomers did not have to wait long





CHARON WAS SPOTTED as a bump on Pluto's image, as seen in this photograph taken at the U.S. Naval Observatory on July 2, 1978 (*left*). James W. Christy realized the bump was an object orbiting the planet. The true scale of the two bodies is obscured by the earth's atmosphere but can be determined indirectly (*right*).

to witness these mutual events. The first predictions indicated that eclipses might begin only one or two years after Charon's discovery. As measurements of the tilt of Charon's orbit were refined, the predicted onset of the mutual events was revised to some time during the first half of the 1980's. If Christy had not noticed the bump on his photographic plates, the current series of eclipses (the first since the time of the U.S. Civil War) could possibly have gone unnoticed.

The impending eclipses generated at least as much excitement in the astronomical community as the discovery of Charon itself. It is hard to imagine a better natural experiment for determining the diameters and surface properties of Pluto and Charon. Timings of the beginnings and endings of eclipses can reveal the diameters of the two bodies. This, combined with the new determinations of the total mass of the system, yields Pluto's density, a crucial clue in unraveling Pluto's internal structure and formation.

The combined brightness of Pluto and Charon varies as the satellite covers dark and light features on the planet's surface, and vice versa. Repeated transits and occultations make it possible to derive crude maps of one hemisphere of each body. Occultations of Charon by Pluto provide a chance to measure the individual spectra, and hence the surface compositions, of Pluto and Charon.

Planetary scientists raced into action to take advantage of this outstanding opportunity. J. Derral Mulholland of the University of Florida and I began systematic observations of Pluto in 1982 at the University of Texas McDonald Observatory. Colleagues who engaged in similar preparations included David J. Tholen of the University of Hawaii and Edward F. Tedesco of the Jet Propulsion Laboratory in Pasadena, Calif. Our observations primarily consisted of telescopic measurements of Pluto's brightness to a precision of a few tenths of 1 percent. Pluto and Charon appear as a single overlapping image to terrestrial telescopes, and so an eclipse would produce a drop in the combined brightness as part of the total surface area became hidden behind Charon or Pluto.

In the first eclipses, Pluto and Charon would only skim each other and the brightness would change just a few percent. Detecting the onset of the mutual events therefore required a detailed understanding of the periodic variations in Pluto's brightness that occur as it rotates. Such variations, presumably caused by light and dark patches on the surface, were first detected in the 1950's and were used to determine the planet's 6.4-day rotation period. Interestingly, as Pluto has neared perihelion, its closest approach to the sun, the amplitude of the fluctuations has increased from about 10 to 30 percent while the planet's absolute brightness has decreased by about 30 percent.

This behavior is almost certainly a result of the changing geometry between Pluto and the earth and the unusual tilt of Pluto's axis of rotation. Most planets rotate about an axis that is roughly perpendicular to the plane of their orbits and turn counterclockwise (prograde) when viewed from above the plane of the solar system.

The discovery of Charon made it possible to determine the tilt of Pluto's axis because the gravitational forces that synchronized Charon's orbit with Pluto's rotation also aligned the plane of Charon's orbit with Pluto's equator. Measuring the satellite's orbit revealed that Pluto's axis is inclined 122 degrees. Pluto is "tipped over," and its north pole (defined by counterclockwise rotation) lies below the plane of its orbit. Venus and Uranus are similarly tipped, with inclinations of 177 and 98 degrees, respectively.

The extreme tilt of Pluto's axis causes the planet's appearance to change significantly over the course of its orbit, as seen from the earth. In the early 1950's Pluto's south pole pointed roughly toward the earth. The planet's orbital motion about the sun has slowly changed this orientation, so that terrestrial observers now see Pluto from a more equatorial aspect.

Robert L. Marcialis of the University of Arizona and Marc W. Buie of the Space Telescope Science Institute have attempted to model the distribution of dark and light spots on Pluto's surface to fit the observed changes in the planet's brightness with the aspect at which it is being viewed.

The dark and light patches that cause Pluto's 6.4-day light variations seem to lie at low latitudes, where they move in and out of view as the planet rotates. The long-term darkening of the planet suggests that Pluto's polar regions have a relatively high albedo, or reflectivity. Pluto appeared brighter in the 1950's because its reflective south polar region was pointed toward the earth. Most of this region was continuously visible, and so each rotation caused only a slight variation in Pluto's brightness. As the darker, more varied equatorial terrain came into view, Pluto grew dimmer, and its brightness fluctuations grew larger [*see illustration on page 54*].

One unknown factor is Charon's contribution to the observed rotational light curve. In the extreme case, Charon might have one black and one white hemisphere and could contribute up to one half of the periodic light variations. Pluto also might experience seasonal changes in the reflectivity of its surface because of the tilt of its axis and the large changes in its distance from the sun.

Uncertainty about the inclination of Charon's orbit and the relative diameters of Pluto and its satellite made it difficult to know when the first eclipses would occur. Also, observations might be obscured by sunlight, moonlight or clouds. Efforts to detect the first eclipses revealed none during 1982, 1983 and 1984. Finally, on the crisp, clear morning of February 17, 1985, the vigilance paid off when my photometric measurements with the McDonald Observatory's 91-centimeter telescope registered a distinct dimming of Pluto by

about 3 percent over two hours, indicating a partial transit of Charon in front of Pluto. The brightness of nearby reference stars remained constant to within .5 percent, which demonstrated that the dimming was not caused by terrestrial clouds or haze.

The timing of the event corroborated a tentative eclipse observation on January 16, 1985, by Tedesco and Bonnie J. Buratti of the Jet Propulsion Laboratory. They did not report their result because of uncertainties in their measurements caused by an instrument problem. On February 20 Tholen confirmed that the Pluto-Charon eclipses had begun, when, using the University of Hawaii's 2.2-meter telescope on Mauna Kea, he measured a 2 percent dimming as Charon slipped behind Pluto on the other side of its orbit.

The changing positions of the sun, the earth and Pluto create a constantly evolving view of the transits and occultations [*see illustration on page 55*]. Were eclipses viewed from the sun, the relative position of Charon and its shadow during successive transit events would follow a simple, constant progression from right to left. The earth, however, shuttles from one side of the sun to the other over the course of six months. This causes a cycle in the apparent orientations of Pluto and Charon: the relative positions of their disks are a function of the earth-Pluto line of sight, whereas the positions of their shadows are determined by the sun-Pluto line of sight.

In the first eclipses of 1985, Charon passed in front of Pluto's north pole and dipped behind its south pole, but their disks barely overlapped. Charon and Pluto more fully obscured each other during 1986. Both transits and occultations blocked the same surface area, but transits resulted in increased dimming. Evidently a given area of Pluto contributes more light than the same area of Charon, which implies that Charon is mostly covered with darker material than Pluto. Overall, Pluto reflects about half the light that strikes it; Charon reflects less than two fifths.

Total occultations of Charon behind Pluto began in 1987, and for the first time it became possible to resolve the individual spectra of the two bodies. Every element or compound absorbs light in a distinct, characteristic manner, and so the spectrum offers a method of inferring an object's composition. During the occultations Charon vanished for about one hour, and for the first time it was possible to make spectroscopic measurements of Pluto alone. Subtracting Pluto's spectrum from the combined spectrum (obtained before or after the occultation) yielded the individual spectrum of Charon.

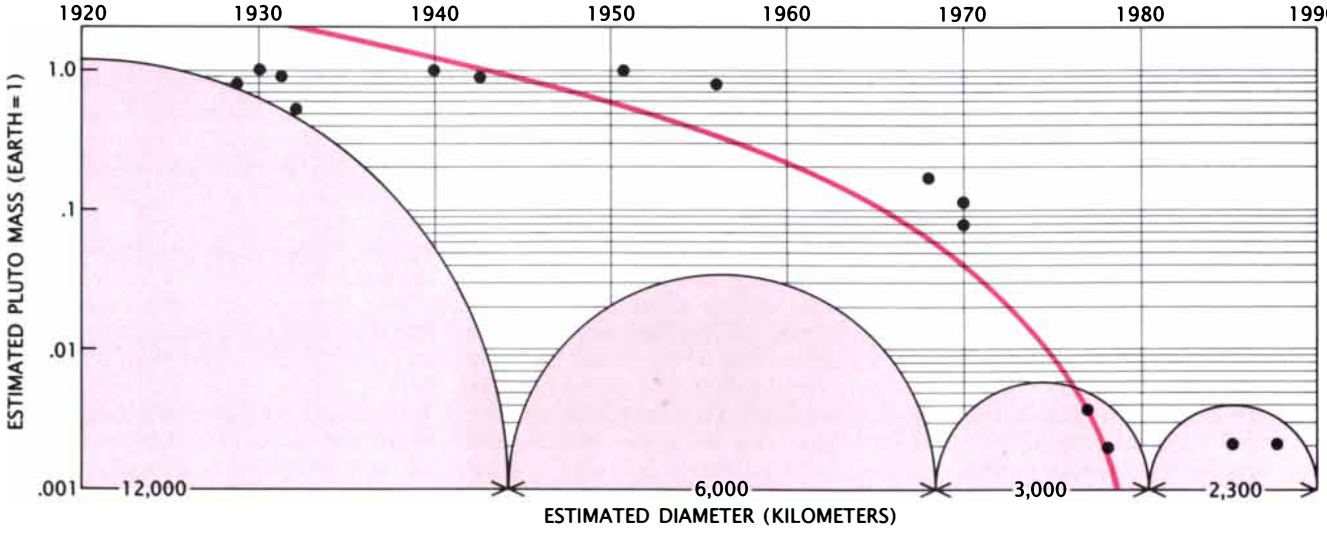
Pluto's spectrum shows a large dip at infrared wavelengths of around .9 micron (just longer than visible red light), caused by absorption of infrared light by methane (CH_4) frost on the planet's surface. This was first discovered in 1976 by Dale P. Cruikshank, David D. Morrison and Carl B. Pilcher of the University of Hawaii.

Charon's spectrum, in contrast, shows no major peaks or dips at wavelengths shorter than one micron. To human eyes, Charon would appear a bland, neutral gray, and Pluto would be reddish. Measurements of Charon's spectrum at longer infrared wavelengths indicate that the satellite is covered with water ice. This different composition probably explains why Pluto is more reflective than Charon.

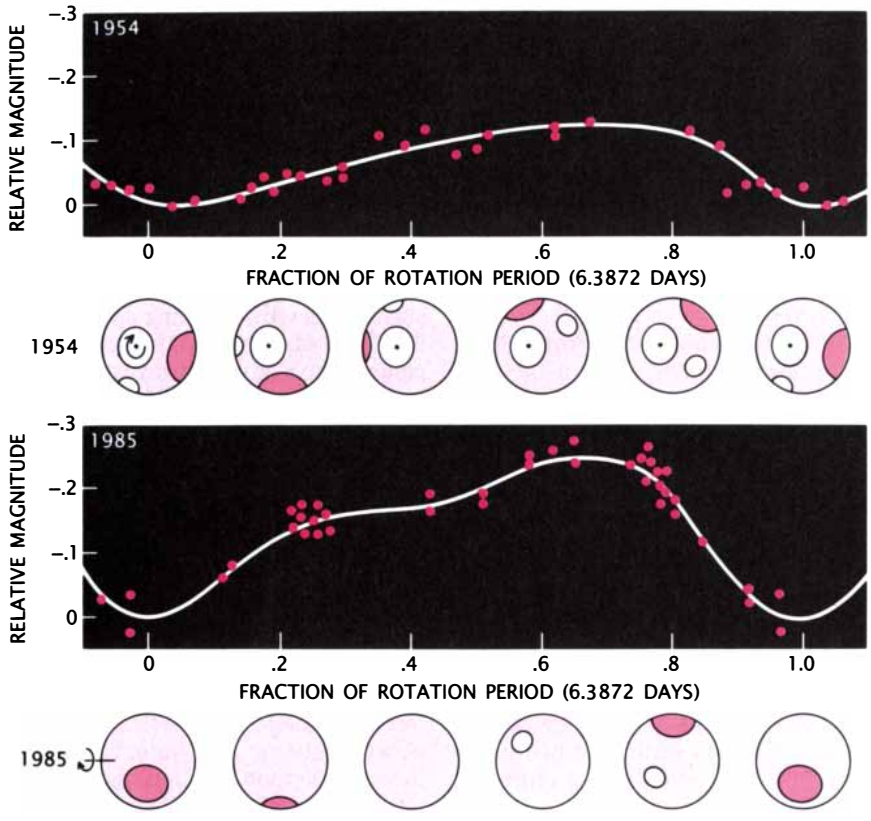
How can two bodies so closely related have such different surfaces? Probably Charon's gravity is so weak that it could not hold onto methane that was vaporized by the heat of the distant sun. Methane was driven off Charon's surface, thereby exposing an underlying layer of denser water ice. Meanwhile Pluto's greater gravity enabled it to retain its outer layer of frozen methane. Astronomers think both bodies have similar internal compositions, so a layer of water ice probably underlies Pluto's methane surface.

Thanks to the series of eclipses, precise measurements of the sizes of Pluto and Charon have finally been obtained. Careful timings of the transits and occultations can be translated into dimensions of the objects, provided one knows the distance between Charon and Pluto. Currently, the best method for finding this distance is a technique called speckle interferometry, which obtains high-resolution measurements by using extremely brief exposures to freeze the blurring effects of the earth's atmosphere. Speckle observations by James Beletic and Richard Goody of Harvard University, combined with constraints imposed by the recorded timings of the eclipse events, yield an estimate of 19,640 kilometers for the radius of Charon's orbit, accurate to about 2 percent.

The most extensive attempt to measure the diameters of Pluto and



ESTIMATED SIZE AND MASS of Pluto initially were biased upward because some astronomers erroneously thought Pluto's gravity was disturbing the orbits of Uranus and Neptune. After decades of downward revisions, some astronomers whimsically noted that a curve fitted to the plummeting estimates of Pluto's mass indicated that the planet would vanish in 1980! Analyses of Charon's orbit finally revealed the system's true mass, about 1/400 that of the earth.



PLUTO'S BRIGHTNESS changes as it rotates. In 1954 the planet's south pole pointed earthward and so was always visible (*top*). Pluto has moved in its orbit and is now seen from the side. Its whole equatorial region rotates in and out of view, which causes its brightness to vary by 30 percent (*bottom*). The planet has also dimmed overall, revealing that the equatorial region is darker than the south pole.

Charon based on eclipse timings, performed by Tholen, gives a figure of 2,300 kilometers for Pluto and 1,186 kilometers for Charon; the uncertainty is roughly 1 percent. Pluto is the smallest planet in the solar system. It is about half the diameter of Mercury (once thought to be the smallest) and only two thirds the diameter of the moon. Charon's diameter is approximately half that of Pluto, making it the largest satellite in the solar system in relation to the planet it orbits. Before the discovery of Charon, that record went to the moon, which is slightly more than one fourth the diameter of the earth. Assuming Pluto and Charon have similar densities, the center of mass of the system lies approximately 1,200 kilometers above Pluto's surface. For every other known planet-satellite system, the center of mass lies deep within the body of the planet. This has prompted some astronomers to call Pluto and Charon a double planet.

Knowing the diameters and combined mass of Pluto and Charon makes it possible to compute their average density. The detection of methane in Pluto's spectrum in the 1970's led astronomers to suspect that Pluto is composed of frozen methane, water and other light compounds thought to have been present in the outer reaches of the nebula from which the solar system formed. This suggested that Pluto's density should be low, probably no greater than the density of water (one gram per cubic centimeter).

Recent calculations reveal that Pluto's actual density is slightly more than two grams per cubic centimeter. This implies that Pluto contains substantial rocky material in addition to ices. Measurements of the orbital velocity and orbital radius of Charon yield only the total mass of the system, so the calculated density represents an average of the densities of Pluto and Charon. From its vantage above the earth's atmosphere, the *Hubble Space Telescope* should be able to determine precisely the orbital radius and center of mass of the system. Then the relative masses and densities of the two objects, and any radical differences in their internal compositions, should be revealed.

Although the eclipses have provided new insights into the nature of the surfaces and interiors of Pluto and Charon, they tell nothing about the possible existence of thin atmosphere around Pluto. The presence of an atmosphere has been hotly debated throughout the past decade. The distinctive signature of methane, spotted in Pluto's spectrum in 1976, was initially interpreted as resulting from methane frost on the surface. In 1980 Uwe Fink of the University of Arizona made more precise spectral measurements and concluded that the methane actually exists in gaseous form. The lack of good laboratory spectra of methane at the temperatures and pressures found on Pluto has prevented astronomers from distinguishing decisively between the presence of ice and gas from telescopic observations. Most researchers have concluded that both are present.

Fortunately, nature offers a method for detecting and measuring an atmosphere unambiguously—a stellar occultation. When a planet or other object passes in front of a star, any atmosphere will distort and diminish the star's light in a characteristic way. For three decades astronomers have sought to identify stars that lie directly in Pluto's path as seen from the earth, but Pluto missed directly occulting any reasonably bright stars. A brief flicker observed during a close brush by a star in 1980 apparently was caused by Charon. A possible occultation in 1985 was obscured by poor observing conditions. Pluto's exact position relative to stars has been difficult to predict because of the wiggle in its motion caused by Charon's gravitational pull. Pluto's uncertain diameter also has confounded astronomers attempting to predict occultations.

In 1985 Douglas J. Mink of Harvard University and Arnold R. Klemola of Lick Observatory identified a 12th-magnitude star in the constellation Virgo that seemed to lie directly in Pluto's path, and they predicted an occultation would occur on June 9, 1988. Additional calculations by Lawrence H. Wasserman of Lowell Observatory indicated that Pluto's shadow would fall on parts of Australia, New Zealand and the South Pacific.

Two teams of astronomers, led by Robert L. Millis of Lowell Observatory and James L. Elliot and Edward W. Dunham of the Massachusetts Institute of Technology, set out on expeditions to record the occultation. They coordinated their efforts with observatories in Australia, New Zealand and Tasmania. In the end, workers at eight sites obtained successful observations.

The star did not vanish abruptly as it slipped behind Pluto's disk but instead dimmed gradually. Such be-

havior is characteristic of starlight being absorbed and refracted as it passes through progressively deeper layers of an atmosphere. The light curve showed a uniform, gradual dip as the star entered the top of Pluto's atmosphere. As the star's image appeared to pass through the lowest levels of the atmosphere, however, the light curve dropped abruptly.

Pluto seems to have a clear upper atmosphere overlying a more opaque lower layer. The boundary between the two appears quite sharp. Two models have been proposed to describe the structure. One assumes that Pluto's atmosphere has a roughly uniform temperature but that sunlight vaporizes the frozen gases on Pluto's surface, creating a low-altitude obscuring haze. In the other model a sharp temperature change between two layers in the atmosphere caused the sudden dimming. Warm and cold air bend light to different extents, an effect that causes the twinkling of stars seen from the earth.

Models by groups at M.I.T. and the University of Arizona have not yet been able to determine which explanation is more plausible. Yet the basic properties of Pluto's atmosphere are now reasonably well understood. It is exceedingly thin—the surface pressure on Pluto is less than one-hundred thousandth of that on the earth. In addition to methane, Pluto's atmosphere may contain heavier gases such as argon, nitrogen (N_2), carbon monoxide (CO) and oxygen (O_2). Nitrogen is the major component of Triton's thin atmosphere, leading many astronomers to suspect that it may make up much of Pluto's atmosphere as well.

It is necessary to know the surface temperature of Pluto to predict what gases might be frozen out of its atmosphere. Using data collected by the National Aeronautics and Space Administration's *Infrared Astronomical Satellite,* Mark V. Sykes of the University of Arizona and his colleagues deduced that Pluto's equatorial surface temperature is about 58 kelvins. This temperature is consistent with the presence of methane in Pluto's atmosphere.

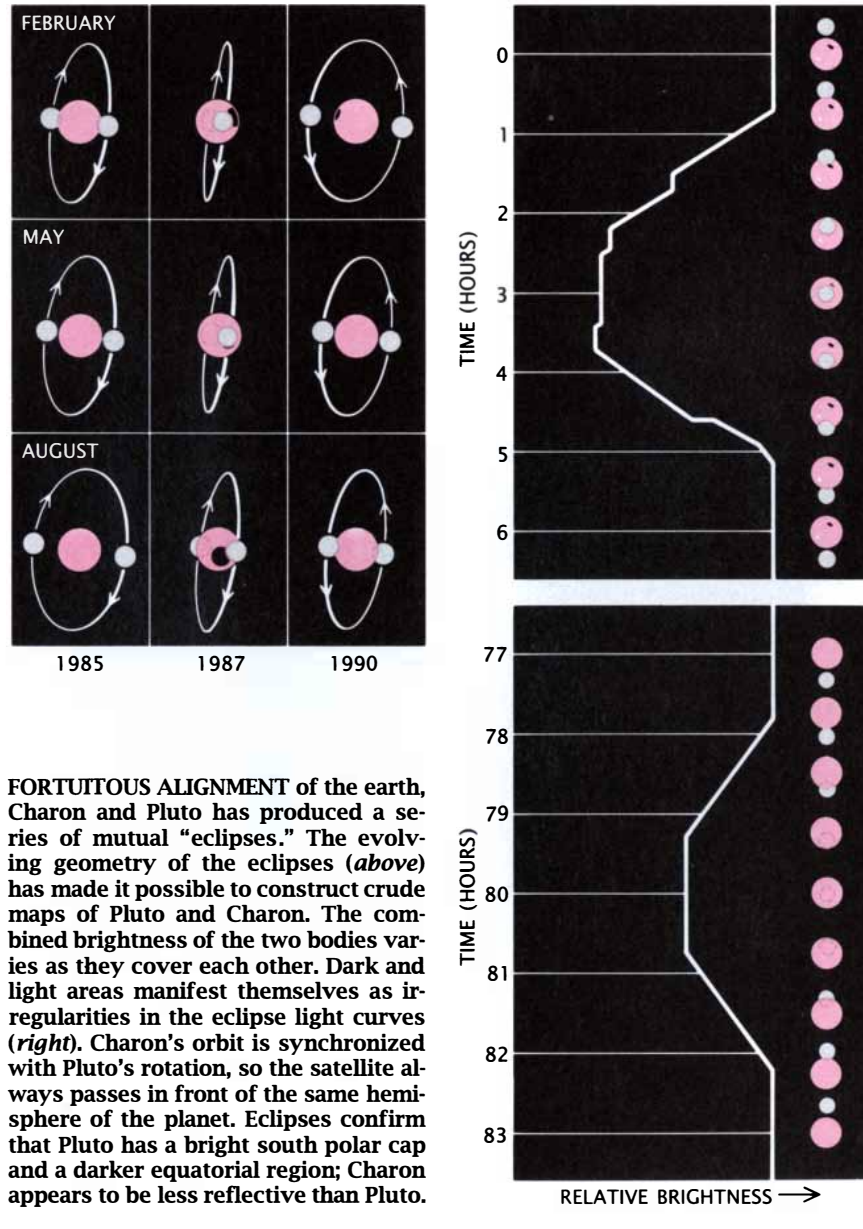
The existence of an atmosphere may answer one question that was raised by the mutual eclipse observations: Why is Pluto's surface so bright? On the average, Pluto is more than seven times as reflective as the moon. This is somewhat surprising because in less than one million years a bright methane ice surface should turn dark and ruddy as a result of chemical reactions caused by ultraviolet radiation from the sun and by energetic particles called cosmic rays. Pluto's reflective surface requires some mechanism to keep the surface ice continuously fresh.

S. Alan Stern of the University of Colorado at Boulder, working with Laurence M. Trafton of the University of Texas at Austin and Randall Gladstone of the University of California at Berkeley, has proposed such a mechanism. Pluto's distance from the sun varies greatly—from 4.5 to 7.4 billion kilometers—as a result of its highly eccentric orbit, producing extreme temperature variations. Depending on its overall composition, Pluto's atmosphere may be only a temporary phenomenon that occurs when the planet is closest to the sun.

Pluto reached perihelion in 1989. As it retreats, it will grow colder. In perhaps 20 to 40 years the atmospheric methane may condense onto the surface, covering the planet with a fresh layer of methane snow. This layer would remain on the surface until Pluto once again approaches the sun.

The Pluto-Charon eclipses and the stellar occultation have unveiled so many new details of Pluto's physical characteristics that it is finally possible to consider the question of Pluto's formation. Pluto's density is greater than those of the gaseous outer planets and most of their icy satellites. This has prompted some investigators to wonder—especially in early years, when Pluto's density was thought to be even greater—if perhaps Pluto formed somewhere else, such as in the vicinity of the earth and the other dense bodies in the inner solar system.

Calculations of Pluto's orbital motion covering a period of 845 million years, performed by Gerald J. Suss-



FORTUITOUS ALIGNMENT of the earth, Charon and Pluto has produced a series of mutual "eclipses." The evolving geometry of the eclipses (*above*) has made it possible to construct crude maps of Pluto and Charon. The combined brightness of the two bodies varies as they cover each other. Dark and light areas manifest themselves as irregularities in the eclipse light curves (*right*). Charon's orbit is synchronized with Pluto's rotation, so the satellite always passes in front of the same hemisphere of the planet. Eclipses confirm that Pluto has a bright south polar cap and a darker equatorial region; Charon appears to be less reflective than Pluto.

man and Jack L. Wisdom of M.I.T., indicate that Pluto's orbit is chaotic over long periods. Pluto could in fact have formed elsewhere and evolved to its present orbit. These researchers still consider it most likely that Pluto formed in the outer solar system and that chaotic behavior led to its current eccentric and highly inclined orbit.

Current theories hold that the solar system condensed out of a collapsed nebula of gas and dust. Several recent studies suggest that relatively dense bodies could have formed in the outer fringes of this nebula. At the low temperatures and pressures in these regions, most carbon binds with oxygen to form carbon monoxide, and only a small fraction of the carbon manages to form methane. Oxygen is more abundant than carbon. Leftover free oxygen can combine with silicon (creating, for instance, SiO_4, essentially common sand) and other metals to create rocky materials. Water ice (H_2O) results when oxygen chemically binds to hydrogen atoms. The studies predict that rocky material and ice should have mass abundances of 75 and 25 percent, respectively. The carbon monoxide gas would have been driven away by strong winds flowing from the newborn sun, leaving the dense material behind.

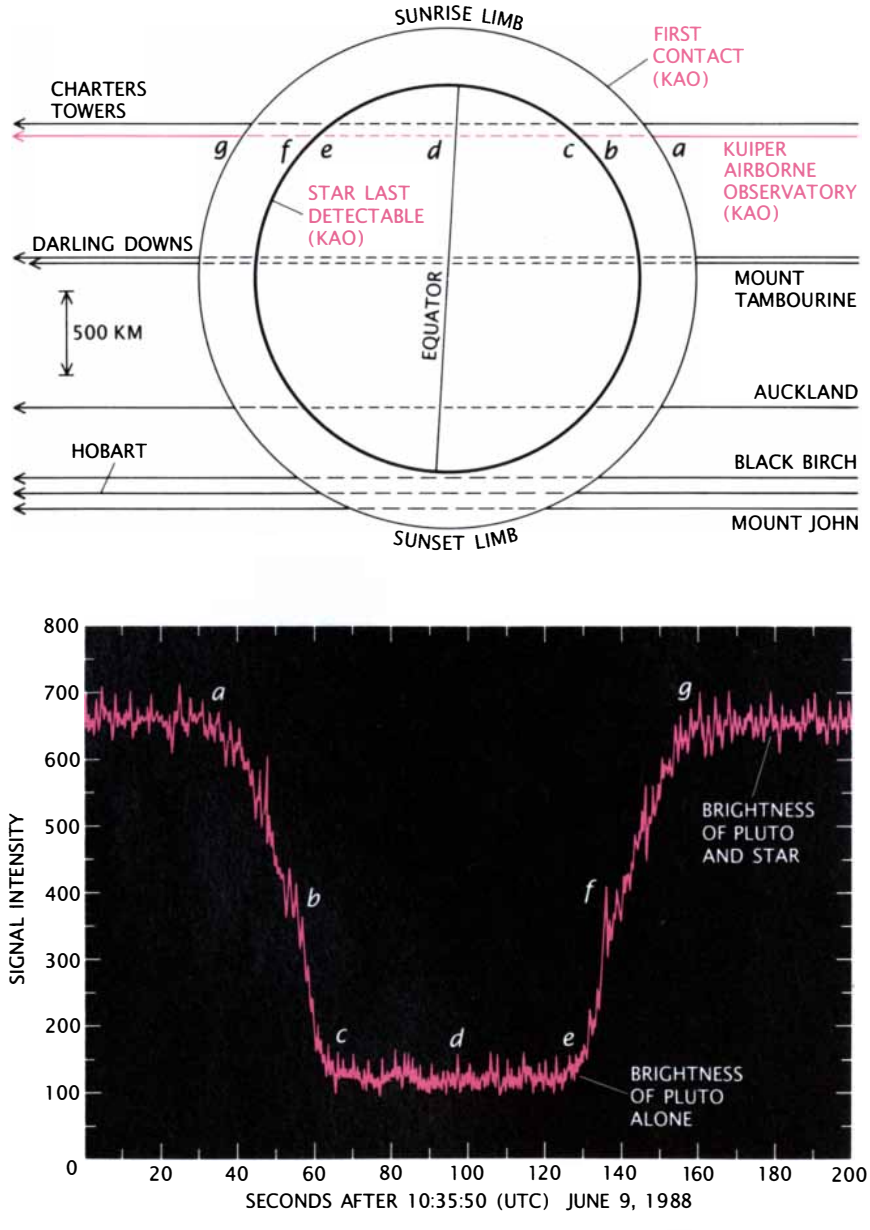
Drawing on this possibility, William B. McKinnon of Washington University, Steven W. Mueller of Southern Methodist University and Damon P. Simonelli of NASA's Ames Research Center constructed detailed models of Pluto's formation and internal composition. Pluto's observed density can be nicely accounted for if the planet is 68 to 80 percent rock and the rest a mixture of ices. This would make Pluto a rockier body than the satellites of Saturn and Uranus. These bodies formed near protoplanets, where the relatively high temperatures and pressures destroyed the carbon monoxide. In these regions the formation of methane and water ice was not inhibited, and so the satellites have high proportions of these lightweight materials. The low densities typical of the satellites of the outer planets eliminate the old hypothesis that Pluto is an escaped satellite of Neptune.

Planetary astronomers have long suspected that Pluto is similar to Neptune's large moon, Triton. Prior to *Voyager 2*'s Neptune encounter last year, astronomers knew more about Pluto than Triton, but the situation is now reversed. Triton's diameter (2,700 kilometers), density (2.08 grams per cubic centimeter) and atmospheric thickness closely resemble those of Pluto. The similar densities suggest that both Pluto and Triton formed as independent bodies in the cold outer regions of the protoplanetary nebula dominated by carbon monoxide.

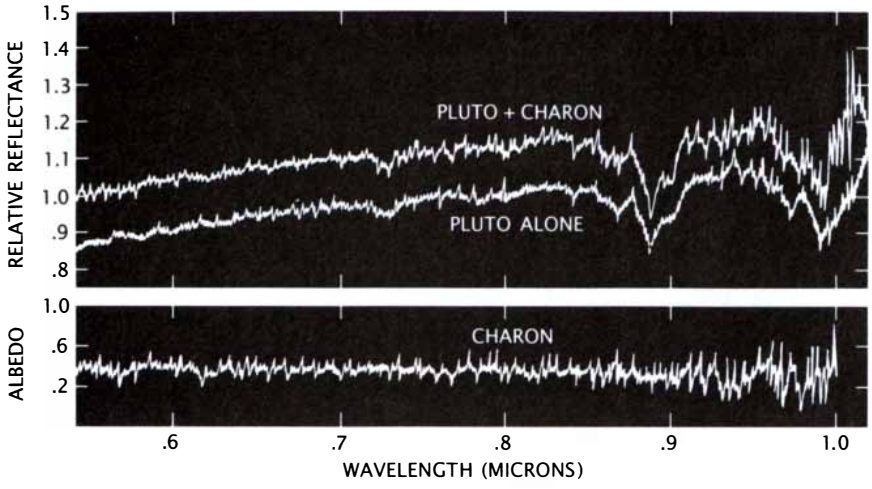
Triton probably was captured shortly after its formation and ended up in its peculiar backward (retrograde) orbit about Neptune. Pluto evidently managed to avoid being swallowed, captured or ejected from the solar system. Instead it settled into a stable 3:2 resonance with Neptune, so that Neptune completes three orbits in the time that Pluto completes two. As a result, Pluto never approaches within 2.7 billion kilometers of Neptune and has been able to avoid a disruptive close encounter.

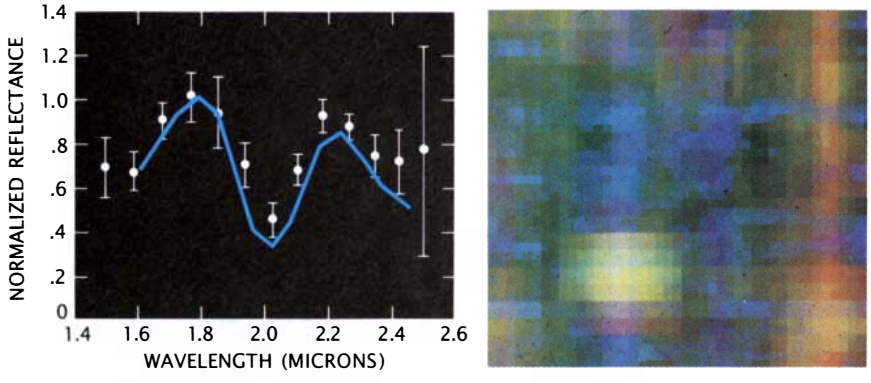
Triton's capture by Neptune set its evolution on a different course. The gravitational stresses and tides Triton experienced would have heated its interior. This heating may be responsible for the baffling, complex structures seen on Triton's surface. Pluto may also have undergone significant internal heating of its own as a result of its interactions with Charon, although this depends on how Charon formed.

When Pluto formed, its interior probably was sufficiently hot for its constituent components to settle out by density: rock would have sunk, creating a core, water would be in the mid-



TWINKLING STARLIGHT demonstrated that Pluto has an atmosphere. Astronomers at eight sites watched as Pluto passed in front of a distant star on June 9, 1988 (*top*). The star dimmed gradually as its light entered the atmosphere. A sharp drop in the light curve (*b* and *f*), observed on board the *Kuiper Airborne Observatory*, indicates a transition layer in Pluto's atmosphere (*bottom*). This may be a low-lying haze or a region of rapid temperature change in the atmosphere.





SPECTRA OF PLUTO AND CHARON normally appear blended together. When Charon is hidden by Pluto, light is received from Pluto alone. Dips in Pluto's spectrum are produced by methane. Subtracting Pluto's spectrum from the combined spectrum reveals the flat spectrum of Charon (*top*). Charon evidently has no methane; its spectrum at longer wavelengths (*bottom left*) resembles that of water ice (*blue line*). Pluto and Charon were observed by the *Infrared Astronomical Satellite* (*bottom right*). Blue and red represent warmer and colder measurements, respectively; the measurements are consistent with icy surfaces and a thin atmosphere.

dle and methane would have floated to the top to create the methane-ice surface that is seen today.

If Pluto and Charon formed together as a double planet, then they may have similar internal compositions and may be nearly unaltered samples of the nebula from which the solar system condensed. If Charon formed as the result of a collision between Pluto and another object (such as a smaller planetesimal), then Pluto also would have experienced additional internal heating after its formation, and the composition of the two bodies might be very different. Such a collision hypothesis is current-ly favored by many researchers to explain the origin of the earth's moon. Determining the relative densities of Pluto and Charon will help unravel Charon's origin.

There also may be differences between the surfaces of Pluto and Triton as a result of Pluto's eccentric orbit and its consequent seasonal variations. Pluto may have the most extensive surface-atmospheric interactions of any planet. Unfortunately, a comprehensive understanding of Pluto's surface and atmospheric dynamics will not be possible until Pluto is examined at close range by a spacecraft. A planned Pluto flyby, originally scheduled as part of the "Grand Tour" concept of the 1970's (which eventually led to the Voyager missions), was scrapped because of funding limitations and the preconception that Pluto was "uninteresting."

The new insights into Pluto's complex nature has renewed interest within the scientific community for a spacecraft mission to this distant world. The trajectory for a Pluto mission will involve a trade-off between the travel time and the duration of the scientifically useful encounter. A high-velocity trajectory provides a faster trip to Pluto and increases the likelihood that the spacecraft will be operating reliably when it reaches the planet. But it also means that the craft will pass Pluto rapidly with only a brief opportunity for high-resolution imaging. A lower velocity increases demands for reliability because of the longer travel time but allows for a more leisurely encounter.

One mission outline being prepared involves a pair of fairly simple spacecraft, each carrying an imaging system, spectrometer and magnetometer (to measure the magnetic fields around Pluto). Each probe would also include one or more particle detectors that would be active throughout the mission, returning measurements of the solar wind and the enormous bubble of charged particles that surrounds the sun. The probes would be sent on separate trajectories, use the earth and Jupiter for gravitational boosts and arrive at Pluto one year apart. They could be launched early next century and would need about 14 years to reach Pluto. The extended encounter phase would last several months, but the detailed measurements possible during a close encounter would occur over only a few hours.

Sending a pair of spacecraft increases the likelihood that at least one encounter will be successful, and because of economies of scale, the cost would be only slightly more than for a single spacecraft. If both were successful, it would be possible to investigate time-dependent phenomena on Pluto (such as changes in its atmosphere) and to image both hemispheres of Pluto and Charon at high resolution, which cannot be done in a single encounter because of their slow rate of rotation.

A mission to Pluto would complete the human endeavor to perform a preliminary reconnaissance of all the major bodies in the solar system. As each planet has shed some of its secrets, the beautiful, bewildering diversity of nature has grown ever clearer. When the assault on Pluto is at last completed, the one thing we can expect to find is the unexpected.

FURTHER READING

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Biosonar and Neural Computation in Bats

Bats extract remarkably detailed information about their surroundings from biosonar signals. Neurons in their auditory systems are highly specialized for performing this task

by Nobuo Suga

It used to be a common misconception that bats' use of sound pulses to navigate and locate prey is a crude system, the acoustic equivalent of feeling one's way in the dark with a cane. But biosonar has since been shown to be anything but crude: an echolocating bat can pursue and capture a fleeing moth with a facility and success rate that would be the envy of any military aerospace engineer.

In addition to providing information about how far away a target is, bat sonar can relay some remarkable details. Doppler shifts—changes in the frequency of the echo relative to the original signal—convey information not only about the relative velocity of a flying insect but also about its wingbeat. The amplitude of the echo, combined with the delay, indicates the size of the target. The amplitudes of the component frequencies correspond to the size of various features of the target. Differences between the ears in intensity and arrival time of sound give the azimuth of the target, whereas the interference pattern of sound waves reflected within the structure of the outer ear gives the elevation.

The complex neural computations needed to extract this information occur within a brain the size of a large pearl. For the past 27 years my colleagues and I have been exploring the neural mechanisms that underlie the echolocating abilities of bats. The well-defined characteristics of a bat's auditory world make the animal ideal for elucidating the information processing that goes on in its auditory system. Similar mechanisms are undoubtedly shared by other animals.

NOBUO SUGA has been professor of biology at Washington University in Saint Louis, Mo., since 1976. Suga was born in Japan and attended the Tokyo Metropolitan University, where he received his B.A. in 1958 and his Ph.D. in biology in 1963. He then went to Harvard University as a research associate, where he first studied the auditory system of bats with Donald R. Griffin.

There are some 800 species of Microchiropteran bats in the world today, all of which are presumed to echolocate. These species live in diverse habitats and vary greatly in behavior and physical characteristics. Their biosonar pulses also differ, even among species within the same genus. Nevertheless, these pulses can be classified into three types: constant frequency (CF), frequency modulated (FM) and combined CF-FM. CF pulses consist of a single frequency, or tone. FM pulses sweep downward and sound like chirps. Combined CF-FM pulses consist of a long, constant tone followed by a downward chirp, *iiiiiiu*. In many bats the tones are not pure but rather consist of a fundamental, or first, harmonic and several higher harmonics (multiples of the fundamental frequency).

Most bat species emit only one type of pulse. The little brown bat, *Myotis lucifuqus,* is an "FM" bat; it emits FM pulses lasting between .5 and three milliseconds and sweeping downward by about one octave. The mustached bat, *Pteronotus parnellii,* is a "CF-FM" bat; it emits long CF pulses lasting between five and 30 milliseconds followed by a short FM sweep lasting between two and four milliseconds. Several species change their pulses, depending on the situation. The fish-catching bat, *Noctilio leporinus,* for example, emits CF and CF-FM pulses while cruising in flight but emits FM pulses while hunting prey.

A long CF pulse is excellent for detecting targets larger than the wavelength of the signal, because the reflected sound energy is highly concentrated at a particular frequency. It is also ideal for measuring Doppler shifts. The CF pulse is not appropriate, however, for locating a target precisely or discerning its details. A larger number of frequencies is needed to obtain more information about target features. Bats broaden their frequency bandwidth by producing harmonics and by emitting FM bursts that sweep over a wide frequency range. FM pulses also contain more information about time and so are used to compute echo delays and thereby determine the distance to a target.

Certain bat species control the energy in each harmonic depending on the distance to a target. If the target is far away, they amplify the lower harmonics, which are less attenuated by the air. But if the target is nearby, they enhance the higher harmonics to obtain finer details of the target. When closing in on prey, Microchiropterans shorten the duration of pulses and increase the rate of pulse emission, up to 200 per second in FM bats and up to 100 per second in CF-FM bats. This adjustment occurs not only because bats need to characterize the prey in greater detail but also because when the distance between a bat and its prey is small, the angular position of the prey changes more rapidly, and so the bat needs to emit more signals to track the prey accurately.

The hunting strategies and behavior of a bat species are directly related to the characteristics of its biosonar. The

MUSTACHED BAT sweeps in for a mid-flight drink from a pond. This species' biosonar has been studied extensively.

key elements of the biosonar, in turn, are reflected in the functional organization of its auditory system. Since bat biosonar was established by Donald R. Griffin and Robert Galambos four decades ago, neuroethologists have studied the auditory system in several bat species but most of all in the little brown bat, the mustached bat and the horseshoe bat, *Rhinolophus ferrumequinum*. Each of these bats produces distinctive biosonar pulses.

The auditory mechanisms of the mustached bat have been the most thoroughly examined. The biosonar and peripheral auditory system of this bat were first described in 1964 and 1972, respectively, by Alvin Novick and his co-workers at Yale University. In 1972 I began research on the peripheral auditory system of the mustached bat with James A. Simmons, now at Brown University, and on the central auditory system with Philip H.-S. Jen, now at the University of Missouri at Columbia. Subsequently, Toshiki Manabe and Kazuro Kujirai, now at Yokohama City University, William E. O'Neill, now at the University of Rochester, and nearly two dozen others have joined in studying this bat's central auditory system and its neural mechanisms for processing biosonar information. This article will mainly describe findings for this species.

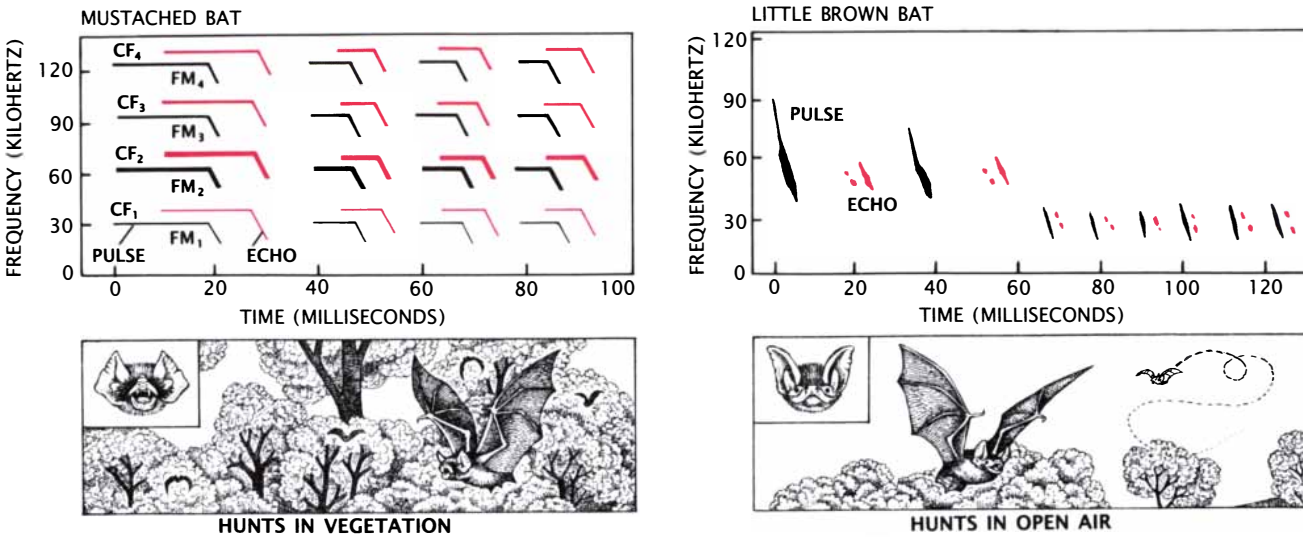
A flying mustached bat detects the relative velocity of objects by the Doppler shift in the echoes. When a bat flies toward a stationary object, the pulses that strike and are reflected by it become compressed, or Doppler-shifted. The echo received by the bat is therefore uniformly higher in frequency than the emitted pulse. When the animal flies toward a flying insect, the insect's beating wings introduce oscillating frequency shifts, which are superposed on the overall Doppler shift, like small surface ripples on an ocean wave.

Certain bats, such as the mustached bat and horseshoe bat, can detect ripples from insect wings against the echoes associated with stationary objects, such as walls and vegetation. How do they do it? Part of the answer lies in a trick called Doppler-shift compensation, first seen by Hans-Ulrich Schnitzler of the University of Tübingen. A mustached bat at rest emits a fundamental tone of around 30.5 kilohertz, along with three higher harmonics; the "resting" frequency of the second harmonic (CF_2) is around 61 kilohertz. If the bat detects a Doppler-shifted echo at 63 kilohertz from a stationary object, it reduces the frequency of emitted pulses by about 1.8 kilohertz, so that subsequent echoes are stabilized at a "reference" frequency of around 61.2 kilohertz.

These bats turn out to be specialized to analyze tiny differences in frequencies near the reference frequency. Hence, Doppler-shift compensation brings the echo CF_2 into the range at which the bat can most easily detect ripples from beating insect wings.

This specialization begins in the bat's ear. Of particular interest is the inner ear, or cochlea, which contains the basilar membrane, a thin, elongated sheet curled up like a snail. When sound waves vibrate the eardrum, this vibration is conducted to the basilar membrane, stimulating tiny hair cells on the membrane. The excitation is transmitted, via the spiral ganglion cells, along the auditory nerve fibers to the brain.

The neural signal produced at the cochlea must contain all the information vital to the bat. The physical properties of an acoustic signal—amplitude, time and frequency—must in



BIOSONAR PULSE of the mustached bat consists of a long, constant-frequency (CF) component followed by a short, frequency-modulated (FM) component. Each pulse contains four harmonics (indicated by subscripts). When closing in on a target, the bat emits shorter pulses at a higher rate, while keeping the same tones. The little brown bat emits only FM chirps. When nearing a target, it emits shorter, lower chirps at a faster rate. Each species emits pulses suited to its behavior.

turn be translated into neural activity. Amplitude is expressed by the rate at which the auditory nerve fibers discharge impulses: the greater the amplitude, the higher the discharge rate. The duration of signals and the intervals between them are mimicked by the pattern of the nerve impulses. The frequency of the signal is expressed by location on the basilar membrane: high frequencies vibrate the portion nearest the eardrum, whereas lower ones stimulate portions farther in.

A certain portion of the mustached bat's basilar membrane is unusually thick. This thickness is related to extreme sensitivity to frequencies of between 61.0 and 61.5 kilohertz (the CF_2 of the Doppler shift–compensated echoes) as well as insensitivity to frequencies of around 59.5 kilohertz (the CF_2 of the Doppler shift–compensating pulses). In other words, the membrane is strongly stimulated by the echoes but poorly stimulated by the animal's own vocalizations.

The frequency selectivity of the spiral ganglion cells is extremely high within the key range of 61.0 to 61.5 kilohertz. They are tuned to single frequencies. That is, each neuron has a "best" frequency (the frequency that evokes the largest response), which differs slightly from that of its neighbors. Indeed, these neurons are so sharply tuned to their best frequencies that they can detect shifts as small as .01 percent. Flying insects can easily evoke frequency shifts an order of magnitude greater. The auditory periphery is also highly tuned to analyze frequency shifts near CF_1 (30-kilohertz) and CF_3 (92-kilohertz) signals.

In the mustached bat the great sensitivity and sharp tuning of the auditory periphery to the CF_2 frequency are combined with Doppler-shift compensation to proffer three advantages. First, the auditory periphery is exquisitely sensitive to the CF_2 echo (near 61 kilohertz) but is insensitive to the bat's emitted CF_2 pulse (near 59 kilohertz) during Doppler-shift compensation; hence, masking of the echo by the emitted pulse is minimal. Second, the sharply tuned neurons are well able to detect the signal even if it is embedded in background noise. Third, the array of sharply tuned neurons has a high likelihood of picking up the echo from the beating wings of a flying insect as the echo sweeps up and down in frequency.

These advantages enable the mustached bat to hunt insects successfully, even in dense vegetation. Doppler-shift compensation and frequency tuning do not exist in FM bats, such as the little brown bat, which hunt in open air.

Once the auditory signal has been coded into nerve signals, it must be further analyzed to extract such information as the velocity or distance of prey. This process occurs in the central auditory system. From the cochlea, signals are processed sequentially, beginning at the cochlear nucleus and proceeding to the lateral lemniscus, inferior colliculus, medial geniculate body and finally to the auditory cortex.

Using slender electrodes to record nerve impulses from single neurons, my colleagues and I studied the responses of neurons in the mustached bat's auditory system as we stimulated the animal with biosonar signals. What we discovered was an extraordinarily developed system for processing that information. In particular, we found that different processing tasks are parceled out among several anatomically distinct areas of the auditory cortex. One region contains neurons that respond only to certain frequencies and amplitudes of echoes. A second region responds only to frequency differences between pulses and echoes. A third region is sensitive to the time interval between pulses and echoes.

By far the largest of the specialized regions in the mustached bat's auditory cortex is the one that processes Doppler-shifted CF_2 signals. This region, called the DSCF area, represents only a narrow sliver of the frequency range, between 60.6 and 62.3 kilohertz (when the bat's resting frequency is 61.00 kilohertz). Yet it occupies 30 percent of the primary auditory cortex. The exact frequencies overrepresented differ among individual bats according to their resting frequencies. In other words, each bat's auditory system is personalized.

Similar overrepresentation is found in the brain wherever the signal being processed is critical to an animal's behavior. For example, in cats and monkeys the visual cortex overrepresents the fovea, the area of the retina where visual acuity is highest. The primate somatosensory cortex overrep-

resents the tactile sense of the fingers.

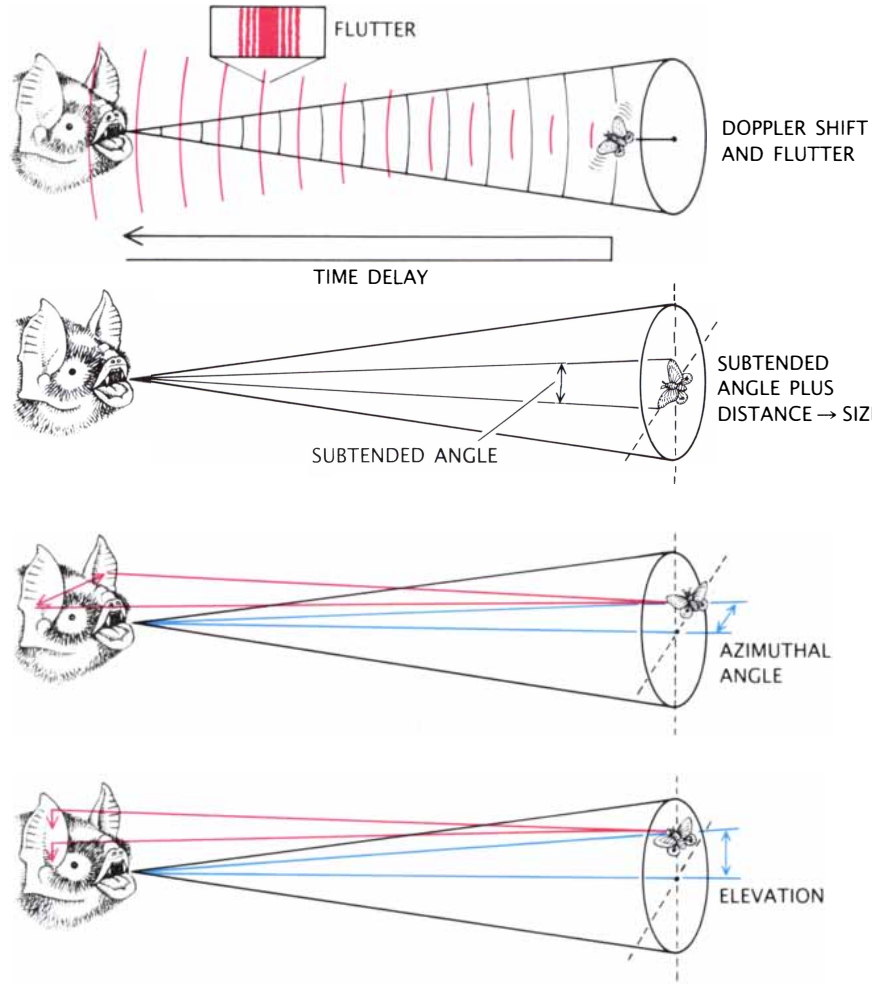
Neurons in the DSCF area are sharply tuned to particular frequencies, even more so than neurons in the auditory periphery. They are also tuned to the amplitude of a signal. Hence, each DSCF neuron has a particular frequency and amplitude to which it responds best. This sharpening of the response is apparently the result of lateral inhibition, a ubiquitous mechanism in sensory systems by which inhibitory signals from adjacent neurons enhance the selectivity of a neuron to a particular stimulus.

The auditory cortex of the mustached bat is about 900 microns, or some 40 to 50 neurons, thick. When we inserted a recording electrode into the cortex, we found that all of the neurons perpendicular to the surface are tuned to an identical frequency and amplitude. Hence, the DSCF area has a "columnar organization." Such columnar organization was first discovered in 1959 in the somatosensory cortex of monkeys by Vernon B. Mountcastle of Johns Hopkins University and later in the visual cortex of cats by David H. Hubel and Torsten N. Wiesel [see "Brain Mechanisms of Vision," by David H. Hubel and Torsten N. Wiesel; SCIENTIFIC AMERICAN, September, 1979].

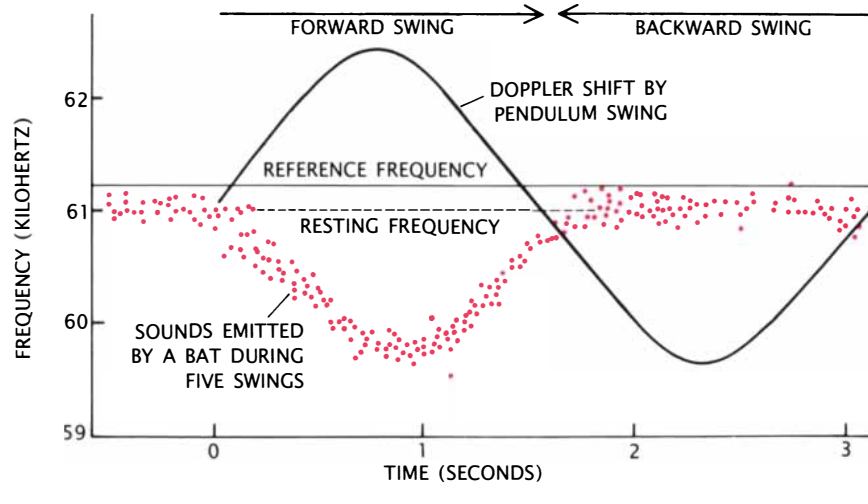
When we inserted an electrode tangentially to the cortical surface of the DSCF area, we found that the preferred frequency and amplitude gradually change, indicating the existence of frequency-versus-amplitude coordinates along the surface of the DSCF area. One can (crudely) picture the area as a bicycle wheel: as one moves outward along a spoke, the best frequency of the neurons increases; as one moves circularly from one spoke to the next, the best amplitude changes.

What is the function of the DSCF area? Neurons in the area respond purely to the amplitude and frequency of the echo CF_2, regardless of the frequency of the emitted pulse. DSCF neurons, then, presumably are related to the acuity of frequency and amplitude discrimination, as well as to the detection of changes in frequency and amplitude that would be evoked by flying insects.

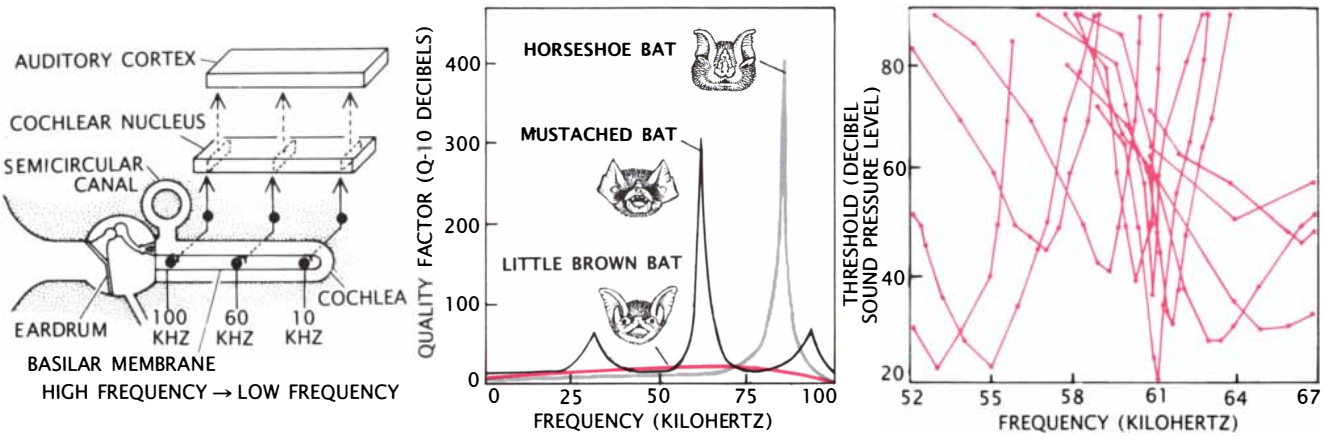
According to recent experiments by Stephen J. Gaioni, Hiroshi Rikimaru and me, if the DSCF area is destroyed, a bat can no longer discriminate tiny differences in frequency—only large ones. The animal requires twice as much time to carry out Doppler-shift compensation and performs the task only half as well. From this we spec-



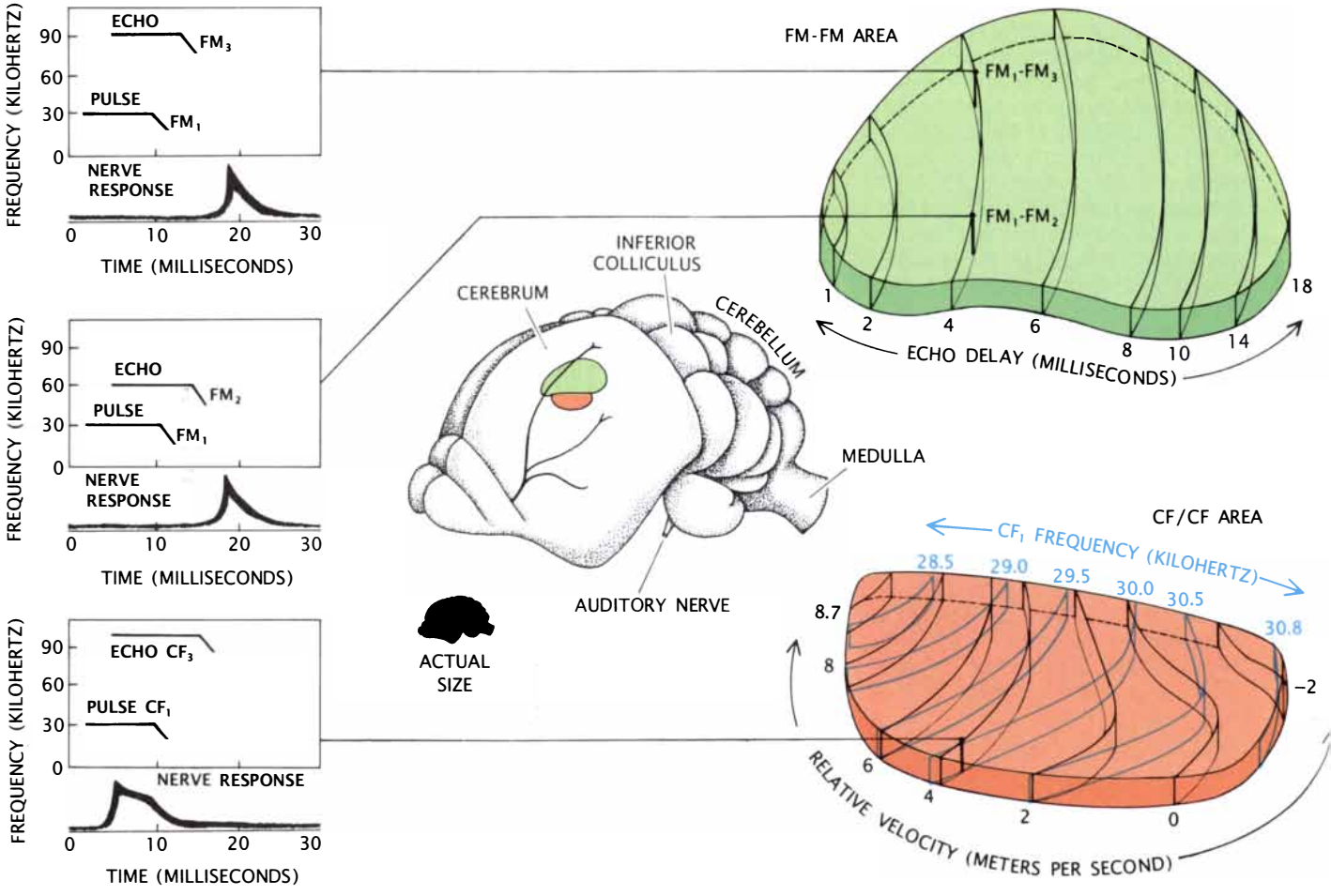
DIVERSE INFORMATION can be extracted from biosonar signals. The time delay and Doppler shift of the echo indicate the distance and relative speed of the target. Rapid flutters betray the presence of beating insect wings. Echo amplitude depends on the relative size (subtended angle) and distance of the target. Interaural time and amplitude differences convey the azimuth of the target. Interference patterns of sound waves reflected within the structure of the outer ear indicate the elevation.



DOPPLER-SHIFT COMPENSATION is demonstrated by placing a mustached bat on a pendulum. During the forward swing the animal lowers the frequency of its emitted pulse (*red*) such that the echo stays at a "reference" frequency. The animal does not compensate for Doppler shift during the backward swing. O'Dell W. Henson, Jr., of the University of North Carolina at Chapel Hill first performed the experiment.



BASILAR MEMBRANE is vibrated at the outer part by high frequencies and at the inner part by lower frequencies. The vibrations excite hair cells, which in turn excite spiral ganglion cells. The middle graph shows the high selectivity in the mustached bat of neurons tuned to the three higher CF harmonics, particularly at 61 kilohertz (CF_2) but also at 30 kilohertz (CF_1) and 92 kilohertz (CF_3). High selectivity is also found in horseshoe bat auditory neurons tuned to 83 kilohertz, the CF_2 harmonic of that species. Because the little brown bat produces only an FM pulse, it has no such neurons. The graph on the right shows response thresholds of 12 mustached bat neurons; for each neuron the threshold plummets at a particular frequency. The plunge is very steep for neurons that respond to frequencies near 61 kilohertz, the CF_2 harmonic.

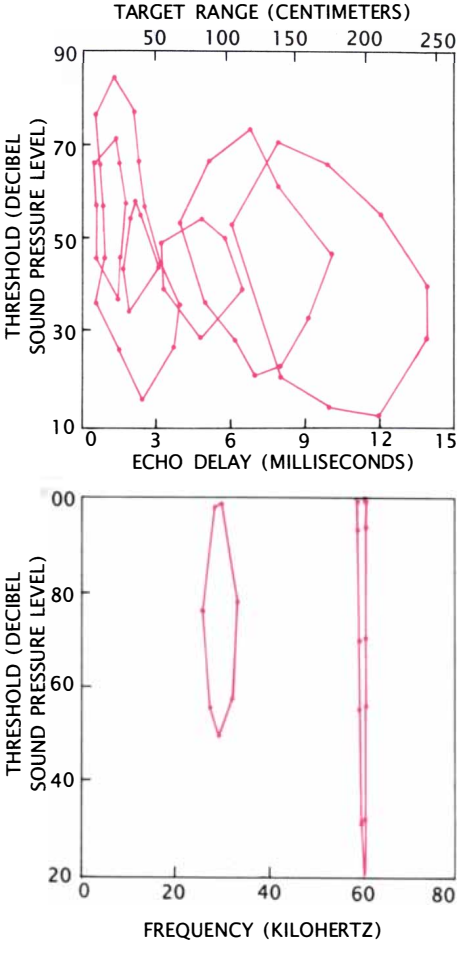


COMPUTATIONAL MAPS in the auditory cortex of mustached bats represent echo delay (or distance) and Doppler shift (or relative velocity). In the FM-FM area (*green*), neurons along each black line respond to a specific echo delay. The top graph (*right*) shows the delay-tuning curves of six FM-FM neurons; each neuron responds to a specific echo delay and amplitude. In the CF/CF area (*tan*), neurons along the blue lines respond to a specific CF_1 combined with varying CF_2. Neurons along the black lines respond to Doppler shifts corresponding to a specific relative target velocity. The bottom graph (*right*) shows

ulate that the DSCF area is responsible for the precision of the Doppler-shift compensation but not for performing the actual compensation. We do not know yet how the DSCF area is connected to other regions that are responsible for executing Doppler-shift compensation.

One important function that we understand well is that of perceiving the relative velocity of a target. To do this, the bat's brain must compute the Doppler shift between the emitted pulse and the echo. In other words, there must be neurons that "examine" the frequency relation between the two sounds.

We have found such neurons in a part of the auditory cortex that we call the CF/CF area. There are two types of CF/CF neurons: CF_1/CF_2 and CF_1/CF_3, each of which forms a distinct region. These neurons are sensitive to the frequency relation between the constant-frequency harmonics. In particular, the CF_1/CF_2 and CF_1/CF_3 neurons respond when a tone of between 28 and 30 kilohertz (CF_1) is coupled with a tone around 61 kilohertz (CF_2) or 92 kilohertz (CF_3), respectively. (The CF_2 and CF_3 frequencies are not exactly two and three times the CF_1 but are slightly higher to account for Doppler shift in the echo.)



the frequency-tuning curves of a CF_1/CF_2 neuron. This neuron is most responsive when stimulated by a CF_1 of 29.38 kilohertz at 63 decibels combined with a CF_2 of 60.52 kilohertz at 45 decibels.

When the pulse, echo, CF tone or FM sound is delivered alone, these neurons respond very weakly. But when the pulse and echo are combined, they show a remarkably strong response, becoming sensitive to paired signals that are as much as 6,300 times weaker than the smallest unpaired signals capable of evoking a response.

The functional organization of the CF/CF area supports our conclusion that these neurons are primarily devoted to processing velocity information. Each column of neurons responds best to a particular combination of two frequencies, for example, 29.60 and 61.20 kilohertz. Neurons at a slightly different location respond to a different combination, say, 30.05 and 61.10 kilohertz.

Further measurements showed that the best combination of frequencies varies in a regular way along the surface of the cortex. The preferred CF_1 frequency increases along one axis, and the CF_2 and CF_3 frequencies increase along the axis at right angles to it. In other words, the CF/CF region is organized by a frequency-versus-frequency coordinate system, in which a specific location represents a particular relative target velocity.

Because the harmonics are simply integer multiples of the fundamental tone, CF_1, a comparison between the pulse CF_1 and the echo CF_2 or CF_3 will yield the Doppler shift. For example, a particular neuron may respond only if there is both a 30-kilohertz pulse CF_1 and a 61-kilohertz echo CF_2; because the pulse CF_2 frequency is double the pulse CF_1 frequency, or 60 kilohertz, the Doppler shift in the echo is one kilohertz. This shift would arise if the target were moving at a relative speed of 2.8 meters per second.

We have determined that within both the CF_1/CF_2 and CF_1/CF_3 regions there is an axis representing velocities between minus two and plus nine meters per second. What is more, a disproportionate number of neurons represent velocities from zero to four meters per second. These speeds arise during activities critical to the animal, such as when a bat is about to land on its roost or capture an insect.

Having found the CF/CF area, we wanted to know where along the auditory pathway the process of comparing frequencies first arises. We already knew that it is absent in the peripheral auditory system, and so it must occur somewhere in the central auditory system. Based on electrophysiological measurements made along the auditory pathway, my graduate student John F. Olsen, now at Stanford University, found that neurons in certain regions of the inferior colliculus are tuned to single frequencies: CF_1, CF_2 or CF_3. They send signals to a certain region of the medial geniculate body, where the signals are integrated, so that neurons there respond to the combination of CF_1 frequencies with specific CF_2 or CF_3 frequencies. These neurons then project to the CF/CF area of the auditory cortex.

So far I have described auditory processing of only the CF components of biosonar. But the mustached bat also produces an FM sound at the end of the CF component. What is the purpose of this FM sound? The FM signal provides the primary cue for measuring the time interval between a pulse and echo—and hence the distance to a target. A one-millisecond echo delay corresponds to a target distance of 17.3 centimeters (at an air temperature of 25 degrees Celsius). Simmons found that several species of bats can detect a difference in distance of between 12 and 17 millimeters, which means they can discriminate a difference in echo delay of between 69 and 98 millionths of a second!

As in the CF/CF area, the processed information, in this case echo delay, is represented by a "map" in a distinct region of the auditory cortex, which we call the FM-FM area. There neurons respond poorly if a pulse, echo, CF tone or FM sound is presented individually, but they respond strongly if a pulse is followed by an echo having a particular delay time. In extreme cases an FM-FM neuron can be 28,000 times more sensitive to a pulse-echo pair than it is to either signal alone.

FM-FM neurons compare the emitted pulse FM_1 with the delayed echo FM_2, FM_3 or FM_4. Each of the three types of delay-sensitive neurons is clustered in its own subdivision. Each FM-FM neuron is tuned to a particular echo delay, and most also prefer a particular echo amplitude. As a result, most FM-FM neurons respond to a target that is located at a particular distance and has a certain size.

The functional organization of the

FM-FM area supports our conclusion that this area is primarily devoted to processing distance information. Each column of neurons responds to a particular echo delay, and the columns are arranged so that the preferred delay increases along one axis. This axis represents delays from .4 to 18 milliseconds, or target ranges of from seven to 310 centimeters. The resolving power of this neuron array is presumably such that an animal can detect a difference in target distance of about 10 millimeters. And indeed, studies of bat behavior by Simmons bear out this presumption.

How do pathways in the auditory system give rise to neurons that are sensitive to pulse-echo delays? As with neurons that respond to combinations of frequencies, those that respond to pulse-echo delays are first found in the medial geniculate body. To find out how these neurons are connected to the rest of the auditory pathway, Olsen injected them with horseradish peroxidase, which diffuses along nerve pathways. The substance made its way to two distinct groups of cells in the inferior colliculus as well as to the FM-FM area of the auditory cortex.

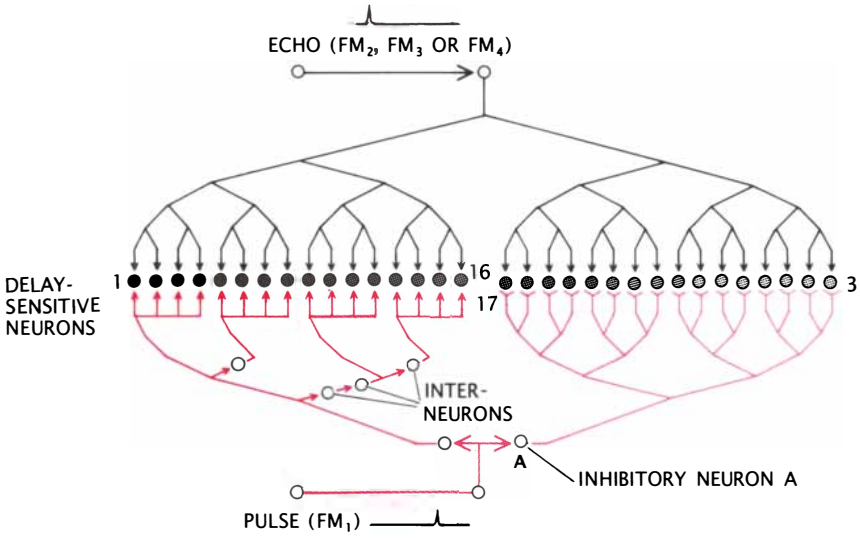
Clearly, the two groups of collicular neurons, one group tuned to the pulse FM_1 and the other to higher harmonics in the echo FM, converge on a single group of neurons in the medial geniculate to create neurons sensitive to combinations of FM components. My graduate student John A. Butman has shown that this combination sensitivity is mediated by the receptor for *N*-methyl-D-aspartate (NMDA) to a large extent. The receptor's biophysical properties cause the neuron's response to be amplified when neural inputs coincide. Hence, the receptor performs the logical AND operation (as in "IF *A* AND *B*, THEN *C*").

How do these neurons become sensitive to echo delays? Olsen has found that FM-FM neurons in the medial geniculate body do not respond to echo delays as strongly as do the FM-FM neurons in the auditory cortex and that they respond somewhat to unpaired pulses and echoes. Significantly, these neurons always take longer to respond to the pulse FM_1 than they do to the echo FM_2, FM_3 or FM_4. What is more, the difference in response latency is the same as the preferred pulse-echo delay for each neuron.

These observations indicate an interesting mechanism for the computation of echo delays. When a bat hears its own emitted pulse FM_1, the neural response is delayed as it travels toward the medial geniculate body. But the response to the returning echo is not delayed. The delayed response to the pulse then arrives at a particular neuron in the medial geniculate body at the same time as the undelayed response to the echo. The coincidence of these two responses causes that neuron to generate its own signal. This theory suggests a neural network in which multiple delay lines form an array of neurons that responds to a range of echo delays.

Where are these delay lines? In the medial geniculate body or closer to the periphery? Because we first saw the difference in response latency for pulses and echoes in the signals issuing from the inferior colliculus, we concluded that some delay lines must be within the inferior colliculus itself. In the mustached bat the inferior colliculus is a huge nucleus protruding between the cerebrum and cerebellum. Nerve fibers ascend from the ventrolateral portion of the colliculus to its dorsomedial portion. Impulses travel a distance of about two millimeters along these nerve fibers, exciting 100 or more neurons along the way, and introduce delays of up to eight milliseconds.

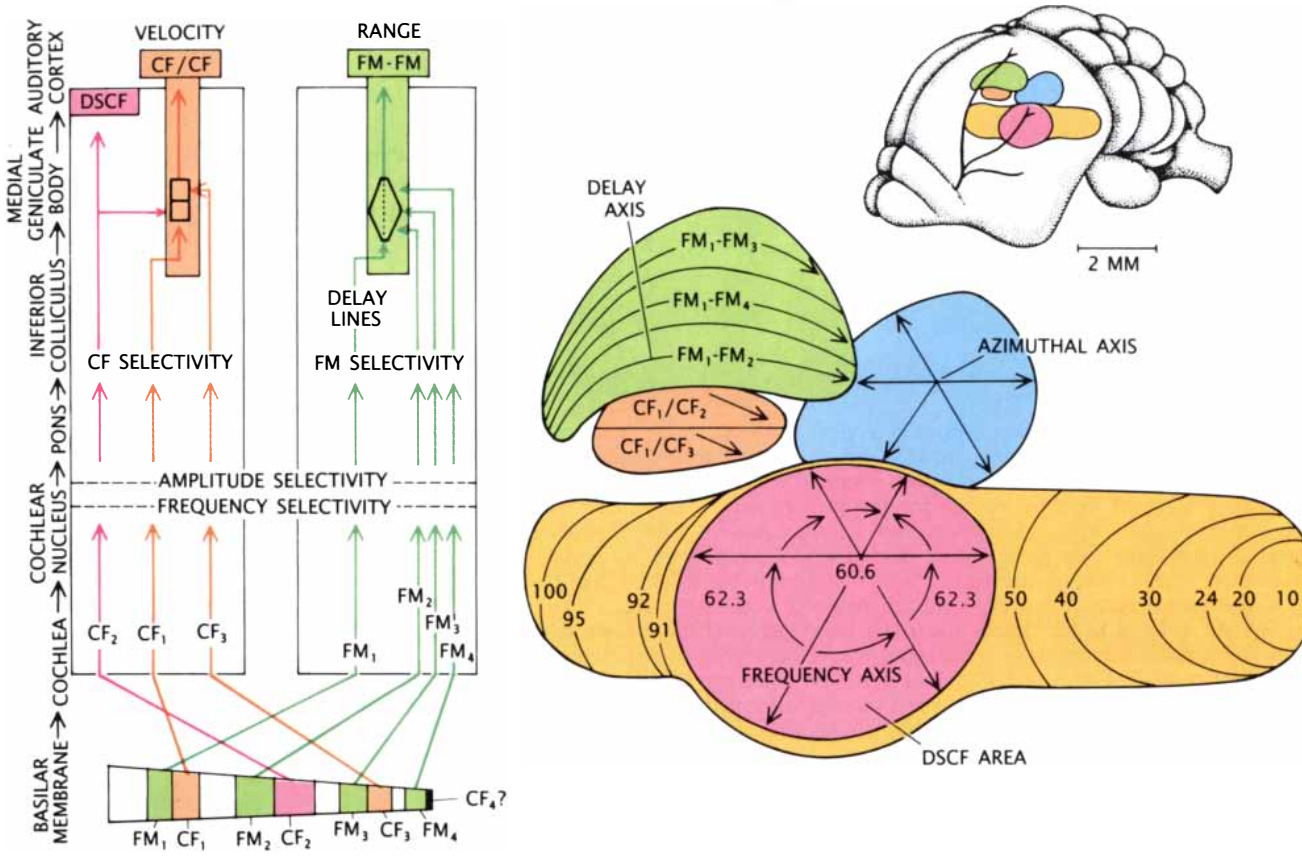
Recall, however, that delays in the FM-FM area of the auditory cortex are as long as 18 milliseconds. Hence, the delay lines in the inferior colliculus do not account for the full range of delays. The data suggest that additional delays are created by inhibitory synapses in the medial geniculate body.



NEURAL NETWORK creates neurons that respond to specific echo delays. The network delays the response to a pulse FM_1, so that it arrives at a neuron at the same time as the response to a higher harmonic of the echo FM, triggering a response from that neuron. The pulse response is slowed by a combination of axonal delays (because it takes time for a nerve impulse to travel along an axon) and synaptic delays. Even longer delays can be created by inhibition. Neuron *A* inhibits neurons 17 through 32; after a time, the inhibition wears off, beginning with neuron 17, and the neurons become briefly excited. (Paler colors indicate longer delays.) The response to the echo, on the other hand, spreads to all of the neurons simultaneously.

So far I have discussed how the mustached bat extracts such information as the velocity and range of a target. But in doing so, I have avoided the question of why the bat emits a variety of harmonics. Why is one harmonic not enough? Technically it should be, but the animal has to cope with another problem. Bats live in colonies with hundreds of other bats, and somehow they must be able to use echolocation without getting confused. Several mechanisms, including binaural hearing, help to cope with this air-traffic controller's nightmare. One important mechanism depends on the first harmonic.

The first harmonic is the weakest component of the emitted pulse, containing less than 1 percent of the total energy in the pulse. Indeed, the pulse is so feeble that other bats can barely hear it. About all a flying bat hears from its roostmates are the higher harmonics. Combinations of the higher harmonics, however, cannot excite FM-FM or CF/CF neurons. When a bat emits a pulse, however, it can hear its own first harmonic, which is conducted from its vocal cords to its ear through the surrounding tissue. This sound, in combination with higher



PARALLEL PATHWAYS process different streams of biosonar information (*left*). Various CF and FM harmonics excite different parts of the basilar membrane, and signals are sent to the auditory cortex via several subcortical nuclei. Higher up in the auditory pathway, the neurons become more narrowly selective for frequency and amplitude. In the primary auditory cortex, frequencies from 10 to 100 kilohertz are tonotopically organized (*yellow*); the large area (*pink*) at the center represents 60.6 to 62.3 kilohertz. CF and FM signals are integrated in the medial geniculate body, giving rise to neurons that respond to specific combinations of CF or FM signals. These combination-sensitive neurons project axons to the CF/CF or FM-FM areas of the auditory cortex, creating maps that correspond to the relative target velocity (*tan*) or distance (*green*).

harmonics that are delayed or Doppler-shifted, can then stimulate FM-FM and CF/CF neurons. In this way, the neural processing of biosonar signals is shielded from the cacophony of echoes generated by the colony.

The suppression of the first harmonic confers another important advantage. To avoid being devoured by bats, many species of moths have "bat detectors," or auditory receptors that are highly sensitive to sounds of between 15 and 40 kilohertz but relatively insensitive to higher frequencies. By suppressing the first harmonic, which is between 24 and 31 kilohertz, a mustached bat can approach moths closely without alerting them.

Hearing is as critical to bats as seeing is to visually oriented animals, and so it is not surprising to find evidence of elegant neural computations in bats' auditory cortex. But sound is also biologically important for many other animals. Do they have similar neural mechanisms? It turns out that many do.

Robert R. Capranica of Cornell University and Albert S. Feng of the University of Illinois at Urbana-Champaign have found that frogs process complex sounds, such as mating calls, by way of neurons that respond to combinations of two essential signal elements. Daniel Margoliash of the University of Chicago has observed similar neurons in songbirds. The processing of biologically crucial sounds by combination-sensitive neurons, then, appears to be an important neural mechanism shared among diverse types of animals.

It seems likely that the human auditory system also uses such neural arrays to process speech sounds. Even though the processing of speech is unique and predominantly a function of the neocortex, the subcortical auditory regions, with their combination-sensitive neurons, may analyze the sounds of speech to a greater extent than has been generally thought. The work pioneered by Mountcastle, Hubel and Wiesel has shown that similar mechanisms underlie the somatosensory cortex and visual cortex in monkeys and cats. Our work on bats' auditory cortex, then, contributes not only to the understanding of hearing but also to the understanding of sensory systems in general.

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The Mid-Ocean Ridge

It is the longest mountain chain, the most active volcanic area and until recently the least accessible region on the earth. New maps reveal striking details of how segments of the Ridge form and evolve

by Kenneth C. Macdonald and Paul J. Fox

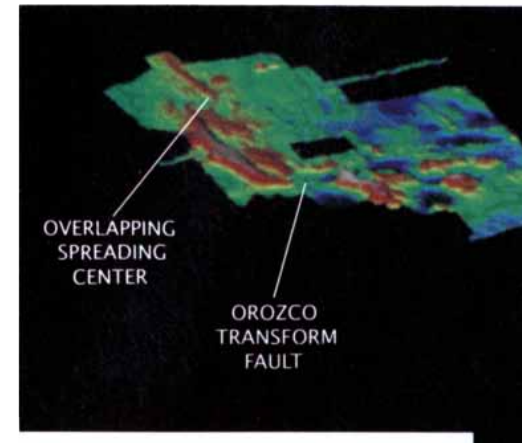
On July 8, 1982, we boarded the research vessel *Thomas Washington* to survey the East Pacific Rise, a volcanic mountain chain that lies under the Pacific Ocean. The Rise is part of the 75,000-kilometer-long formation known as the Mid-Ocean Ridge. Like the seam of a baseball, the Ridge winds around the globe from the Arctic Ocean to the Atlantic Ocean, around Africa, Asia and Australia, under the Pacific Ocean and to the west coast of North America. Even though the Ridge is by far the longest structure on the earth, less was known about its features than about the craters on the dark side of the moon.

Our colleagues from the Scripps Institution of Oceanography had recently equipped the *Thomas Washington* with a new type of sonar system, made by the General Instrument Corporation. Called SeaBeam, it could map a two-kilometer swath of the ocean floor in a single ping of the sonar. It would, we hoped, reveal the ocean floor in unprecedented detail, providing new insights into the forces that form and shape the Mid-Ocean Ridge.

After cruising southeast 2,500 kilometers from the Scripps marine facility in San Diego, we intersected the crest of the East Pacific Rise, located at a depth of about 2.5 kilometers. The Rise marks the boundary between the Pacific and Cocos tectonic plates, each a slab of the earth's crust and upper mantle. The plates separate at a rate of about 120 millimeters per year (twice the rate at which a fingernail grows). As the plates move apart, cracks form along the crest of the rise, allowing molten rock to seep up from the mantle. Some of the molten rock overflows onto the ocean floor in tremendous eruptions. The magma then solidifies to form many square kilometers of new oceanic crust each year. Only a few kilometers above this activity, we felt like Lilliputians crawling along the spine of a slumbering giant that might awaken at any time.

As the SeaBeam probed the spine of this giant, we watched images of the seascape appear on monitors on board the *Thomas Washington*. We saw some familiar features: the elevated terrain that defines the axis of the ridge and large breaks, called transform faults, that offset ridge segments by hundreds of kilometers. Yet we and Peter F. Lonsdale of Scripps also observed several unknown structures: segments that bend, ridges that overlap and oceanic crust that is warped and distorted near these features.

Since the early 1980's our colleagues in France, the U.K. and the U.S. have also surveyed many stretches of the East Pacific Rise as well as other parts of the Mid-Ocean Ridge. These efforts have revealed that the Ridge has many lateral discontinuities that partition its axis into segments. Although discontinuities differ in form and behavior, most of them are deeper and less active volcanically than the segments they define. As a result, the crest of the Ridge undulates up and down by hundreds of meters over distances of from 10 to 1,000 kilometers. During the past several years we have come to understand how these discontinuities and segments evolve and how they are related to processes deep in the earth's crust and mantle.



Sea-Floor Spreading

American oceanographer Bruce C. Heezen aptly described the Mid-Ocean Ridge as "the wound that never heals." In 1956 he and W. Maurice Ewing noticed that the earthquakes in the ocean basin define a continuous belt encircling the world. Because the belt coincided with portions of the Mid-Ocean Ridge that were known at the time, they proposed that the earth was girdled by a continuous system of ocean ridges. Ever since their discovery oceanographers and geologists have tried to get a closer look at the Mid-Ocean Ridge to understand its origins.

The global geologic processes that form and shape the Ridge were not understood until 1960 when Harry H. Hess of Princeton University introduced the concept of sea-floor spreading. Other workers further refined and developed his idea into the theory of plate tectonics. The theory posits that the crust and upper mantle are divided into a few dozen plates, such as the Pacific and the Cocos, which can move with respect to one another. If two plates separate, material from the man-

KENNETH C. MACDONALD and PAUL J. FOX have collaborated on many expeditions to the East Pacific Rise and the Mid-Atlantic Ridge. Macdonald is professor of marine geophysics at the University of California, Santa Barbara. In 1975 he received his Ph.D. in marine geophysics from the Massachusetts Institute of Technology and the Woods Hole Oceanographic Institution. Macdonald is drawn to the sea by his research, wind surfing and his wife, marine geologist Rachel M. Haymon. Fox is professor of oceanography at the University of Rhode Island. In 1972 he earned his Ph.D. in marine geophysics from Columbia University. When Fox and Macdonald are not cruising the seven seas, they wade in secluded mountain streams, where they try to catch unsuspecting trout with a well-presented fly.

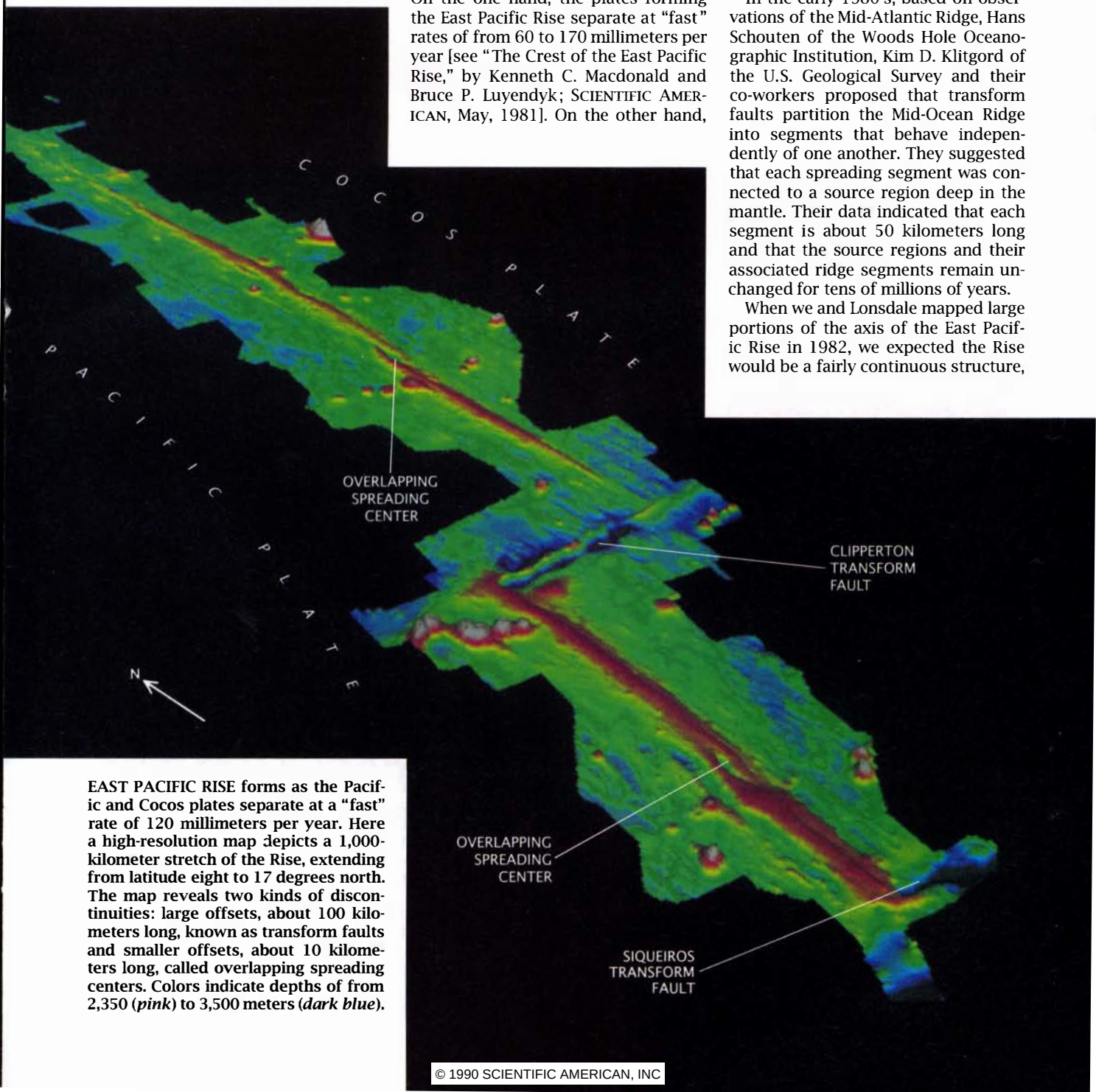
tle can well up, forming a ridge and new oceanic crust.

The theory of plate tectonics accounts for the largest structures of the Mid-Ocean Ridge. Yet as early as 1960 H. William Menard of Scripps and Heezen discovered that the Mid-Ocean Ridge is a discontinuous structure. As they mapped the Ridge with sounding devices, they found several places where it was offset at right angles to its length. In 1965 J. Tuzo Wilson of the University of Toronto identified these discontinuities as transform faults: a boundary formed perpendicular to the length of the ridge, where the edges of tectonic plates slide past each other in opposite directions. Later Richard N. Hey of the University of Hawaii realized the segments defined by two transform faults could shift in a direction parallel to the length of the ridge. This type of discontinuity was called a propagating rift.

By the 1980's oceanographers had identified many transform faults and propagating rifts. They had also determined that different parts of the Mid-Ocean Ridge evolved at different rates. On the one hand, the plates forming the East Pacific Rise separate at "fast" rates of from 60 to 170 millimeters per year [see "The Crest of the East Pacific Rise," by Kenneth C. Macdonald and Bruce P. Luyendyk; SCIENTIFIC AMERICAN, May, 1981]. On the other hand, the plates forming the Mid-Atlantic Ridge are pulled apart at slower rates of about 30 millimeters per year. Because of variations in spreading rates and the rate at which magma is supplied to ridges, the topography of fast-spreading ridges differs from that of slow-spreading ones. The crest of a fast-spreading ridge is defined by an elevation of the oceanic crust several hundred meters high and five to 20 kilometers wide. In contrast, the axis of a slow-spreading ridge is characterized by a rift valley a few kilometers deep and about 20 to 30 kilometers wide.

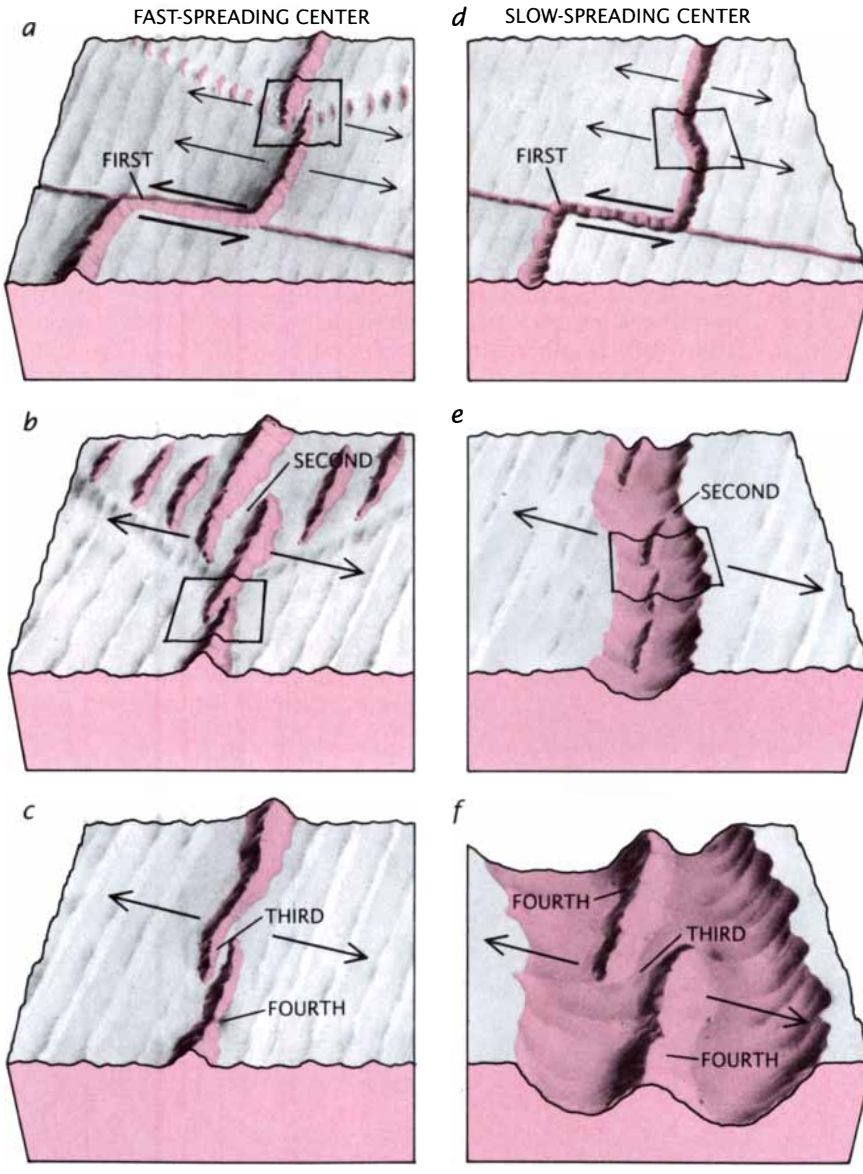
In the early 1980's, based on observations of the Mid-Atlantic Ridge, Hans Schouten of the Woods Hole Oceanographic Institution, Kim D. Klitgord of the U.S. Geological Survey and their co-workers proposed that transform faults partition the Mid-Ocean Ridge into segments that behave independently of one another. They suggested that each spreading segment was connected to a source region deep in the mantle. Their data indicated that each segment is about 50 kilometers long and that the source regions and their associated ridge segments remain unchanged for tens of millions of years.

When we and Lonsdale mapped large portions of the axis of the East Pacific Rise in 1982, we expected the Rise would be a fairly continuous structure,



EAST PACIFIC RISE forms as the Pacific and Cocos plates separate at a "fast" rate of 120 millimeters per year. Here a high-resolution map depicts a 1,000-kilometer stretch of the Rise, extending from latitude eight to 17 degrees north. The map reveals two kinds of discontinuities: large offsets, about 100 kilometers long, known as transform faults and smaller offsets, about 10 kilometers long, called overlapping spreading centers. Colors indicate depths of from 2,350 (*pink*) to 3,500 meters (*dark blue*).

because only nine widely spaced transform faults had been discovered along its 5,000-kilometer length. To our surprise, the axis of the Rise was frequently disrupted by many small offsets (more than 40 have been mapped to date). These discontinuities partitioned the Ridge into segments ranging in length from 10 to 200 kilometers. Unlike transform faults, these offsets were characterized by overlapping ridge tips, and they did not have a clearly defined fault that connected the tips [*see illustration below*]. Since their discovery we have mapped the off-axis regions around these overlapping offsets and have learned that the features evolve rapidly. In addition, we have found that the discontinuities can migrate along the Ridge, at varying speeds and in various directions. Individual segments bounded by those discontinuities can apparently lengthen or shorten. High-resolution maps have also documented similar nonrigid discontinuities on the slow-spreading Mid-Atlantic Ridge.



DISCONTINUITIES in the Mid-Ocean Ridge can be classified according to shape, size and longevity. For a fast-spreading center, such as the East Pacific Rise, a first-order discontinuity (*a*) is a transform fault, where rigid plates slide past each other. It offsets the ridge by at least 50 kilometers. A second-order discontinuity (*b*) is usually a large overlapping spreading center that offsets the ridge by at least two kilometers. A third-order discontinuity (*c*) is a small overlapping spreading center that offsets the ridge by .5 to two kilometers. A fourth-order discontinuity (*c*) is characterized by slight deviations in axial linearity. For a slow-spreading center, such as the Mid-Atlantic Ridge, a first-order discontinuity (*d*) is also typically a transform fault, but it represents a break in a rift valley rather than a ridge crest. A second-order discontinuity (*e*) is a bend, or jog, in the rift valley. A third-order discontinuity (*f*) is a gap between chains of volcanoes, whereas a fourth-order discontinuity (*f*) is a small gap within a chain of volcanoes. First- and second-order structures are usually flanked by distorted crust that formed as the discontinuity evolved. They are known to persist longer than third- and fourth-order discontinuities, because the oceanic crust near the higher-order structures does not show evidence of distortion.

Magma-Supply Model

To determine the origin of these discontinuities, we and our colleagues attempted to find connections between segmentation and volcanic activity. Although volcanism can change greatly from one segment to the next, it does vary systematically along the length of each segment. The least active regions are deep discontinuities, whereas the most active regions are shallow centers of segments [see "The Oceanic Crust," by Jean Francheteau; SCIENTIFIC AMERICAN, September, 1983].

From these observations and others, we, Schouten and our colleagues developed a magma-supply model of ridge segmentation. In the mantle at a depth of from 30 to 60 kilometers, rocks are heated to high temperatures, but because they are usually subjected to high pressure, they remain in a solid state. The environment is somewhat different at the boundary between tectonic plates. As plates separate, some of the rock decompresses and melts. The molten rock then percolates up through the mantle and fills a shallow chamber in the crust beneath the crest of the ridge. As the chamber swells with magma and begins to expand, the crest of the ridge can be pushed upward by the buoyant forces from both the molten rock in the magma chamber and the broader region of hot rock in the upper mantle [*see illustration on page 76*].

According to the magma-supply model of segmentation, the greater the supply of molten and hot rock to a region, the higher the overlying ridge segment will be elevated. Furthermore, the rate and volume of the molten rock supply can change from region to region, creating variations in the morphology of the different overlying segments.

The magma-supply model also accounts for smaller structural variations. As magma in the chambers migrates laterally along the ridge axis, the thin, brittle crust above the magma chamber stretches and fractures. The magma can erupt through these fractures to the ocean floor. As the cracks

continue to grow, volcanic eruptions follow in their wake. The eruptions will continue until the production of magma subsides and the supply of magma is exhausted. Temporal variations in melt delivery affect a segment's evolution: when a segment is well supplied with molten rock as compared with its neighbors, the segment tends to lengthen, and when it is poorly supplied, the segment shortens. It is this swelling and shrinking of the magma-supply system, in response to plate separation, that initiates the lengthening or shortening of segments and the migration of small discontinuities.

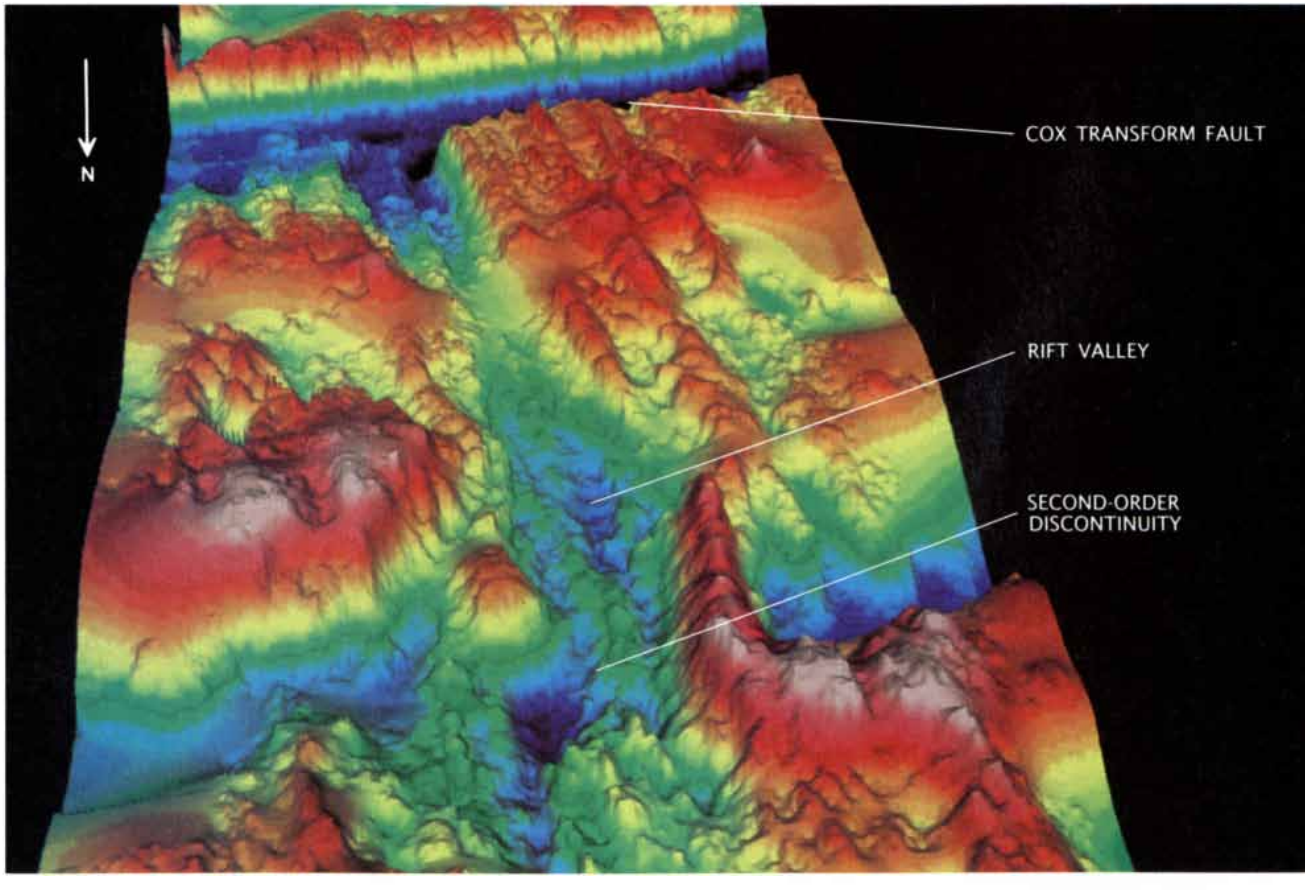
The magma-supply model appears to agree with seismic and gravitational measurements of the East Pacific Rise. Seismic measurements reveal that a good reflector of sound energy exists about 1.2 to 2.5 kilometers beneath the shallow portions of each ridge segment. This reflector often deepens and then disappears near discontinuities. In 1987 Robert S. Detrick of the University of Rhode Island and his co-workers proposed that the reflector is the roof of a magma chamber. The strength of sound reflection can be explained by a thin cap of nearly 100 percent melt along the top of the chamber.

Most geologists and oceanographers now agree the reflector is a long, shallow body of magma beneath the ridge surrounded by hot rock. John A. Orcutt of Scripps and his colleagues have made seismic measurements along the northern East Pacific Rise, which suggest such a chamber of molten rock is only two to four kilometers wide and less than one kilometer thick. The magma chamber is surrounded by a wider region of very hot (perhaps slightly molten) rock. The reservoir may be six to 10 kilometers wide and three to six kilometers thick. This region of hot rock extends at least to the base of the oceanic crust and probably a few kilometers into the upper mantle [*see illustration on page 79*].

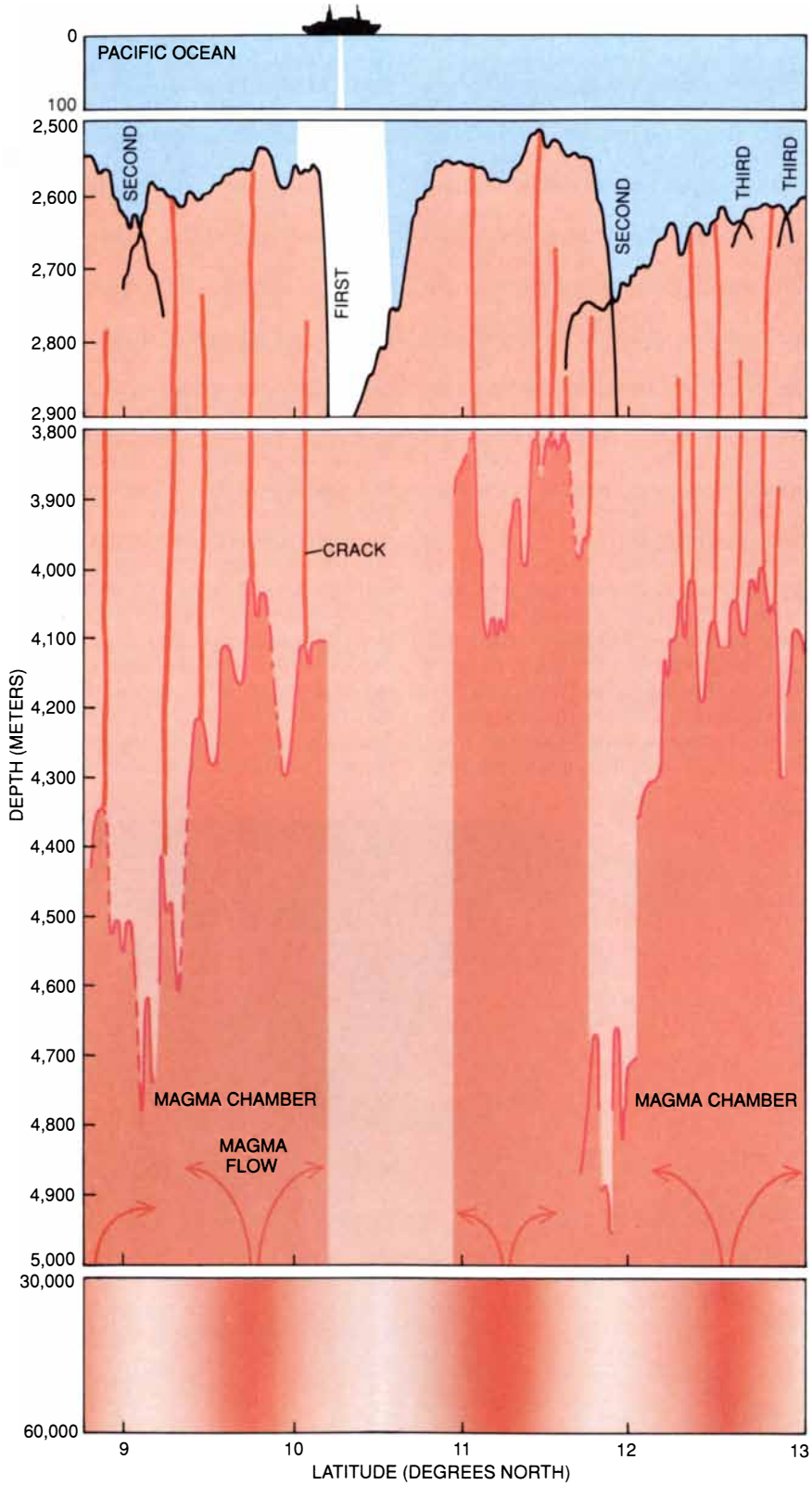
The presence of magma chambers and hot-rock reservoirs has been supported by precise measurements of the gravitational field there, which indicate the presence of a buoyant mass beneath the ridge axis. From both seismic and gravitational measurements, workers have deduced that the magma chamber resembles a mushroom in cross section: it has a narrow stalk of partial melt feeding a wide but very thin lens of pure melt.

Seismic evidence has not definitively proved that magma chambers exist beneath slow-spreading formations such as the Mid-Atlantic Ridge. Other measurements, however, seem to support a magma-supply model for slow-spreading ridges. Donald W. Forsyth and Ban-Yuen Kuo of Brown University and Jian Lin and G. Michael Purdy of Woods Hole found anomalies in the gravitational field, which were centered over the shallowest portions of several segments of the Mid-Atlantic Ridge. The best explanation for these anomalies is an upwelling of hot mantle material or a thickening of the oceanic crust beneath the shallow portions of each segment. Both interpretations are consistent with the magma-supply model.

It was a great relief that the seismic and gravitational measurements supported, at least in a general sense, the magma-supply model of segmentation. We and many other tectonicists and geochemists had stuck our necks out fairly far with that hypothesis. True, some of us thought the chamber would



MID-ATLANTIC RIDGE emerges as the South American and African plates pull apart at the "slow" rate of approximately 30 millimeters per year. The axis of the ridge is marked by a two-kilometer-deep rift valley, which is typical of most slow-spreading ridges. The map reveals a 12-kilometer jog of the rift valley, a second-order discontinuity, and also shows a first-order discontinuity called the Cox transform fault. Colors indicate depths of from 1,900 (*pink*) to 4,200 meters (*dark blue*).



MAGMA seeps up from deep within the mantle to form the East Pacific Rise (shown in cross section along the crest of the ridge). Investigators speculate that partially melted rock from depths of 30,000 to 60,000 meters percolates upward and is produced in greater quantities in some areas (*dark red*) than in others (*light red*). They propose that the molten rock fills and expands magma chambers. Seismic measurements suggest that the tops of the chambers are at the depth indicated by the broken red line. Molten rock ascends from the magma chamber through cracks in the crust and then solidifies or erupts onto the ocean floor. The depth of the ridge (*black line at top*) was determined from sonar measurements. The chamber breaks below discontinuities of order one, two and sometimes three.

be larger, and it remains to be seen if magma actually flows laterally below the ridge axis, but significant evidence has been found to support the model.

Discontinuities

The magma-supply model has been quite successful in accounting for the many different types of discontinuities and segments. Such structures are classified as first, second, third or fourth order according to their size, longevity, geometry and behavior. It has been demonstrated that first-, second- and third-order structures are fundamental components of both fast- and slow-spreading ridges. (The role of fourth-order features remains unsolved.) Because these structures have been investigated in more detail on fast-spreading ridges, we will describe them in that setting first.

The most common type of first-order discontinuity is the transform fault. It appears where rigid plates slide past each other. First-order discontinuities offset the ridge segments by at least 20 kilometers and usually more than 50 kilometers. Hence, most transform faults were large enough to be revealed by early reconnaissance-mapping efforts. These discontinuities typically define segments from 200 to 800 kilometers long.

On the ocean floor, transform faults appear to be narrow, straight bands linking the ends of segments. These bands can be traced in the flanks of a ridge for hundreds to thousands of kilometers [*see illustration on page 73*]. Such traces indicate that first-order structures persist for millions to tens of millions of years.

A first-order segment can be broken up by several second-order discontinuities that are usually spaced from 50 to 300 kilometers apart. Unlike first-order structures, however, second-order segments are not rigid, and their motion is not concentrated along a narrow fault zone. Second-order discontinuities are complex features characterized by oblique and overlapping structures.

Second-order discontinuities are typically features that resemble the arms of two people who are preparing to shake hands. The arms (ridges) are extended in such a way that the hands (the curved ends of ridges) overlap. The distance between the "hands" varies from one to 20 kilometers. The offset is typically three times shorter than the distance that the ridges overlap. Such a feature is known as an overlapping spreading center [*see illustration on opposite page*].

When overlapping spreading centers were discovered in 1982, we could not account for many of their characteristics. Why did so many centers have an overlap-to-offset ratio of 3 to 1? What happened to the crust that lies between the overlapping ridges? Why did the ridges create a distinctive curving pattern?

In 1984 David D. Pollard of Stanford University, Jean-Christophe Sempere, then at the University of California at Santa Barbara, and one of us (Macdonald) found that the highly repetitive shape of overlapping spreading centers could be explained by the way cracks develop and propagate along ridges. As tectonic plates are pulled apart, cracks form perpendicular to the direction of tension. In the middle of a segment the direction of stress is usually perpendicular to the ridge axis, so the cracks will lengthen parallel to the ridge. In the region of overlapping segments, however, the direction of stress can vary. As a crack from the middle of a segment begins to grow toward the region of overlap, the crack first deflects away from the region and then hooks toward it [*see illustration on next page*]. The crack allows magma to erupt onto the ocean floor, and a new ridge tip is formed. But once the cracks overlap by a distance that approaches three times their offset, the crack propagation stalls abruptly. Soon after, a new crack begins to develop behind the first. As the second develops, the first ridge tip is shed off onto the flanks because of plate separation.

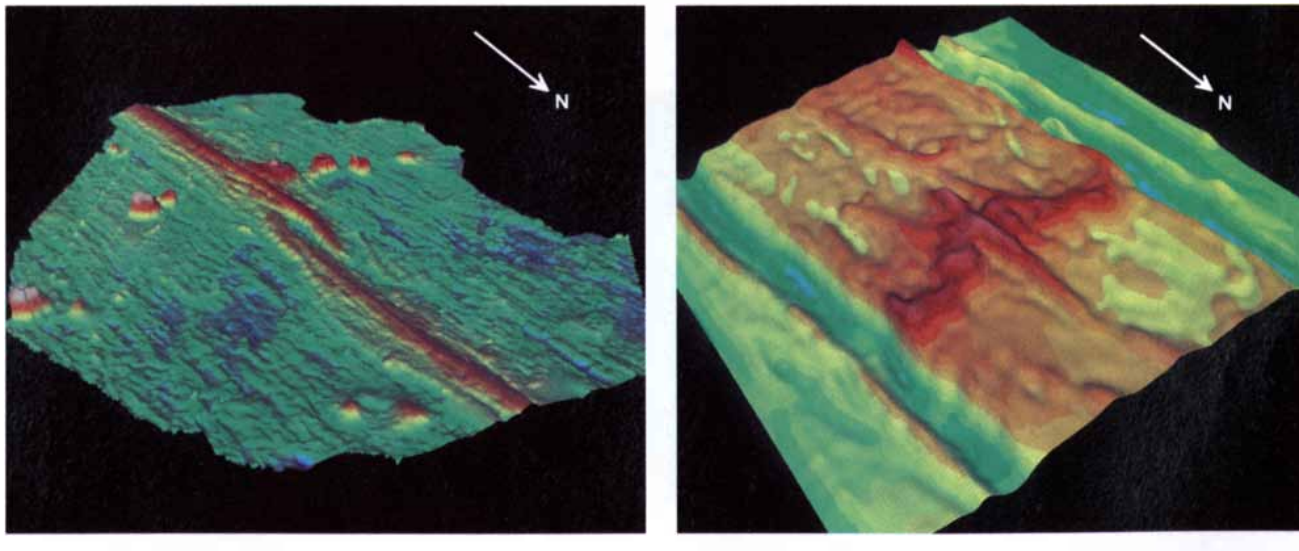
Off-Axis Structures

Spreading centers that overlap by more than several kilometers usually leave "wakes" of deformed oceanic crust up to 80 kilometers wide. The ocean floor within such a disturbed region, called a discordant zone, is 100 to 300 meters deeper than the surrounding ocean floor; in like manner, the overlapping spreading centers lie 100 to 300 meters deeper than the shallow, magmatically robust portions of the ridge segments. These features have emerged from maps that several expeditions have made of the flanks of the East Pacific Rise. The maps of the discordant zones also show curved fossil ridge tips 10 to 40 kilometers long, which have been cut off at overlapping spreading centers.

The magma-supply model appears to account for the structure of the overlapping spreading centers. It seems that overlapping spreading centers are at the ends of magma sources and tend to be deprived of magma. If this is true, the crust created at overlapping spreading centers may be up to 50 percent thinner than the six-kilometer-thick crust near the centers of each segment. Detailed seismic and gravitational measurements need to be made in these areas to test this idea.

Measurements of the earth's magnetic field at overlapping spreading centers support the idea that such centers occur where the magma supply is low. It turns out that lava that erupts from small magma chambers, which alternately solidify and become replenished, tends to contain more iron-rich minerals in a highly magnetized state. On the other hand, magma chambers large enough to remain molten between episodes of magma replenishment produce lava that is magnetically weak. Because rock near overlapping spreading centers is often much more strongly magnetic than rock elsewhere along the ridge, it seems likely that the centers are fed discontinuously from isolated pockets of magma.

Based on the age of the crust into which the discordant zones extend and on the patterns of off-axis wakes, Laura J. Perram, Suzanne M. Carbotte and Marie-Helene Cormier of the University of California at Santa Barbara have demonstrated that second-order segments persist as discrete entities for up to several million years. The discontinuities may slowly oscillate in position by 10 to 20 kilometers on the ridge or may migrate along the ridge many tens of kilometers at rates of 20 to 100 millimeters per year. A disconti-



OVERLAPPING SPREADING CENTER, which cuts across the East Pacific Rise near latitude 12 degrees north, was surveyed to determine its topography (*left*) and magnetization (*right*). The topographic map shows that the overlapping spreading center offsets the Rise by eight kilometers. Colors indicate depths of from 2,350 (*pink*) to 3,500 meters (*dark blue*). The two arms of the discontinuity overlap by 27 kilometers. The arms narrow and deepen near the discontinuity, presumably because the supply of magma to the region is low. The ocean floor near the discontinuity—also known as the wake—is unusually deep and is littered with ridge tips, especially on the west side. It turns out that regions that are not well supplied with magma are highly magnetized. In the map at the right, magnetization decreases in strength from red to yellow regions. The map reveals the wake (*red*) of the overlapping spreading center. The green-blue troughs were created 700,000 years ago when the earth's magnetic field reversed polarity. The wake shows that the overlapping spreading center emerged about 700,000 years ago, migrated north a short distance and then moved slowly south at 70 millimeters per year. In the past 200,000 years migration to the south has accelerated to 200 millimeters per year.

nuity tends to move in spurts; a ridge segment can lengthen at rates of several hundred millimeters per year but then may retreat and shorten for a time before making the next surge forward. In this way, the ridge tips at a second-order discontinuity appear to be "dueling" as they surge back and forth along the ridge, generally making slow progress in either direction [*see illustration below*].

Small Overlaps and DEVAL's

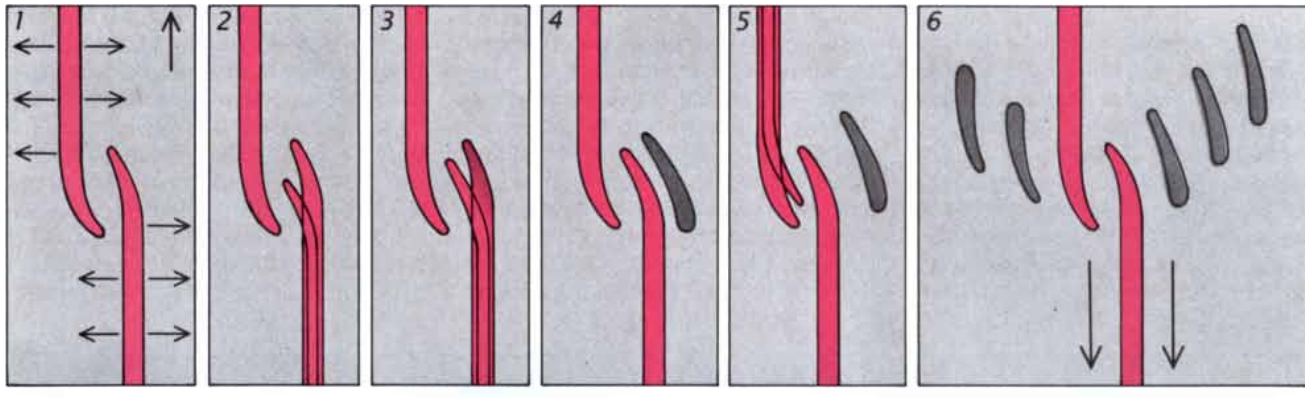
Along the East Pacific Rise, third-order discontinuities usually consist of overlapping spreading centers that offset the ridge by less than three kilometers. Segments defined by third-order discontinuities are from 30 to 100 kilometers long. Third-order discontinuities have been shown to correspond with breaks in magma chambers.

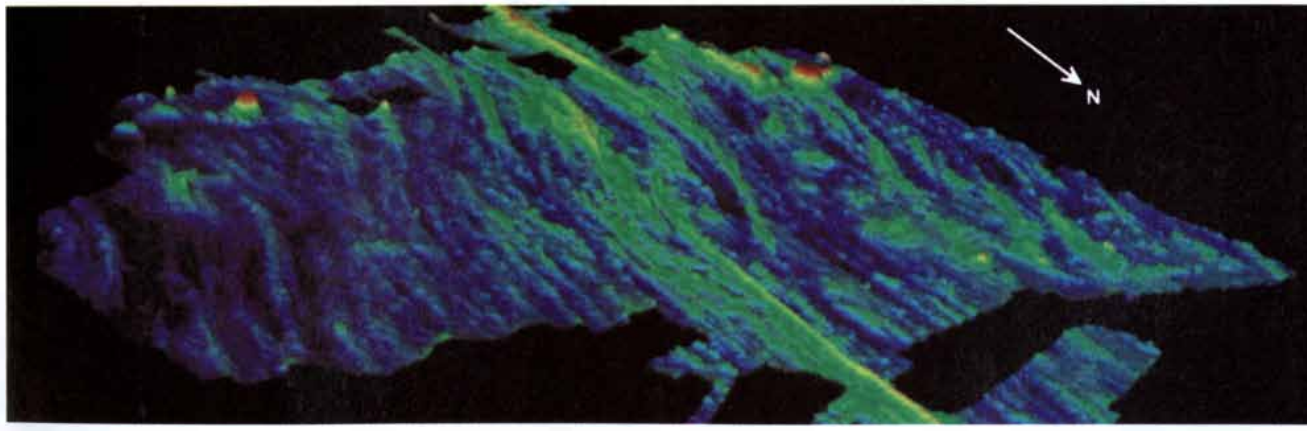
The ridge segments defined by third-order discontinuities leave little or no evidence of off-axis wakes. Because they produce little trace in old oceanic crust on the ridge flanks, we can conclude that third-order discontinuities are geologically short-lived. In fact, we estimate that they are younger than 10,000 years—the time it takes a fast-spreading ridge to generate two kilometers of crust.

Fourth-order discontinuities are either subtle bends or tiny offsets less than 500 meters in size. The structures are often called DEVAL's (for slight DEViations in Axial Linearity). DEVAL's are usually spaced from 10 to 40 kilometers apart. A DEVAL may be the manifestation of a single major eruption and therefore may be as young as hundreds to thousands of years old.

DEVAL's are very difficult to detect. They can barely be resolved with sonar systems such as SeaBeam, and seismic measurements are not much help either. In some cases the magma chamber beneath a DEVAL deepens slightly and, in rare instances, exhibits an apparent break. In most cases the chambers below fourth-order discontinuities are fairly continuous. During the 1982 cruise one of us (Fox) pointed out to the other (Macdonald) that he had found several DEVAL's in the SeaBeam maps. Macdonald then told Fox that he had been staring at the maps too closely on a rolling ship. We soon agreed that we should focus on the larger offsets if we wanted people to believe our ideas.

Indeed, fourth-order segments (the sections of ridge between DEVAL's) were not recognized as distinct and significant features until 1986, when Charles H. Langmuir of the Lamont-Doherty Geological Observatory, John F.



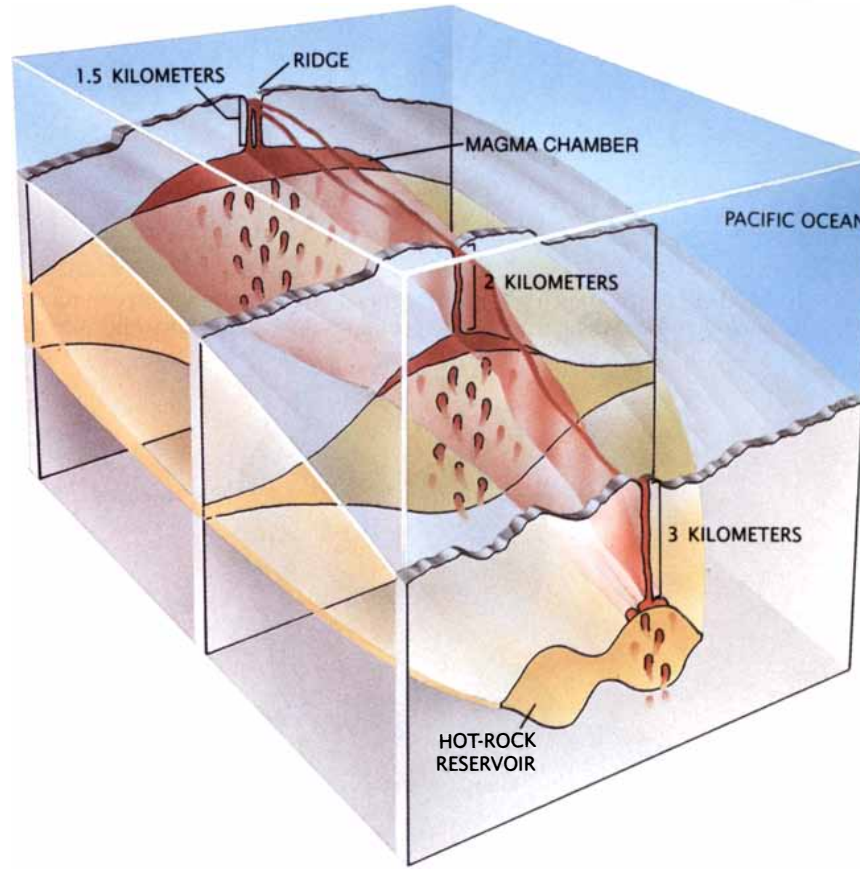


OFF-AXIS FEATURES are generated by an overlapping spreading center, as illustrated in the diagram (*top*) and the map (*bottom*). An overlapping spreading center is depicted (*1*). A crack develops to the south of the eastern ridge tip (*2*), allowing molten rock to surface and form a new tip. The new tip lengthens until it overlaps the western ridge by three times the distance that separates them (*3*). As the regions of rock continue to pull apart, the original eastern ridge tip breaks off and migrates away (*4*). A new western tip begins to form (*5*). After many episodes of ridge-tip formation and migration (*6*), the off-axis structures show a net migration to the south. The high-resolution map of a region near 21 degrees south reveals an overlapping spreading center that offsets the East Pacific Rise by 12 kilometers. The discontinuity has had a complex evolution during the past two million years. Migration rates have exceeded 200 millimeters per year as northern and southern ridge tips have surged back and forth, but net migration toward the south has averaged 20 millimeters per year. Numerous abandoned ridge tips within a wake of unusually deep sea floor can be seen on both sides of the overlapping spreading center. Sea-floor structure is disrupted across an 80-kilometer-wide swath adjacent to this discontinuity. Colors indicate depths of from 2,350 (*pink*) to 2,900 (*yellow*) to 3,500 meters (*dark blue*).

Bender of the University of North Carolina at Charlotte and their colleagues analyzed the geochemistry of a 500-kilometer stretch of the East Pacific Rise. The workers collected rock samples from precise sites on the ocean floor to see if structural segmentation could be associated with variations in rock chemistry. They found that the rocks within each fourth-order segment had a similar composition, whereas rocks from other segments had different chemical signatures. Such measurements have documented the fundamental nature of segmentation over a range of scales and have helped to identify many other DEVAL's.

Why do DEVAL's differ in chemical composition? One theory posits that small blockages divide the magma chamber beneath adjacent fourth-order segments. These divisions would prevent the mixing of the magma in the chambers. Yet only a few such breaks have been detected in magma chambers beneath DEVAL's. Another theory suggests that small batches of molten rock from isolated sources in the upper mantle may be injected locally into a magma chamber and may erupt onto the ocean floor before much mixing occurs. This process would create a fourth-order segment with a distinctive rock chemistry. More evidence is needed to confirm or refute these ideas.

We, Carbotte and Nancy R. Grindlay of the University of Rhode Island have documented several kinds of first-, second- and third-order discontinuities at slow-spreading ridges in the South Atlantic. Like the first-order discontinuities on fast-spreading ridges, the slow-spreading counterparts are transform faults. Second-order discontinuities on slow-spreading ridges are defined by a lateral step of the rift valley or by a deep oblique basin along which the offset rift valleys are linked. The second-order discontinuities persist for millions of years—longer on average than second-order discontinuities on fast-spreading centers. Second-order discontinuities on slow-spreading centers also migrate more slowly along the ridge axis than their fast-spreading counterparts. Third-order discontinuities at slow-spreading centers are small offsets in long volcanic chains within the rift valley floor, whereas fourth-order discontinuities may be small gaps between volcanoes.



MAGMA CHAMBER is thought to extend below fast-spreading ridges. The magma chamber is a lens of mostly molten rock. The chamber sits atop a reservoir of partially melted rock. The chamber and reservoir are small and poorly supplied with molten rock near a discontinuity (*deep region in foreground*). Yet they can be larger and well supplied at a distance away from the discontinuity (*background*).

Aquatic Life and Segmentation

Oceanographers, tectonicists and geochemists have just begun to understand some of the implications of segmentation for both slow- and fast-spreading ridges. We have found clear examples of first-, second-, third- and fourth-order structures and everything in between. Do segments evolve from fourth through first order and back again? We know that segmentation has been a fundamental process for at least 100 million years. Has segmentation played a role over a much longer period? Investigators have studied exotic faunal communities that flourish near hot springs on the Mid-Ocean Ridge. Can the survival and migration of these communities be linked to the longevity of a given segment?

These questions will be the focus of research for a program called the Ridge Interdisciplinary Global Experiments (RIDGE). Among the many goals of the program are to map the axis and flanks of the entire Mid-Ocean Ridge and to generate more detailed images of off-axis features. Even today geologists and oceanographers have mapped less than 5 percent of the sea floor. More than half of the earth's crust remains to be explored.

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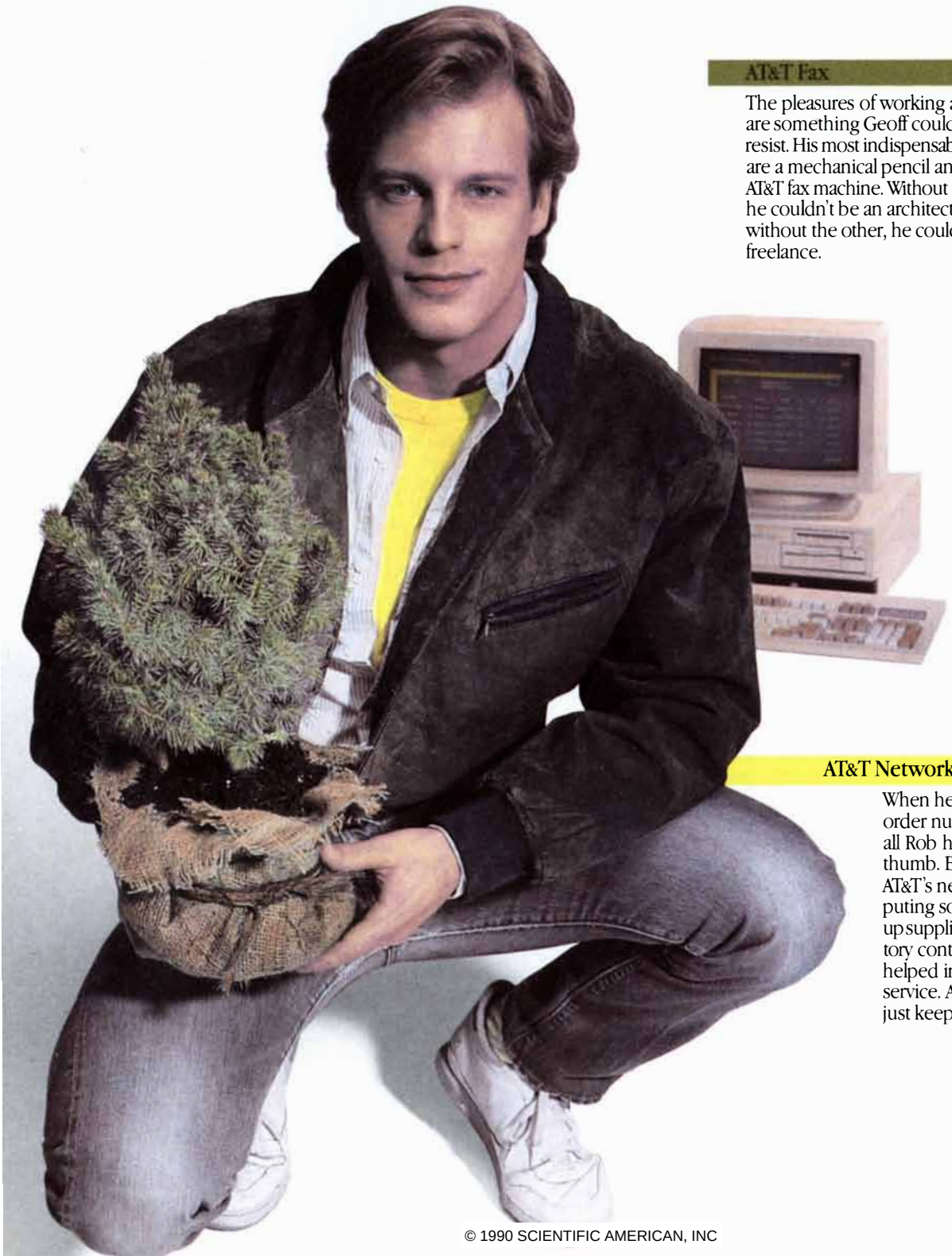

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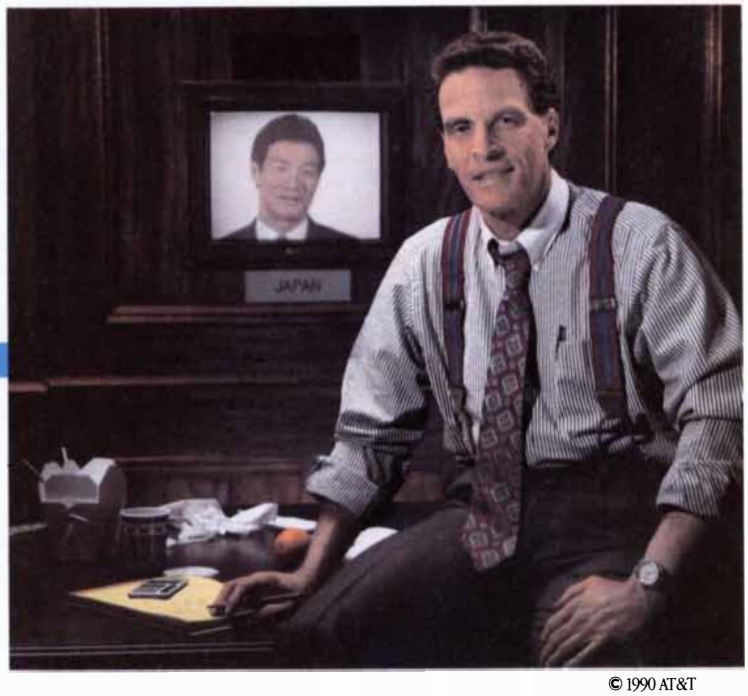

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Talking Policy

The administration devises an industrial policy—sort of

Nurturing industry, smog-sensing laser, cleaning chips, productivity paradox

The battle over "industrial policy" in Washington, D.C., seems over. The winners: those who believe that government should not directly support high-technology industries. As a consolation prize, the Bush administration is promising to back "generic, precompetitive, enabling" technologies.

"That jargon is chosen very appropriately to avoid some of the contentiousness that surrounds these matters," Thomas J. Murrin, deputy secretary at the Department of Commerce, says tensely as he fiddles with a paper clip. Last year Murrin and other proponents of a strong government role in technology began to lose ground when the administration squashed a Commerce Department plan for supporting high-definition television (HDTV) technologies. A more recent casualty was Craig I. Fields, director of the Defense Advanced Research Projects Agency (DARPA), an outspoken advocate of government funding for HDTV. Fields was relieved of his post in late April following DARPA's decision to fund a small microelectronics company.

"We take seriously the government's commitment to R&D," says Michael J. Boskin, who chairs the Council of Economic Advisers. But Boskin and others oppose targeting specific industries for assistance. "The government should not be picking winners and losers," Boskin asserts. "The history of doing that is one of dismal failures."

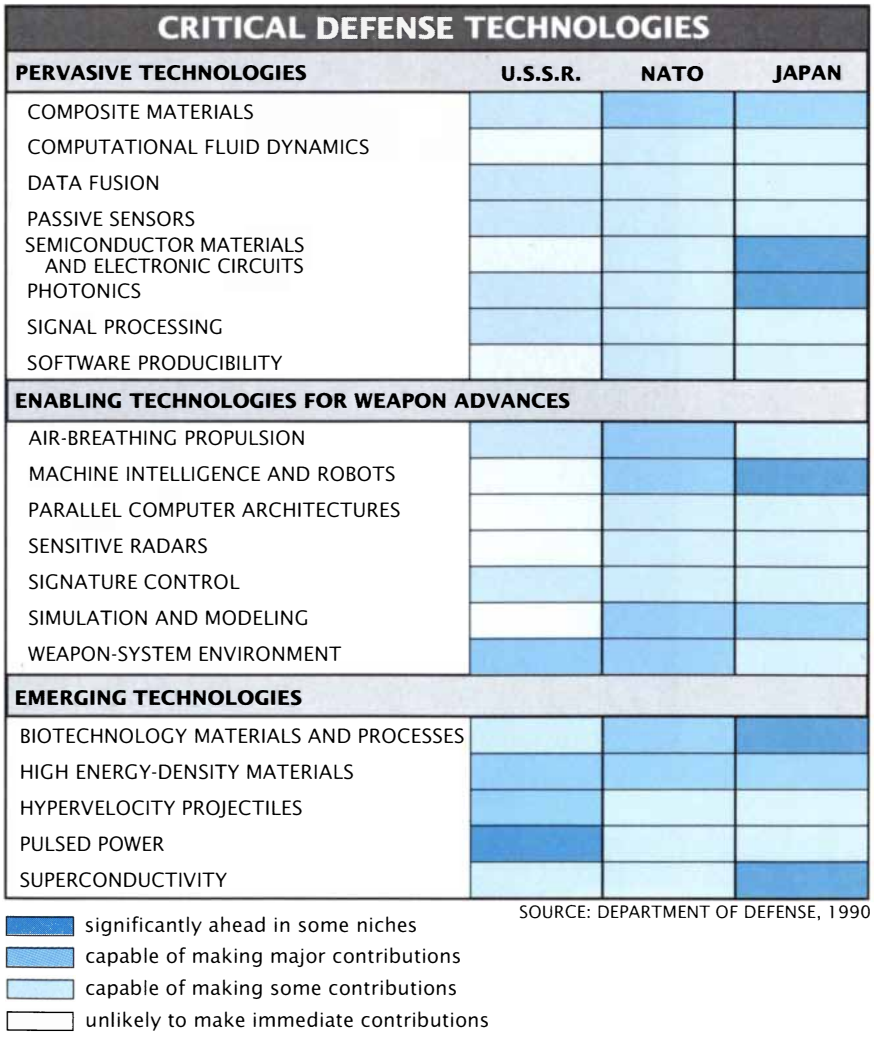
So the administration's current plan is to "assist in the precompetitive phase of technology that can affect a great many industries," says D. Allan Bromley, director of the Office of Science and Technology Policy (OSTP). The technologies selected will be those that "may not have a big enough impact on any one industry to justify [companies] spending what would be required to do the development," he adds.

To identify technologies worthy of government nurture, the administration is looking to a series of reports on "critical" technologies produced by the departments of defense and commerce, as well as the OSTP. The Defense Department's effort, released in mid-March, identifies 20 technologies deemed essential to weapon design. (The Commerce Department's report was scheduled for release in April; the OSTP report in October.)

These are far from the first reports on critical technologies, however. "We've got reports ad nauseam," Murrin concedes. It also comes as no surprise that the reports list many of the same technologies, he says. So what will the government do after it identifies the usual suspects? The administration will "move aggressively to develop consortiums and cooperative efforts involving private-sector entities, with or without government ones," Bromley insists. That way, he points out, companies will share the risks and costs of developing technology and possibly reduce the time to market.

One mechanism for supporting such precompetitive consortiums will be the Advanced Technology Program, recently unveiled by the National Institute of Standards & Technology (NIST). The ATP will assist in developing technologies that are underfunded or facing severe technical barriers. The money will be in the form of matching funds for small companies or consortiums.

Still, even the ATP is quite modestly funded: $10 million in fiscal 1991, al-



SOURCE: DEPARTMENT OF DEFENSE, 1990

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

There were times when we didn't think we could make the deadline, but it came down to a personal thing. We'd said we would have this done. So we made sure we would.

Management let us decide how we would divide the work and set up our schedule. All they asked for was a good final result.

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

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though Congress has expressed some interest in pumping up the budget tenfold. Although DARPA has won kudos for helping to develop advanced technologies, NIST will not be "funding finished products," says John W. Lyons, director of NIST. "We're pulling products through the development process." A program in high-temperature superconductors, for instance, might try to improve techniques for generating high currents in the presence of strong magnetic fields but not try to build superconducting motors.

"The HDTV exercise taught us a lot," Lyons notes. "On the civilian side—where you can't know the customers and markets nearly as well as you can on the military side—it's a mistake for the federal government to focus on the end products." In the case of HDTV, Lyons recalls, industry had hoped that the government would fund specific products. "And that, it turns out, is not what this administration believes is correct or possible," he adds.

Another mechanism the government might employ is one that Bromley often cited when he taught science policy at Yale University: the government might offer to buy a fixed number of products at a set price. Manufacturers are then left alone to figure out how to make the goods profitably. "The government as first customer is obviously an important technique that has been used extensively in the military and space sectors," Bromley says. "It is certainly one that will be considered" by the current administration.

Congress, nonetheless, remains unconvinced that the administration is giving serious enough consideration to the issue of industrial competitiveness. Some representatives have been chafing to develop more explicit ways of assisting industry. A group of senior Democrats is planning to introduce a complex "competitiveness" bill. Senator John Glenn of Ohio, along with a few colleagues, has reintroduced a bill to create a "civilian DARPA." Representative Mel Levine of California has proposed founding a "Technology Corporation of America" that would use federal funds to spur joint ventures and consortiums for developing and commercializing technologies neglected by industry.

Still, Congress and the administration have found some common ground. Both agree that particular financial features of the U.S. business environment are problematic: the high cost of capital and the variable nature of the R&D tax credit have discouraged investment. Bromley says that in the international arena the U.S. may have to form—and stick to—long-range research plans. "We may even consider 'treatylike' arrangements so that we as a nation are committed to something beyond the duration of an individual administration," he says.

For now, however, the administration is determined to support only "generic" technologies. "It was only recently the president himself said in an address to the American Electronics Association that this administration believes that it has an important role to play in the development of generic technologies up through the precompetitive phase," Bromley says. He adds: "That's an official statement of policy, in as succinct a form as I can say it." *—Elizabeth Corcoran*

***MOTION SICKNESS** is investigated at Wright-Patterson Air Force Base.*

Sick of Work

Air Force researcher has new idea about nausea

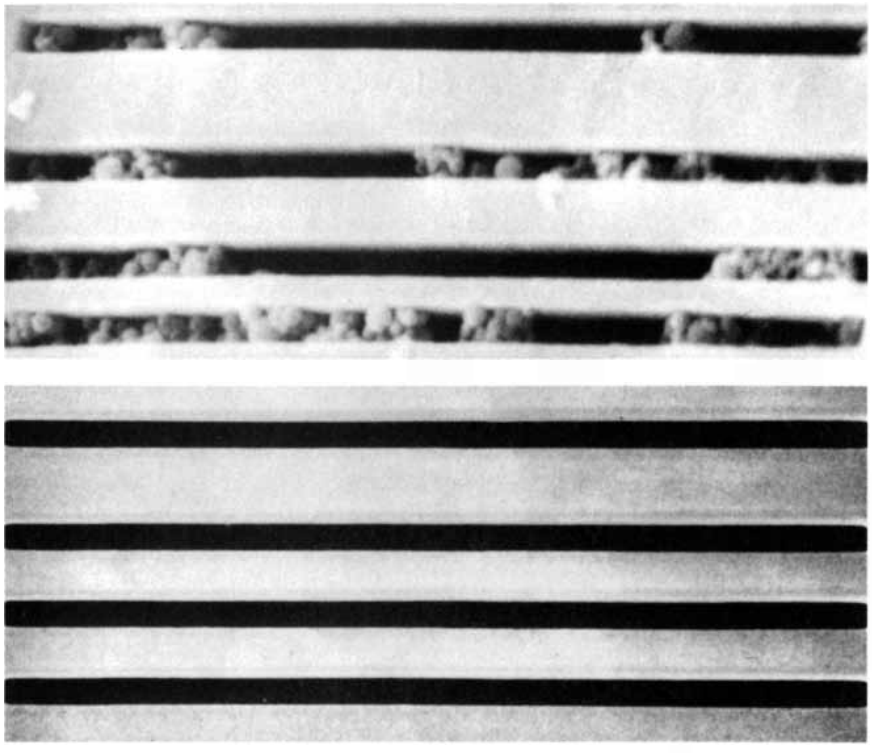
Bumping, bouncing and being jerked about is all part of a day's work for pilots, navigators, astronauts and other aircrew. For them, nausea in the workplace is not something to be joked about over lunch. Sick time for these workers, especially astronauts, is expensive as well as miserable.

Until recently little research had gone into understanding the physiology of motion sickness, although its symptoms of nausea, sweating, sleepiness and dizziness are familiar to most travelers. No one had thought to study people's low-frequency brain waves during the evolution of motion sickness. That is why no one anticipated the results of a just completed study at the Air Force Institute of Technology at Wright-Patterson Air Force Base.

It turns out that brain-wave patterns during motion sickness are remarkably similar to those produced during certain epileptic convulsions. Physician William E. Chelen was scheduled to reveal the information at the Aerospace Medical Association annual meeting in New Orleans this May. When Chelen recognized the unusual waves, he decided to see if he could treat motion sickness with the well-known anticonvulsant drug Dilantin, a phenytoin compound. "It's working," he says. "Not only do the subjects not throw up, they feel good." The effectiveness of the drug leads Chelen to believe that motion sickness may be caused by a partial seizure in the brain or brain stem, as are the convulsions of epilepsy.

While pilots are not allowed to take medications, astronauts try to fend off motion sickness by taking pills or wearing patches that release scopolamine through the skin. That drug prevents vomiting and nausea, but astronauts also take Dexedrine, an amphetamine, to counteract the side effect of sedation. The combination does not work well, Chelen points out. "Seventy percent of people who've taken it in space have still reported motion sickness. It doesn't disable them completely, but it sure makes things difficult."

The decision to measure the low-



***SUBMICRON SPECKS clog stencils used to print circuits on silicon wafers* (top). *IBM is developing an excimer laser system that removes them* (bottom).**

frequency brain waves of a spinning, sweating person was straightforward enough, the researcher says. But actually doing it was tricky, recalls Matthew Kabrisky, one of the Air Force investigators. He explains: "The usual stuff is pretty easy—pulse, eye motion, breathing rate, number of volts coming off their churning guts." But conventional electroencephalography (EEG) equipment is about the size of a dishwasher and weighs a few hundred pounds. It is not designed to sit next to a person on a rotating chair.

So Chelen combined his skills as an electrical engineer, physician and radio ham to build a miniature, battery-powered EEG only a few inches square. It mounts to the head and measures brain waves at frequencies a tenth as low as those usually recorded by hospital versions. The machine can detect brain signals on the order of 10 to 50 millionths of a volt. Chelen inserts miniature platinum needles just under the skin, in addition to surface electrodes, which tend to slip off and give inaccurate data because of sweat.

Although Dilantin is stopping the symptoms of motion sickness, the Air Force investigators say they do not have enough data to determine the drug's effect on the aberrant brain waves that accompany the illness. No matter. Although the peculiar patterns tipped Chelen to a new route for study, he explains that "you could have seizures without EEG changes, and you could have changes in brain waves and not have clinical convulsions." To see if there is any correlation, the team will commence brain mapping this year to track where EEG changes originate during motion sickness and how they spread through the brain.

The next step for the Air Force researchers is to test other, newer anticonvulsant drugs—such as carbamazepine—that have no structural relation to phenytoin. Such studies will help decipher whether motion sickness is actually a form of partial-seizure disorder or whether Dilantin is working for some other reason. "We're ultimately interested in something compatible with flying. Maybe nothing ever will be suitable for pilots—but we might find something good for passengers," Chelen says. A flight surgeon at Edwards Air Force Base has already begun in-air testing of Dilantin against motion sickness.

The public should keep its hopes for a more effective antimotion-sickness drug down to earth for now. Dilantin's manufacturer, Parke-Davis, reports that it is interested in the results of the Air Force study and may consider conducting similar research on its own. Other pharmaceutical companies may take up the investigation as well, because Dilantin's patents have long since expired. Drugmakers are turning increasingly to rational drug design, tweaking established compounds to get them to behave just a bit differently. So it is conceivable that a variation of this well-known anticonvulsant could one day send motion sickness packing. —*Deborah Erickson*

Dust Busters

Lasers wipe submicron motes from silicon wafers

They stick like glue. Washing them off doesn't work. Nor does blasting them with gas jets. But these nettlesome motes the size of a virus have got to go. As the circuit lines on semiconductor chips shrink below one micron, such particles can cause defects and turn likely profits into losses for chip makers.

Semiconductor factories are already the cleanest places in the world. Sematech, the chip-manufacturing consortium in Austin, Tex., has a clean room where the density of dust is equivalent to that of one dry pea in a cubic mile of air. But cleanliness alone does nothing to solve the problem of debris that forms as circuits are printed onto silicon wafers. Process contaminants cause nearly half of all chip defects.

What cleanser is strong enough to pry off tiny particles yet mild enough to leave the wafer unscathed? Several researchers are exploring techniques that use laser light to blast dirt from semiconductor wafers. "There are really no alternatives for getting rid of these particles," says Susan D. Allen, a chemist at the University of Iowa, who is patenting a method of using lasers to clean chips.

Other techniques work well so long as the particles to be removed are larger than about half a micron. But circuit elements below one micron can be disrupted by grains measuring .1 micron or less. At such sizes van der Waals forces glue particles to chip surfaces with nearly the strength of a chemical bond. Gas jets, for example, are too weak to overcome these forces. Gas jets fortified with bits of dry ice can dislodge some particles, but these seeded jets are themselves prone to contamination.

Liquid rinses agitated by ultrasound cannot be filtered at submicron scales, so they add as much dirt as they remove. Plasmas, or ionized gases, remove particles cleanly by reacting chemically with them; unfortunately, they also react with the substrates. Electrostatic attraction can pull dirt

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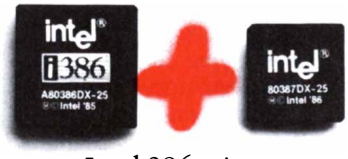

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from a chip onto a thin sheet touching it, but here again, the sheet itself cannot be cleaned adequately.

Lasers have two advantages: they do not touch the chip, and they emit wavelengths that some substances absorb more readily than others. Allen's technique exploits such absorption differences. She exposes silicon wafers to dust-free water vapor, which collects in crevices under the particles. Then she zaps the wafers with lasers whose infrared output matches water's absorption band but not silicon's. The water explodes into steam, launching the particles far enough from the wafer to be swept away by air currents.

So far, Allen says, she has removed dirt from unpatterned silicon without damaging the substrate. Allen Bowling, head of thermal and control research at Texas Instruments, says he is interested in Allen's technique. The incentive to TI and other chip makers is obvious—perhaps a laser cleaning system could replace some of the $300 million or so that is now invested in cleaning facilities at chip-fabrication plants. As it is, U.S. microelectronics manufacturers generally scrap about 40 percent of the several hundred chips produced from each six-inch silicon wafer. Japanese companies are believed to scrap only 10 percent of their chips.

But Bowling still has reservations. "My only concern is that the water might get under pattern lines etched in the silicon and lift them off," he says. Allen agrees but notes that her system need not rely on water vapor. "In principle, we could even use argon," she adds. Of course, that would require a laser that emits a wavelength argon can absorb.

Another method, developed by Werner Zapka's group at the IBM German Manufacturing Technology Center in Sindelfingen, acts directly on the dirt. The researchers found that shining a powerful ultraviolet beam from an excimer laser at particles makes them jump off a wafer. Andrew C. Tam of IBM's Almaden Research Center in San Jose, Calif., who is helping to refine Zapka's technique, says the excimer laser removes particles even from substrates with similar melting points.

This is significant, Tam says, because the lack of damage to the substrate proves that the laser cannot be vaporizing the particles. He thinks heat alone somehow makes the particles jump like popping corn. Robert J. Baseman and Douglas W. Cooper of IBM's Thomas J. Watson Research Center in Yorktown Heights, N.Y., have actually watched particles fly off under the prodding of an excimer laser. "My guess is that you could clean some particles from some substrates without damage," Baseman says.

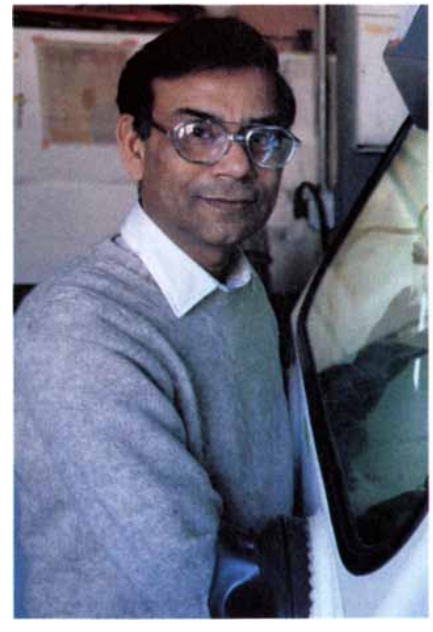
In any case, neither laser system can solve all of Silicon Valley's dirt problems. "There are millions of particles consisting of different substances," Tam says. "Who knows which can and cannot be removed." Yet solutions must be found, or the incredible shrinking chip will choke on its own dust. —*Philip E. Ross*

Patent Power

The oil-eating bacterium that spawned an industry

Turning crude oil into cattle feed with genetically altered bacteria seemed like a reasonable idea to Ananda M. Chakrabarty. It was the late 1960's, oil was cheap and General Electric was willing to pay for the research at its laboratory in Schenectady, N.Y. The project was put out to pasture when oil prices rose but not before GE had applied for a hotly contested patent on a bacterium modified to degrade oil more efficiently than its natural cousins.

That first patent on a living organism became the cornerstone of the biotechnology industry. After eight years of denials by the U.S. Patent and Trademarks Office, public protest and legal appeals that carried the case to the Supreme Court, the patent was awarded 10 years ago this month. The landmark 5–4 decision said a "patent can be granted on anything under the sun which can be made by man."



ANANDA M. CHAKRABARTY won the first patent on an altered life-form in June of 1980. Photograph by Valentina von Schacht.

Although the patent gave the fledgling biotechnology industry the assurance that it could profit from its research, it did not provide Chakrabarty with the right to turn his oil-eating bacteria loose. Chakrabarty had hoped to use the bacteria to clean up oil spills. But permission to release the altered organisms into the environment has still not been granted. Chakrabarty doesn't mind. In his gentle, East Indian accent he says, "I am not personally interested in seeing the bugs applied. That is for the entrepreneurs and the ingenious to satisfy the EPA."

Convincing the Environmental Protection Agency was certainly not something GE was eager to tackle. The firm was already grappling with adverse publicity over its contamination of the upper Hudson River Valley with polychlorinated biphenyls (PCB's). At the same time, some activists were predicting environmental disaster from the modified bacterium. By the late 1970's GE decided to discontinue research on the organisms; Chakrabarty decided to escape the pressures of commercial science and return to the University of Illinois at Chicago. "We had learned to cross the evolutionary barrier," he muses, "but people said tinkering with life was a bad thing to do."

Fortunately for the biotechnology startups with their scant resources, GE had a major, long-standing commitment to patenting its inventions. Although the economics did not justify further development, the industrial giant felt obligated to test the patentability of a new technology, says Edward F. McKie, the lawyer who argued GE's case before the Supreme Court. "Even then it was apparent that if genetic manipulation could not be protected, it would not be encouraged," he explains.

Back at his Chicago lab bench, Chakrabarty was trying to find a way to sidestep the regulatory quagmire that awaited live organisms. He decided to take the same approach as the biotech companies developing such drugs as human insulin: he would use the bacteria as factories to produce useful substances. A company called Petrogen in Arlington Heights, Ill., became a willing partner. The startup believed it could sell a microbial surfactant to oil producers. This detergentlike substance does not degrade oil but rather spreads it out, the way dishwashing detergent disperses bacon fat in a pan.

Chakrabarty gave Petrogen a first batch of surfactant in 1986. But the

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(Back Row) **Weightstill William Woods** — sensors, Boeing Aerospace & Electronics, Seattle; **Mervin C. Vincent** — low observables, Boeing Military Airplanes, Seattle; **Frank C. Fickeisen** — flight controls and systems engineering, Boeing Commercial Airplanes, Seattle; **Albert M. Erisman** — scientific computing and numerical analysis, Boeing Computer Services, Seattle; **Paul E. Rubbert** — aerodynamics and computational fluid dynamics, Boeing Commerical Airplanes, Seattle; **Ulf Goranson** — structures engineering, Boeing Commercial Airplanes, Seattle; **George T. Campbell** — communications and systems engineering, Boeing Aerospace & Electronics, Seattle.

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Andrej Martin Savol
Machine vision, Boeing Commercial Airplanes

Kurt Schuppisser
Engine technology and propulsion systems, Boeing Commercial Airplanes

Harold A. Scott
Computer simulation and modeling, Boeing Aerospace & Electronics

Frederick H. Simpson
Ceramic engineering, Boeing Aerospace & Electronics

Jerome Sugamele
Structural dynamics and vibrations, Boeing Commercial Airplanes

Edward N. Tinoco
Aerodynamics, computational fluid dynamics, Boeing Commercial Airplanes

Johannes H. van der Velden
Hydraulics and fluid systems, Boeing Commercial Airplanes

Mark A. Wilhelm
Advanced composites, Boeing Commercial Airplanes

Donald E. Young
Electromagnetic scattering, Boeing Military Airplanes

The Boeing Fellows joined by Associate Technical Fellows.

BOEING

timing was off once again—oil prices had dropped. So petroleum producers were no longer interested in using surfactants to recover oil from the sludge that builds up in storage tanks. It was cheaper to throw the gunk away. Petrogen also tried injecting the surfactant into nearly played-out oil wells. It did not increase yields.

Chakrabarty remains undaunted, even though he admits that oil-eating bacteria may never see the light of day. Life outside a test tube is quite rigorous for altered organisms. Yet the severity of nature pales next to that of the political environment. "It's a conundrum. There are just too many variables to be accounted for," explains Edward L. Korwek, an attorney/scientist who sits on several government advisory committees on the safety of releasing genetically engineered organisms.

These days Chakrabarty is busy developing "higher priority" organisms than oil eaters. Unaltered organisms can recycle oil over time, he points out, because it is organic. "But toxic wastes like PCB's and dioxin don't exist in nature, so natural organisms will not eat them." Chakrabarty thinks "the solution to our toxic-waste problem is to teach microorganisms to degrade synthetic compounds."

So far the researcher believes he is making progress. Using a process he calls "directed evolution," Chakrabarty is slowly weaning microorganisms from their usual food and gradually introducing them to chemicals such as Agent Orange. They would be used in bioreactors to cleanse soil and water of hazardous waste. Chakrabarty is hopeful that this technology will be in the right place at the right time. As the cold war thaws, governments may realize "we don't need any more missiles. We need to take care of our health and the environment." —*D.E.*

Remote Possibility

Infrared pollution sensor could be clean-air catalyst

One bad apple can spoil a whole basket. The same is true of automobiles and air quality. Just 10 percent of all vehicles on U.S. roadways are spewing out half of the automobile-emitted carbon monoxide pollution that fouls our cities' air. Finding a way to identify these so-called gross polluters quickly and inexpensively—so they could be taken in for repair—would be a feat.

FEAT is exactly what Donald H. Stedman, a chemistry professor from the University of Denver, calls his novel invention. The acronym stands for Fuel Efficiency Automobile Test, and Stedman is convinced it's just the thing to spot the bad apples of the highway.

Stedman's device employs remote sensing to take snapshot readings of the emissions from passing vehicles, up to thousands a day. As cars drive through an infrared laser beam, a sensor reads the amount of carbon monoxide (CO) and carbon dioxide (CO_2) coming out of their tail pipes. Then a computer calculates the ratio between properly and improperly burned fuel.

As a car ages, the odds increase that protective parts, such as catalytic converters or oxygen sensors, will wear out. Without these components, cars that burn too much fuel, or run rich, get fewer miles per gallon. They also begin churning out pollutants. To identify the offending vehicles, FEAT clicks a picture of the license plate at the same time it makes a reading.

So far Stedman has spent a frustrating 10 years trying to win acceptance for his technology. A decade ago the Environmental Protection Agency dismissed FEAT as just another good idea whose development it could not afford to fund. Since then the inventor says he has met with more active resistance from the EPA. Sources who refused to speak on the record confirm his complaints. But EPA director of emission-control technology Charles L. Gray denies any ill treatment: "The idea that this idea is being suppressed and just needs to be moved ahead is not true."

What is true is that Stedman's device measures pollution in a different way than the EPA does. The standard the EPA uses to determine if an area is in violation of air-quality codes is based on mass-emissions readings from a sample population of vehicles. (FEAT's readings of grams per gallon of fuel reflect volume.) The EPA's mass-emissions data base contains readings of 11,600 vehicles analyzed since 1975, each in a two-day, $1,500 test. The information is run through a computer model, with data that varies by region—such as weather, topography and age of vehicles on the road—to produce an estimate of fleet emissions for that area. Places that are not in compliance with EPA standards must begin programs to improve air quality or risk fines and the loss of federal funds.

"The EPA is intentionally trying to obscure the issue by comparing FEAT, a 50-cent test, to the $1,500 test," Stedman objects. FEAT should be compared with the $10 annual idle test that the EPA has mandated states perform. Idle tests also measure the percentage of CO—not mass. "The idea is to scan a lot of cars and find the few really dirty ones," Stedman says.

Such on-road sensing could become a mandatory part of states' antipollution efforts; Representative Joe L. Barton of Texas, a member of the House Energy and Commerce Committee, has added an amendment to the proposed Clean Air Act calling for such remote sensing. "Annual inspections are about as effective in reaching gross polluters as an annual breathalizer test would be in locating a drunk driver," he says.

Even the EPA is beginning to show some interest in Stedman's technology. Last year Stedman got his first chance to demonstrate FEAT to the agency through an innovative research program grant awarded by the EPA regional office in Las Vegas. And he won a convert in Marc L. Pitchford, a meteorologist based there. Stedman's device would "change our whole way of thinking about controlling emissions," Pitchford proclaims. "People have to overcome some institutional mind-set and get excited about a new tool."

Another proponent of FEAT is Douglas R. Lawson, who supervises air-quality field studies for the notoriously tough California Air Resources Board. Lawson ran a double-blind test of FEAT with a special car provided by General Motors "to see if there were more clunkers clunking in certain parts of L.A. than others." He concludes that "the device gives accurate readings of a vehicle's CO output, at speeds from rolling up to 60 miles an hour, in less than a second per vehicle."

This summer the EPA will take another look at FEAT. It plans to test two sensors set some distance apart to evaluate how weather and placement of the apparatus—for instance, on the way up or down a hill or on a straightaway—affect performance. Stedman is confident the agency's tests will prove the technology's worth in measuring CO. And he is readying a new sensor to measure hydrocarbon emissions. "There are all sorts of things we could look at with remote sensing," Stedman says with characteristic enthusiasm. "We could detect all the new kinds of chemicals that oxygenated fuels will be pouring into the atmosphere."

EPA's Gray, however, remains cautious. "It's one thing to be hopeful about a technology," he says. "It's another to suggest there's been sufficient experimental data to mandate that this is the way we should be doing inspection and maintenance programs." For Stedman, any attention from the EPA raises hope that his invention is on the way to helping clear the urban air.—*D.E.*

THE ANALYTICAL ECONOMIST

Sixteen tons of coal

Productivity is the holy grail of competitive industries. Corporations whose workers are more productive assemble more cars, etch more microchips or sell more encyclopedias than their rivals. Nations, too, pursue productivity gains and measure their standing by whether their productivity is improving faster or slower than that of others. But increasing productivity is not as simple as toting another barge or lifting another bale per worker-hour.

Measuring the productivity of a coal miner or steelworker is easy: divide output by hours worked, and if necessary multiply by the price of coal or steel. But how to measure the productivity of people who produce memos?

Even if one focuses on the information-age equivalents of assembly-line workers, useful numbers are hard to come by. The number of checks processed per hour in a bank may be a useful indication of productivity, but other measures, apparently equally objective, have proved disastrous in practice. Counting the keystrokes per hour of word processors does not guarantee that those are the right keystrokes. Interviews with some telephone operators have revealed that they occasionally resort to hanging up on rafts of callers at a time to meet their hourly quotas. In addition, says Eileen Appelbaum, an economist at Temple University, one telephone company found that the increased stress from computer monitoring drove absenteeism to a level that negated any gains from increased productivity when workers were on the job.

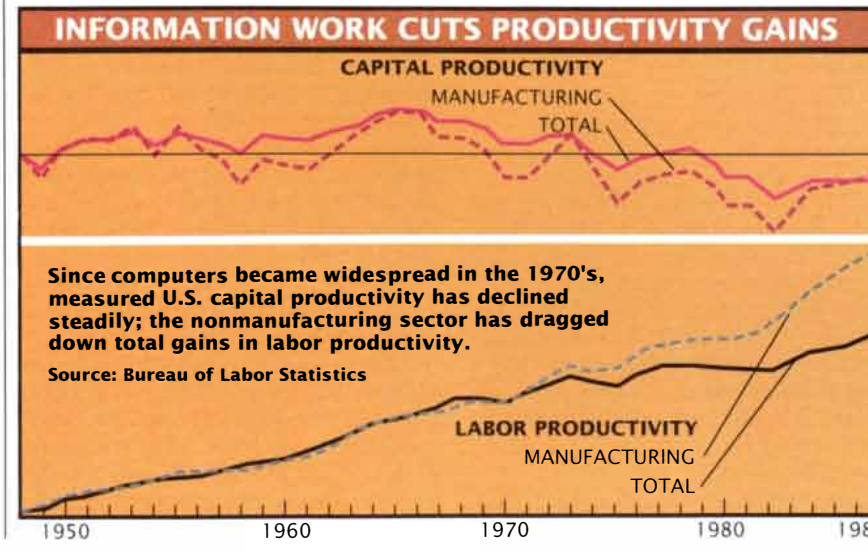
Rather than wade into this morass, government statisticians calculate the output of information workers, and in fact almost everybody outside the manufacturing sector, by "deflated value series." They simply count the money paid to information workers for their services, adjust it for inflation and divide by hours worked to get a productivity figure.

There is only one small hitch: inflation adjustments are based largely on how much the workers earn. Pay people more because their work is more valuable, and productivity figures stay flat. Information workers' productivity remains essentially constant by definition.

So it should come as no surprise that the transition to a postindustrial economy has brought with it a massive decline in measured productivity gains. Nor is it surprising that lackluster white-collar numbers persist even as companies strew their offices with billions of dollars' worth of computers.

What is needed to demonstrate the true productivity gains of white-collar workers, it would seem, is a way of measuring the quality of nonmanufacturing output. Anyone who has ever stood in line can tell a productive information worker from an unproductive one, but quantifying that intuition remains an unsolved problem. The National Academy of Sciences is now planning a project to define nonmanufacturing productivity measures.

Then again, maybe even with all the advances of technology, nonmanufacturing productivity really is stagnant. Appelbaum, among others, points out



that many companies use computers merely as paperless typewriters, give workers minimal training and attempt to automate existing procedures rather than restructuring work to take advantage of automation. She cites the typical insurance-company practice of filling out policies and forms by hand and mailing them to suburban "campuses" where acres of data-entry clerks retype the information into terminals. Other acres of clerks later retrieve the data. "Then," Appelbaum comments, "they say the reason productivity is low is that the women don't type fast enough."

Retired Xerox vice president Paul Strassmann has developed a method he calls return on management. It calculates the contribution of nonmanufacturing workers to their employers' bottom line. It is a purely financial determination: count the profit a white-collar group oversees, subtract from it the cost of their salaries and support equipment, and then divide by that cost to get a percentage. Sometimes the return is as high as 600 percent, he says; sometimes it is negative. Strassmann says he has identified overall characteristics of firms that have high return on management but stops short of making such claims for individuals.

The hazards of trying to quantify white-collar productivity are spreading as the information economy grows. Furthermore, says Marjory S. Blumenthal of the NAS, jobs whose parameters were formerly easy to define are rapidly becoming "informated." Thanks to point-of-sale terminals, retail clerks and even waiters and bartenders, once responsible only for so many dollars in sales per hour, are now also data-entry operators with entire computerized inventory and distribution systems depending on their inputs.

Even the traditional ways of calculating manufacturing productivity may soon change. More and more goods (from cars that talk to wallets that know exchange rates) rely on embedded computers for many of their functions and much of their perceived quality. Last year the Commerce Department revised its estimates of inflation in the computer industry to take better account of the fact that a few more dollars now buys a lot more computing. The new inflation estimate in turn raised estimates of productivity, the real gross national product (by about $70 billion) and a host of other indicators back to 1982. Until the NAS or someone else develops accurate measures of productivity for the information age, initiatives to increase the productivity number could hurt a nation's economy rather than help it. —*Paul Wallich*

Frogfishes

Masters of aggressive mimicry, these voracious carnivores can gulp prey faster than any other vertebrate predator

by Theodore W. Pietsch and David B. Grobecker

On the morning of December 29, 1696, a Dutch captain and his crew were searching for the survivors of a ship that had gone down not far off the coast of Western Australia. Although no survivors were ever found, what the crew did find washed up on the shore of a nearby island—amid rats as big as house cats—was a most remarkable fish. The fish, unlike any the sailors had ever seen, was described as being "about two feet long, with a round head and a sort of arms and legs and even something like hands." There is no doubt in our minds (although its specific identity will never be known) that this strange fish—sketchily described so long ago—was a frogfish.

Aptly named, these unusual fishes do bear a surprising resemblance to frogs: their bodies (which range in length from one to 16 inches) are globose and equipped with well-developed leglike fins that enable them to clamber across rocks, sand and coral reefs, much as a tetrapod might move about on land. They occur in nearly every imaginable color and can alter their hue to match a background object, such as a piece of coral, within a matter of days (in some species within a matter of seconds). As a result, a frogfish that moves from one type of substrate to another can change its color and still blend in with its surroundings. For that reason, most frogfishes are virtually impossible to distinguish from their backgrounds, and so many are overlooked—not only by their predators but by experienced divers and ichthyologists as well.

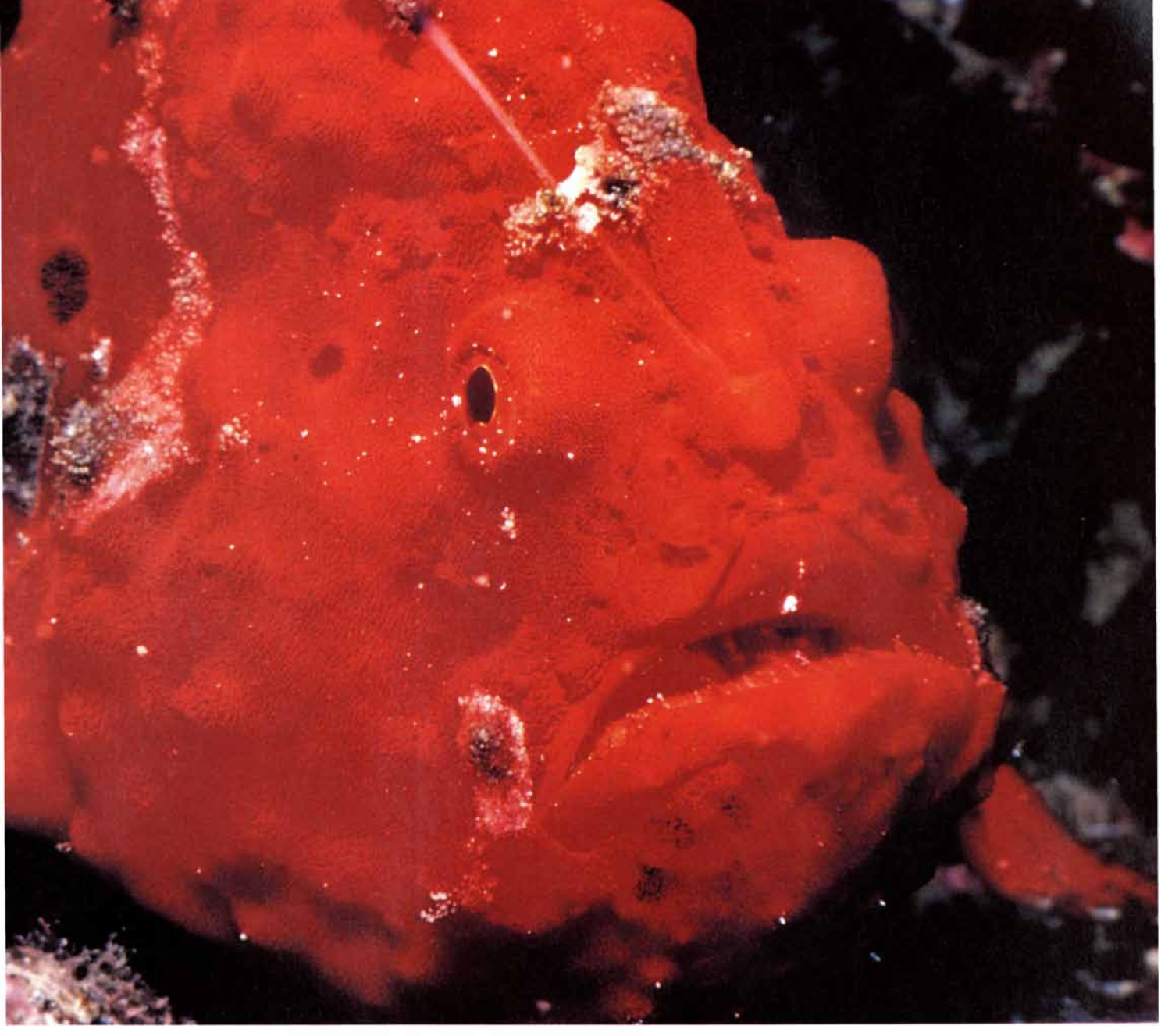
Commerson's frogfish, *Antennarius commersoni*, which is widespread in the Indian and Pacific oceans, is representative of the group in many ways. Males and females occur in a wide range of colors (including red, yellow, brown, creamy white, black and various hues in between); their skin, moreover, is accentuated by a regular pattern of small brown spots and pink blotches. In shallow water, where streaks of sunlight mottle the ocean floor, the fish bears a remarkable—almost uncanny—resemblance to an algae-encrusted rock. And there it sits, the classic example of a lie-in-wait predator, ready to strike at any fish or crustacean that passes by. Should a suitable animal swim too close, the large, cavernous mouth of the frogfish opens, engulfing its hapless victim in a matter of milliseconds.

Mastering the art of mimicry has thus imbued frogfishes with an important evolutionary advantage. By appearing to be inanimate, frogfishes are not only overlooked by those that prey on them, but they are also overlooked by their own prey. In addition, they are surprisingly effective at enticing prey within striking distance—in large part because they possess a small appendage called a lure that projects forward from just above the animal's lip and can be wiggled when prey come into view.

As long ago as 344 B.C., Aristotle remarked on the role of the lure: "The fishing-frog has a set of filaments that project in front of its eyes; they are long and thin like hairs…and are used as baits." Those observations were reconfirmed in 1875 by the Reverend S. J. Whitmee of Samoa, who described angling in a frogfish: "It angled…for

PAINTED FROGFISH,* Antennarius pictus, *lives in the warm shallow waters surrounding the Hawaiian islands. Like

THEODORE W. PIETSCH and DAVID B. GROBECKER have collaborated on a number of research projects. Pietsch is professor of fisheries at the University of Washington, where he has been a member of the faculty since 1978. In recognition of his work on the systematics, behavior and ecology of marine fishes, he has been made a fellow of the Linnean Society of London and also of the California Academy of Sciences. Pietsch has a B.S. from the University of Michigan and a Ph.D. from the University of Southern California. Grobecker is now scientific director of the Pacific Ocean Research Foundation in Kailua-Kona, Hawaii; before that he was a graduate student working with Pietsch in Seattle. Grobecker has a B.S. from California State University, Long Beach, and a Ph.D. from the University of Washington.



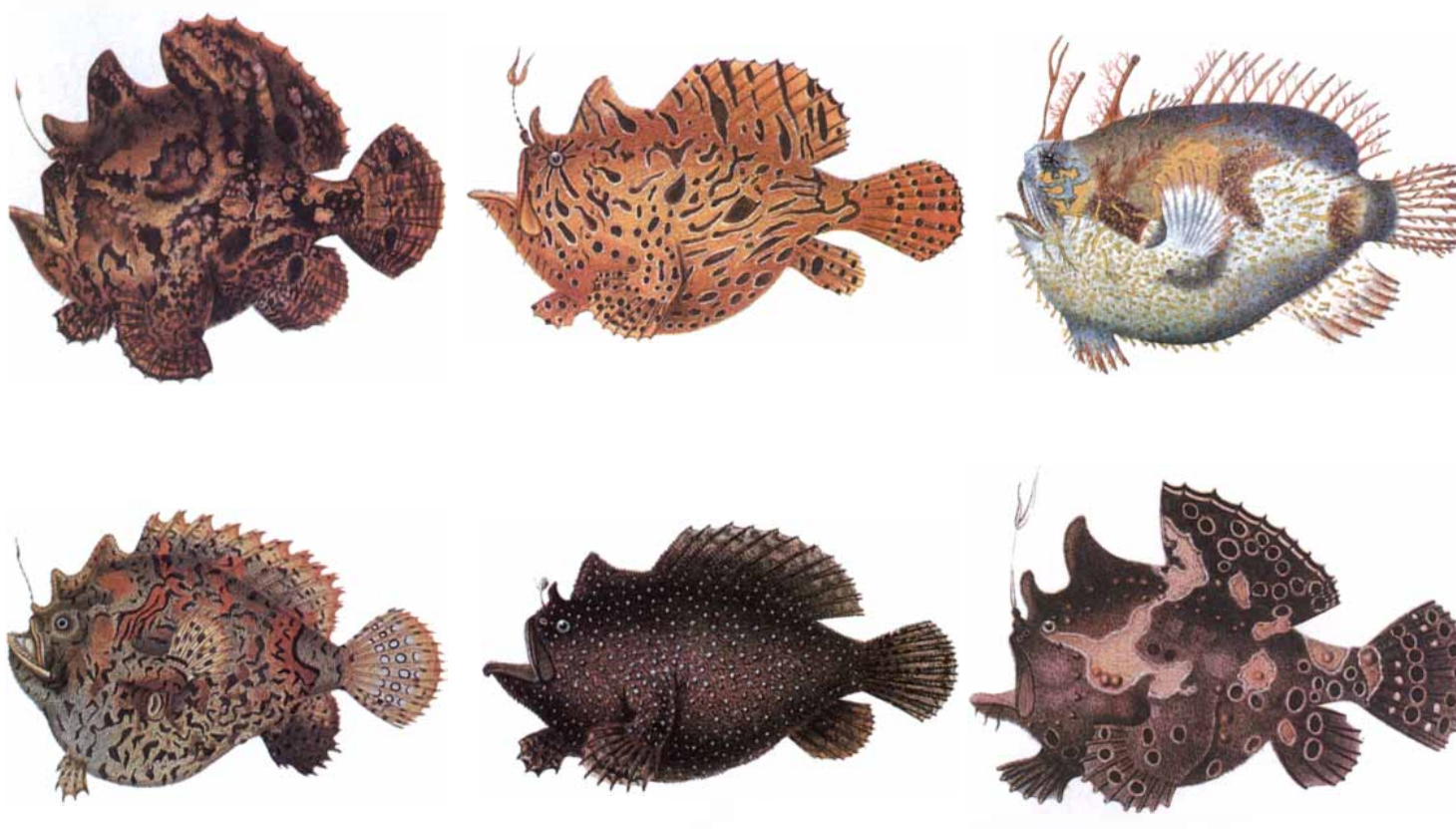
all frogfish species, it attracts prey by wiggling a lure, which is a modified, elongated dorsal-fin spine. The lure, seen here extending diagonally upward between the fish's eyes, terminates in a structure called the esca, or bait. Animals that are attracted to the lure and come too close to the cavernous mouth of the frogfish are engulfed in a matter of milliseconds.

some of the small fish in the aquarium. I hoped to see it catch one; but they were too wary."

Whitmee's observations, which were later substantiated by others, represent a concept in behavioral biology that is known today as aggressive mimicry. Unlike passive mimicry (whereby camouflage, or resemblance to one's background, provides a certain degree of protection from one's predators), aggressive mimicry requires that an animal imitate a specific object, both physically and behaviorally, in order to gain some advantage from it. In other words, by mimicking not only an inanimate object but also the behavior and appearance of a particular food item, a frogfish can lure another animal into its strike zone. Studies we have carried out now indicate that the frogfish, with its wide array of specialized adaptations, is one of nature's best (most highly evolved) examples of aggressive mimicry.

Frogfishes belong to the family Antennariidae, which in turn belongs to a larger assemblage of bony fishes, the anglerfishes. As the name implies, anglerfishes are largely sedentary, lie-in-wait predators that attract prey with the aid of a lure. In the case of frogfishes, the lure—a highly conspicuous extension of the first spine of the dorsal fin—sways forward from the face, imitating the jigging action of a fisherman's rod. In some species the entire apparatus can be folded back into a narrow groove on top of the head, and thus, the lure is protected when not in use.

Lures, which vary from species to species, consist of two major parts: the spine itself and a conspicuous fleshy structure at the tip called the esca, or bait. Depending on the species, the



FROGFISHES belong to a large and diverse family (the Antennariidae) as the above drawings—which were made more than 100 years ago—indicate. From left to right at the top, the species shown are Commerson's frogfish* (Antennarius commersoni)*, the striated frogfish* (Antennarius striatus)*, the tasseled frogfish* (Rhycherus filamentosus) *and the painted

esca may range in size and shape from a simple ball of tissue, perhaps 1/16 of an inch in diameter, to a highly ornate and filamentous structure an inch or more in length. In some species the esca mimics a small fish; in others it seems to mimic a crustacean or a worm.

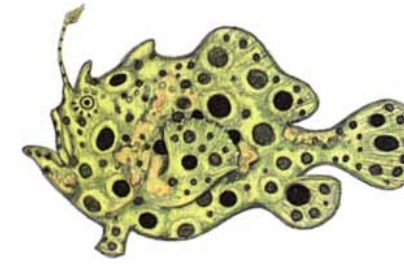
Although widely distributed in tropical and subtropical waters around the world, including the Gulf of California and the Red Sea, the vast majority of frogfishes are confined to the coastal areas of Indonesia, the Philippines and various other island groups of the South Pacific. One species, *Histrio histrio,* lives amid floating sargassum weed; the remainder spend their lives either on the ocean bottom (in areas where the water is shallow to moderately deep) or on rock or coral reefs.

Most taxonomists now agree that there are about 41 known species of frogfishes, although as many as 165 have been formally described over the past century or two. Such taxonomic confusion can be blamed in part on the amount of variation in both color and pattern that occurs within a single species.

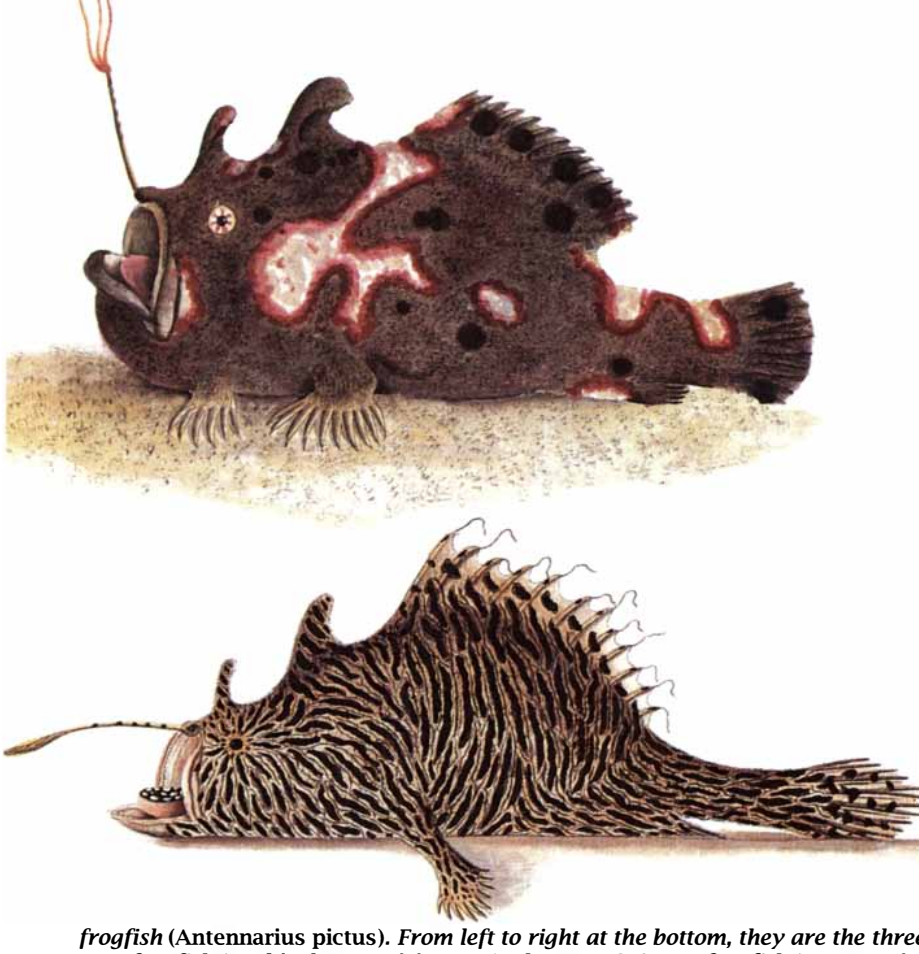
Individuals have the ability to switch back and forth between two color phases: a light phase (usually yellow or tan) and a dark phase (often green, dark red or black). Although the light phase seems to predominate in most habitats (for reasons that are not well understood), it is not uncommon to find an area where the entire color range for the species is represented.

The striated frogfish, *Antennarius striatus,* for example, maintains at least four distinct color phases: a green phase, during which it looks very much like an algae-covered rock; an orange phase, during which it has the appearance of an orange sponge; a white phase, during which it seems to mimic a white sponge; and a black phase, when it is reminiscent of a black sponge. We surmised that such marked change in color must occur when the fishes move to a slightly different habitat—say, a region of the coral reef where orange sponges rather than white ones predominate.

In order to test the response of frogfishes to background visual cues, we devised an experiment involving two species: the tuberculated frogfish, *Antennatus tuberosus,* and Commerson's frogfish, *A. commersoni*. We placed individuals in separate observation tanks and after a period of habituation changed the color of the gravel substrate (from white to black) and also added rocks and coral in various color combinations to the tank. Although the tuberculated frogfish changed from dark gray to light cream and Commerson's frogfish changed from lemon yellow to brick red, we were unable to determine the precise stimuli responsible for the color transformation. Clearly, further studies under natural field conditions are necessary.



VARIATION IN PIGMENTATION can be quite marked within a single species of



frogfish* (Antennarius pictus). *From left to right at the bottom, they are the three-spot frogfish* (Lophiocharon trisignatus), *the New Guinean frogfish* (Antennarius dorehensis), *the warty frogfish* (Antennarius maculatus) *and the striated frogfish.

We do know that the frogfish is a voracious and highly successful predator. Not only is it virtually indiscriminant in its dietary preferences, but it will attempt to swallow anything within striking distance, including animals slightly bigger than itself. By studying the feeding behavior of frogfishes, we have determined, for example, that a frogfish can enlarge its mouth by a factor of 12; moreover, it can do so in about six milliseconds—less time than it takes for a normal striated muscle to contract. We have also analyzed locomotion in these fishes, which ranges from "walking" across the substrate to jet propulsion.

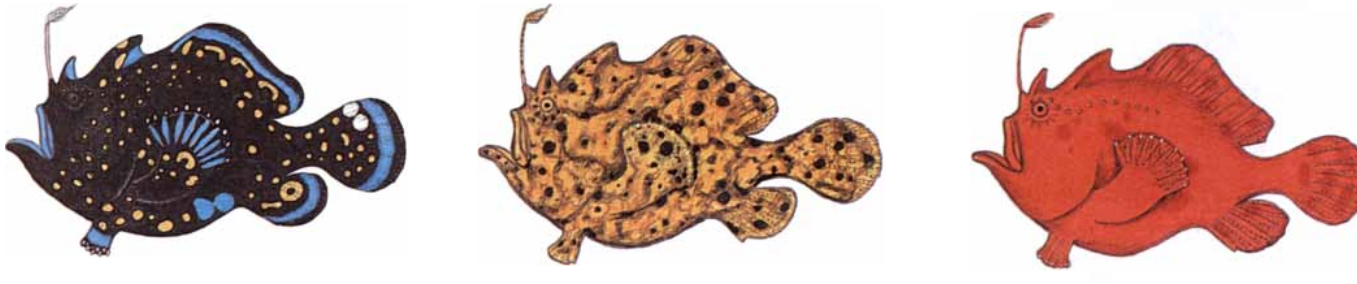
Our studies, which have been carried out both in the laboratory and at field sites off the coast of Oahu, Hawaii, and in Sydney Harbor, Australia, during the past 15 years, have enabled us to amass varying amounts of behavioral and ecological data for eight different species: Commerson's frogfish, the striated frogfish, the tuberculated frogfish, the hispid frogfish (*A. hispidus*), the warty frogfish (*A. maculatus*), the scarlet frogfish (*A. coccineus*), the bloody frogfish (*A. sanguineus*) and the three-spot frogfish (*Lophiocharon trisignatus*).

We began our research by analyzing luring behavior; in particular, we wanted to know whether luring directly influences the kinds of prey that a frogfish captures. Are lures species-specific, that is, does each species of frogfish have a morphologically unique lure? And is there a correlation between the appearance of the lure and diet, that is, does the lure resemble the preferred food items of the species attracted to it?

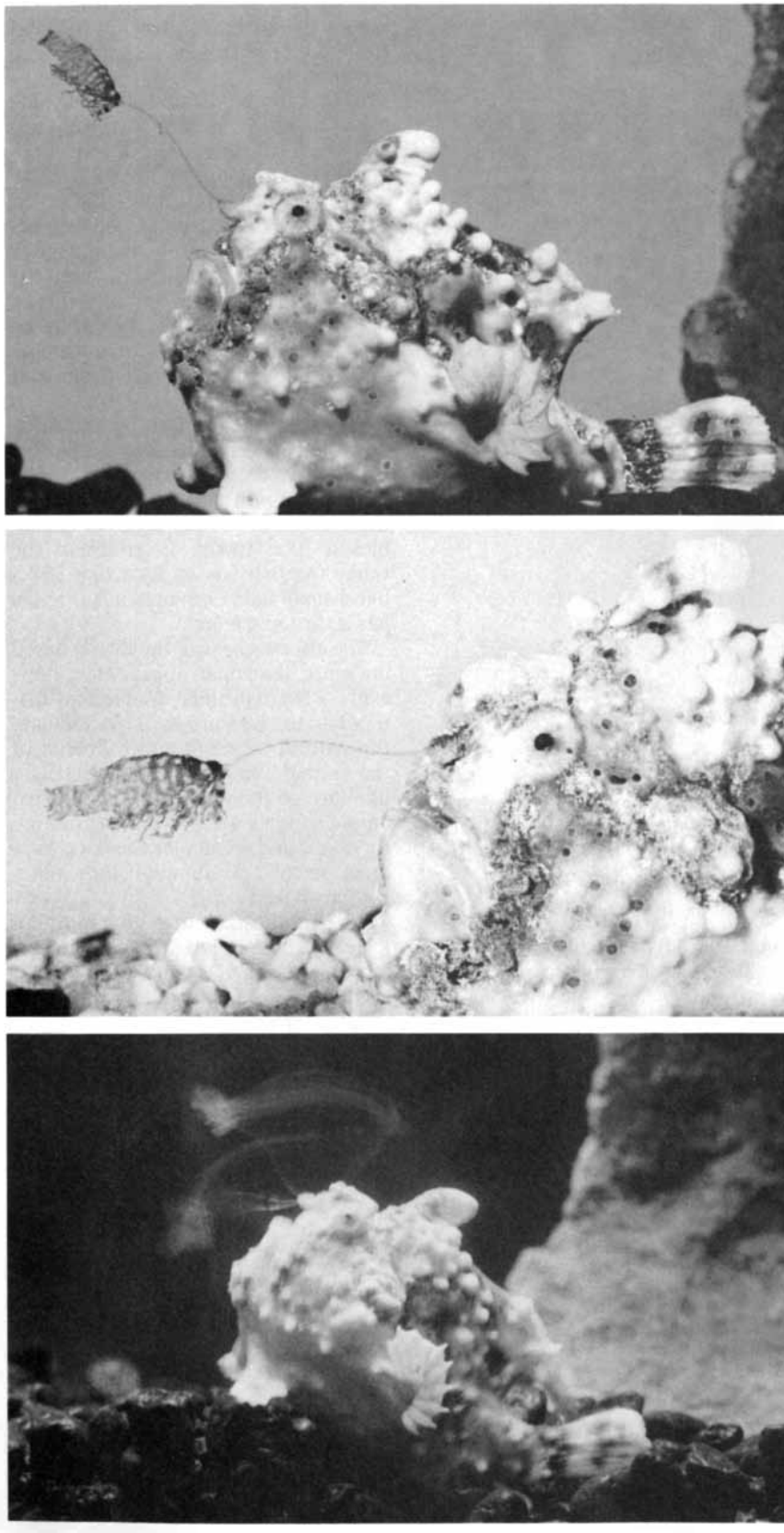
The shape and size of the lure, it seems, are unique to most species; in fact, a species can often be identified on the basis of its lure alone. The esca of the striated frogfish looks something like a polychaete worm, whereas the esca of the hispid frogfish resembles a tube worm. In contrast, the warty frogfish has an esca that looks like a small fish; Commerson's frogfish has a shrimplike one.

The effectiveness of the lure is based on more than just appearance, however. A frogfish must wiggle and manipulate the lure in ways that simulate the natural swimming movements of the animal being mimicked. The fishlike lure of the warty frogfish, for example, ripples as it is pulled through the water and so mimics the lateral undulations of a swimming fish [*see illustration on next page*].

We hypothesized that such morphologically distinct lures might reflect a highly specialized diet. After all, it seemed reasonable to suppose that a striated frogfish, with its wormlike esca, might feed primarily on species that normally prey on (and are therefore most attracted to) polychaetes or other marine worms. To test our hypothesis, we decided to analyze the stomach contents of four species: *A. striatus, A. pictus, A. commersoni* and *Antennatus tuberosus*. Somewhat to our surprise, our study revealed that frogfishes are not specialized feeders



frogfish. It is thought that individuals change color to mimic particular objects in their environment, such as rocks, sponges or pieces of coral. Only four (of many) color and pattern phases of the painted frogfish,* A. pictus, *are shown here.



APPEARING TO MIMIC its background, in this case an algae-encrusted rock (top), *the warty frogfish,* A. maculatus, *sits for hours waiting for potential prey to swim by. The tip of the lure (called the esca) varies from species to species, but here it resembles a small fish* (middle). *If another animal comes into view, the frogfish wiggles its lure* (bottom) *in a way that mimics the movements of a small fish.*

but eat a highly varied, overlapping assortment of prey.

Our findings were unexpected. Why, we wondered, should evolution favor such complex and apparently species-specific lures when the average frogfish is successful at attracting a wide variety of prey? One possible explanation is that food acquisition in the marine environment is both unpredictable and complex. Many individuals will randomly enter a frogfish's strike zone without being specifically attracted to the lure; others are attracted to the area not by the wriggling lure but by the frogfish itself, which may be mistaken for an appropriate site (such as a piece of coral) on which to lay eggs, graze or seek shelter.

Another possibility is that the lure may elicit a defensive or territorial response from nearby fishes. In a laboratory experiment involving the damselfish, *Dascyllus aruanus*, we observed that individual damselfish placed in the same tank as a frogfish would repeatedly direct aggressive displays toward the lure. On several occasions, in what seemed to be an overly aggressive attack, a damselfish entered the strike zone of the frogfish and was eaten.

Capture under those circumstances is instantaneous; indeed, almost any fish that swims within the strike zone (an area whose radius is roughly two thirds the length of the frogfish) has little chance of survival. To our knowledge, a frogfish can extend its mouth and engulf its victim at a speed greater than that of any other vertebrate predator. In fact, such rapid prey capture is perhaps the most remarkable of all the frogfish's attributes.

With the aid of such modern techniques as high-speed cinematography, we have spent a considerable amount of time analyzing the biomechanics of feeding in three species: *A. striatus*, *A. hispidus* and *A. maculatus*. By integrating frame-by-frame analyses of high-speed film (from 800 to 1,000 frames per second) with anatomical analyses of the bones, muscles and ligaments in the fish's head, we have come to realize that prey capture in the frogfish involves a highly choreographed sequence of behaviors.

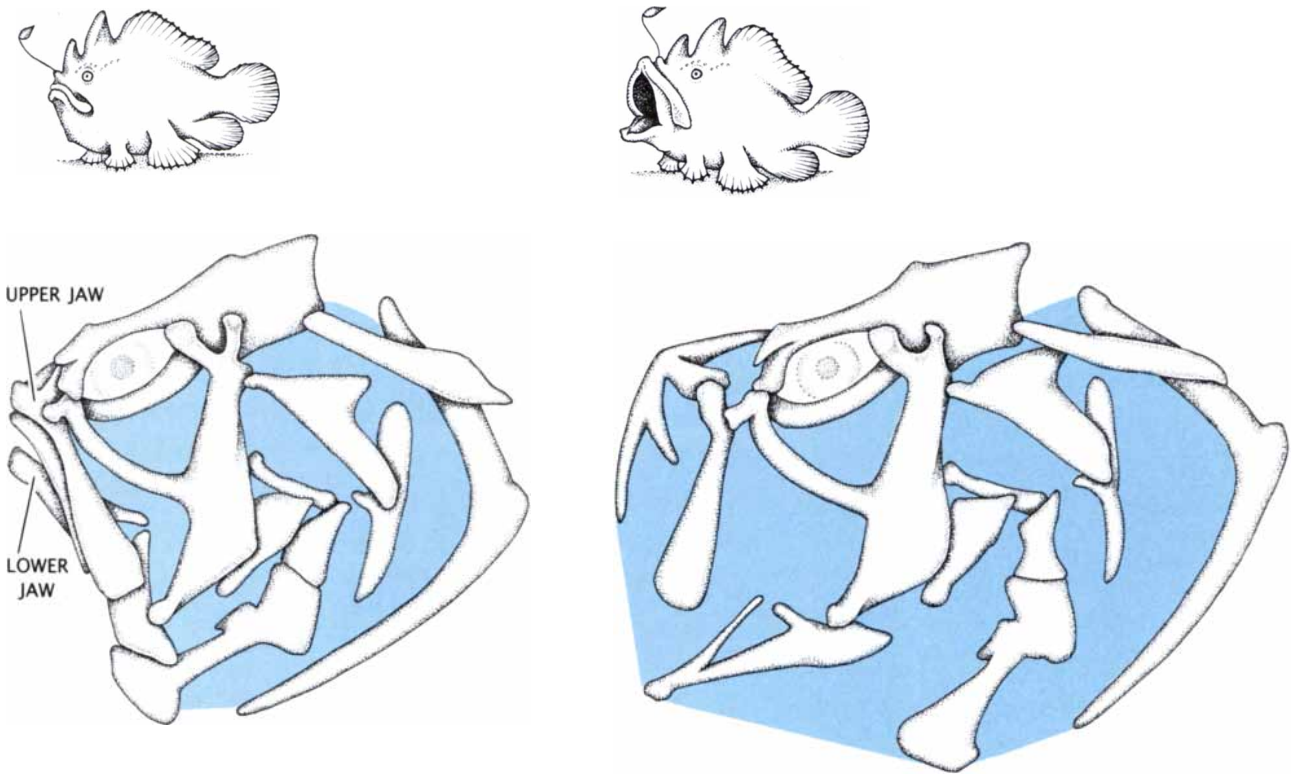
Three functionally distinct phases can be identified. Phase one consists of prestrike behavior, phase two is the strike itself and phase three is prey manipulation, which involves swallowing. During the prestrike phase, prey are followed visually until they come within a certain distance (about seven body lengths) of the frogfish. At that point, the frogfish begins wiggling its lure. If

RADIOGRAPH shows that the longlure frogfish,* A. multiocellatus, *has swallowed a scorpion fish* (Pontinus *sp.*), *which is longer than itself. A frogfish can swallow such large prey because its mouth expands in size by a factor of 12 or more.

the prey responds by approaching the lure, the frogfish then enters the strike phase. If the prey does not respond, the frogfish may start moving toward it—rapidly at first but then much more slowly. During the slow phase the frogfish flattens its body into what looks like a crouching position; doing so presumably renders it less conspicuous to its victim. When the targeted prey is about one body length away, the frogfish (now in the strike phase) orients itself by twisting or rocking its body into the proper position for attack.

The frogfish waits for the prey to enter its strike zone and then lifts its head and opens its mouth by depressing the lower jaw at the same time that it expands the upper jaw. In that configuration, the mouth forms an extended tube, which sucks a victim inward in much the same way that a vacuum cleaner pulls dust from a carpet. Once the prey is taken into the mouth, the frogfish enters the prey-manipulation phase. As the prey is swallowed, a large quantity of water is also ingested, which facilitates the passage of large prey into the frogfish's gullet. When swallowing is complete, excess water is ejected through the gills and a sphincter muscle at the base of the esophagus closes, which prevents the prey from escaping.

This method of prey capture, which is practiced by most of the world's fishes, is known as gape-and-suck feeding. The underlying principle is a simple one: negative pressure (suction) is created by the rapid expansion of the gill cavity and mouth, which creates an inward flow of water and so increases the speed with which prey are engulfed. Unlike fast-swimming predators that incorporate body speed to engulf prey, the lie-in-wait predator depends on the rapid expansion of its oral cavity in order to surprise and capture its prey. The gape-and-suck predator can also feed on prey without advertising its presence to other potential prey. Fish in close proximity to one another, for example, are often apparently unaware of the sudden loss of one of

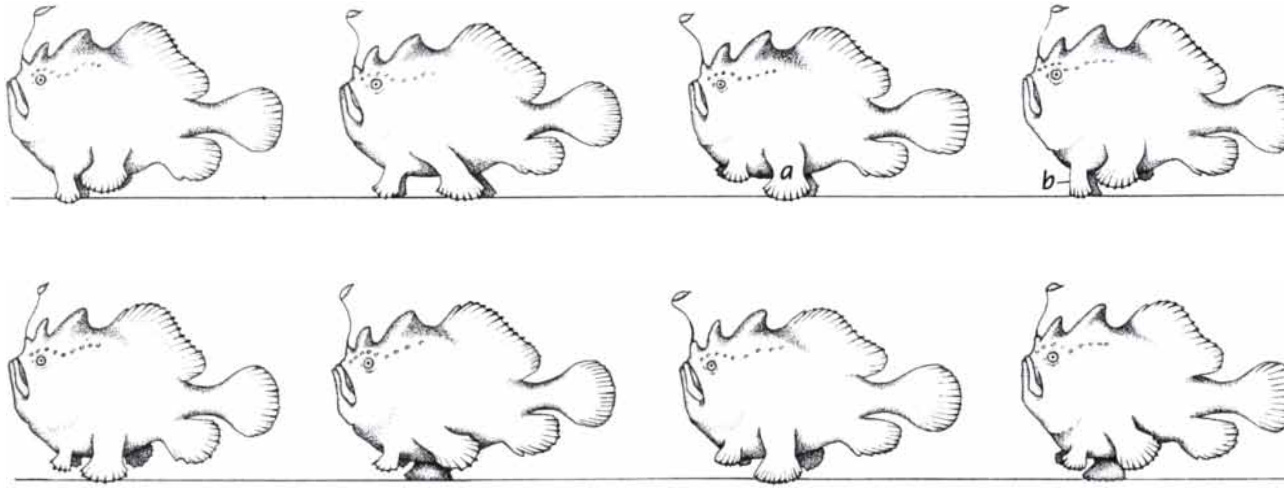


FROGFISH'S MOUTH remains closed **(left)** ***until suitable prey comes within striking distance. The frogfish then contracts the muscles of its upper and lower body and throat, which causes the head to lift and the mouth to open*** **(right)***; these same muscle contractions cause the upper jaw to push outward and the lower jaw to descend. As the mouth expands, it extends forward (a process that takes about six milliseconds), which enables the frogfish to suck in its victim.*

their neighbors and so remain vulnerable to repeated strikes by a lie-in-wait carnivore.

The difference between frogfishes and other fishes is the degree to which the mouth expands as well as its rate of expansion. We have determined, by injecting liquid paraffin into both the closed and fully expanded mouths of preserved fishes, that frogfishes can expand their mouths to a much greater extent than other gape-and-suck feeders. The European perch, *Perca fluviatilis*, for example, expands its mouth by only a factor of six when feeding.

Moreover, the frogfish's mouth expands with incredible rapidity. Analyses of high-speed films indicate that the hispid frogfish opens its mouth and engulfs its prey in less than six milliseconds. Similar times were meas-



FROGFISHES MOVE across the substrate with the help of leglike fins. They do so either by "crutching" **(top)** ***or by "walking"*** **(bottom)***. When crutching, the fish moves forward by resting its weight on the pectoral fins* **(a)***; the pelvic fins* **(b)** *bear the animal's weight only while the pectoral fins are being repositioned. When walking, the frogfish alternates its pectoral fins, pushing forward first with one, then the other, much as humans move their legs when walking.*

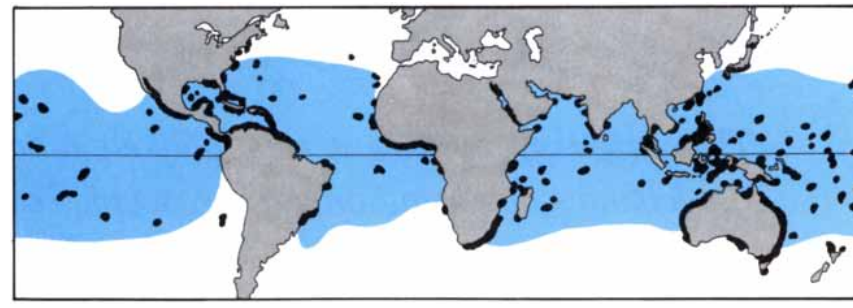
ured for the striated and warty frogfishes. By comparison, the stonefish, *Synanceia verrucosa,* which is thought to be the next fastest gape-and-suck feeder, requires 15 milliseconds, and the European perch needs a full 40 milliseconds.

We wondered about the mechanism that makes such speed possible. Do frogfishes have specially modified jaws? A unique set of muscles? What accounts for their remarkable prey-capturing ability? To answer those questions, we dissected the heads of several species and carefully examined the muscles responsible for opening the jaw. Our results were unexpected: there are no significant structural differences between the jaw muscles of frogfishes and those of other vertebrates. Moreover, we found no significant differences in bone structure.

Although we have yet to determine the means by which frogfishes open their mouths so quickly, we suspect that a currently unknown mechanism may be responsible. Perhaps frogfishes possess a biomechanical feeding mechanism similar to the mechanism in fleas that enables them to store elastic energy in the thorax and so jump to incredible heights [see "The Flying Leap of the Flea," by Miriam Rothschild et al.; SCIENTIFIC AMERICAN, November, 1973]. Is it not possible that frogfishes have a catapault mechanism in the jaw that enables them to store elastic energy and then quickly release it? We think such a modification may exist, although further studies are needed to confirm our hypothesis.

The family Antennariidae enjoys many other highly complex and fascinating adaptations, including novel forms of locomotion. To move across the substrate, either in pursuit of prey or in search of a new resting site, frogfishes rely on one of two tetrapodlike gaits. One is reminiscent of a person on crutches: the pectoral fins (like crutches) bear the weight of the fish's body as it moves forward; only at the end of the stroke is weight transferred briefly to the pelvic fins. The other gait superficially resembles the walk of terrestrial vertebrates, which ambulate by moving alternate limbs. The pectoral fins provide power for walking, while the pelvic fins serve only to stabilize the fish. Frogfishes also swim, doing so by undulating their body as they move. In addition, they often jet propel themselves through the water, a feat the fishes accomplish by ingesting large amounts of water and then forcing it backward through gill openings.

Ultrafast feeding mechanisms, jet propulsion and aggressive mimetic devices by themselves are not unique to frogfishes; each adaptation can be found in a wide variety of other fish species. Yet in no other group are so many highly evolved and complex adaptations integrated into a single organism. It is not just the ability to lure prey or to change color or to clamber across the substrate that makes frogfishes so interesting. More important, perhaps, is that natural selection has favored the evolution of so many specializations within a single family of fishes. Understanding the specialized morphological and behavioral adaptations of these aggressive mimics is—without question—a challenge that will continue to occupy investigators for many years to come.



***GEOGRAPHICAL DISTRIBUTION** of frogfishes is widespread in tropical and subtropical waters. They are most abundant in coastal waters of Indonesia, the Philippines and other island groups of the South Pacific. Few species occur either north or south of the region indicated in color on the map; most prefer areas where the average annual water-surface temperature is greater than 20 degrees Celsius.*

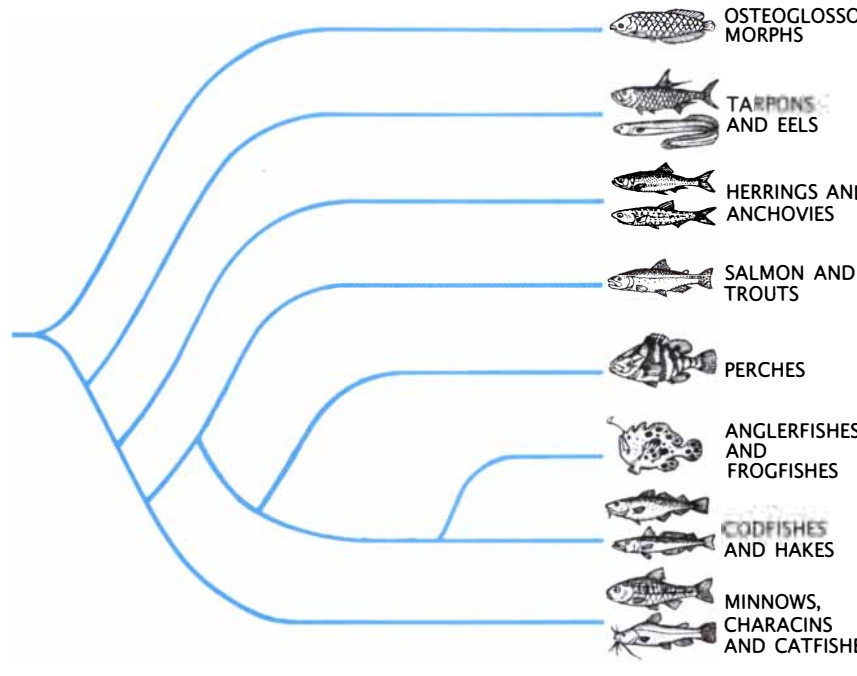


***DIAGRAM** of the evolutionary relationships among bony fishes (the teleost fishes) indicates that anglerfishes are most closely related to codfishes and hakes.*

FURTHER READING

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The ^{3}He Superfluids

The curious properties of this millikelvin liquid show quantum mechanics operating on a macroscopic scale. At nanokelvin temperatures even more bizarre liquids may exist

by Olli V. Lounasmaa and George Pickett

The intensely hot conditions that prevailed at the universe's birth probably lie forever beyond the reach of even the largest particle accelerators. Investigators of low-temperature physics, however, have long surpassed nature. In the 15 billion years since the big bang, no point in the universe at large has reached a temperature cooler than three kelvins (the temperature of the cosmic microwave background). In laboratories, however, temperatures measured in nanokelvins and picokelvins are being achieved. The phenomena being studied at such temperatures are not only new to physicists, they have never occurred before in the history of the cosmos.

Of all the unusual phenomena that ultralow temperatures elicit, perhaps the most spectacular are superfluidity—the frictionless flow of a fluid—and its electronic analogue, superconductivity. Superfluidity in liquid ^{4}He, the common isotope of helium, has been known since 1938. In 1972 Douglas D. Osheroff, Robert C. Richardson and David M. Lee of Cornell University found that the rare isotope ^{3}He could also become superfluid. Exploration of the properties of this new kind of matter has been a central project of ultralow-temperature physics for the past decade and a half.

OLLI V. LOUNASMAA and GEORGE PICKETT study the behavior of materials at millikevin and microkelvin temperatures. Lounasmaa is research professor of the Academy of Finland and director of the Low Temperature Laboratory at the Helsinki University of Technology; his research interests include cryogenics, ultralow-temperature physics and magnetoencephalography (the study of the brain by means of highly sensitive magnetic probes). Pickett is professor of low-temperature physics at the University of Lancaster, where his work concentrates on condensed-matter physics and techniques for carrying out experiments near absolute zero. In 1979, with his colleagues Tony Guénault and Ian Miller, he established the Lancaster microkelvin facility.

The behavior of superfluid ^{3}He can be very intricate even though its structure is that of a simple liquid, composed of identical, chemically inactive, rare gas atoms. In addition to being worthy of study for its own sake, this combination of the simple and the complex makes superfluid ^{3}He an ideal substance in which to study many other condensed-matter problems, ranging from the properties of neutron stars to those of high-temperature superconductors.

Helium at low temperatures is a "quantum liquid." That is to say, quantum mechanics plays an important role, not only in its microscopic properties but also in its macroscopic behavior. Helium's superfluid nature arises from the interplay of quantum mechanics, which imposes a fundamental minimum of uncertainty on the behavior of individual atoms, and the third law of thermodynamics, which requires a substance to become perfectly ordered as its temperature approaches absolute zero. At high temperatures, substances are gaseous, and their atoms fly about at random. As the temperature falls, a substance condenses into a liquid and ultimately freezes into a solid, in which the position of every atom should be fixed.

On the quantum side, Heisenberg's uncertainty principle states that a particle's momentum and position cannot both be precisely known at the same time; measuring one produces uncertainty in the other. Helium atoms are very light and interact only weakly; as a result, their positions are quite uncertain even at absolute zero. They cannot be kept stationary enough to form a solid at low pressures because of their large zero-point motion.

The result is something of a paradox: superfluid helium atoms remain liquid even at the lowest temperatures, but unlike ordinary liquids, whose fluid motion is a sign of internal disorder, low-temperature liquid helium is perfectly, though subtly, ordered.

The particular ordering that takes place in liquid helium is a consequence of a fundamental division that exists in quantum mechanics between fermions (named after Enrico Fermi) and bosons (named after Satyendra Nath Bose). Bosons comprise such force-carrying particles as photons and pions. Their spin is an integer multiple of the fundamental quantum of angular momentum, $\hbar$, Planck's constant divided by 2π. Any number of bosons can occupy the same quantum state simultaneously. This means that at absolute zero all the bosons in a given system can condense into a single lowest-energy quantum state.

Particles whose spin is a half-integer multiple (1/2, 3/2 and so on) of $\hbar$, such as electrons, protons and neutrons, are fermions. They are the particles from which matter is built. At any given time, only one fermion can occupy a particular quantum state; this rules out the condensation of all the particles to a single lowest level.

A ^{4}He atom consists of two electrons, two protons and two neutrons, each with half-integer spin. As a result, the atom is a boson. When ^{4}He is cooled below a critical temperature, called the lambda point (2.17 kelvins under zero pressure), the liquid starts condensing to the lowest-energy state. At very low temperatures, almost the entire liquid is in this state, and so a single quantum-mechanical wave function describes not just the behavior of individual particles but that of the whole macroscopic liquid.

Furthermore, a significant amount of energy and momentum is required to promote the liquid into an excited state. This condition produces superfluidity. In a normal fluid, collisions between atoms or between atoms and the walls of a container can easily shift an

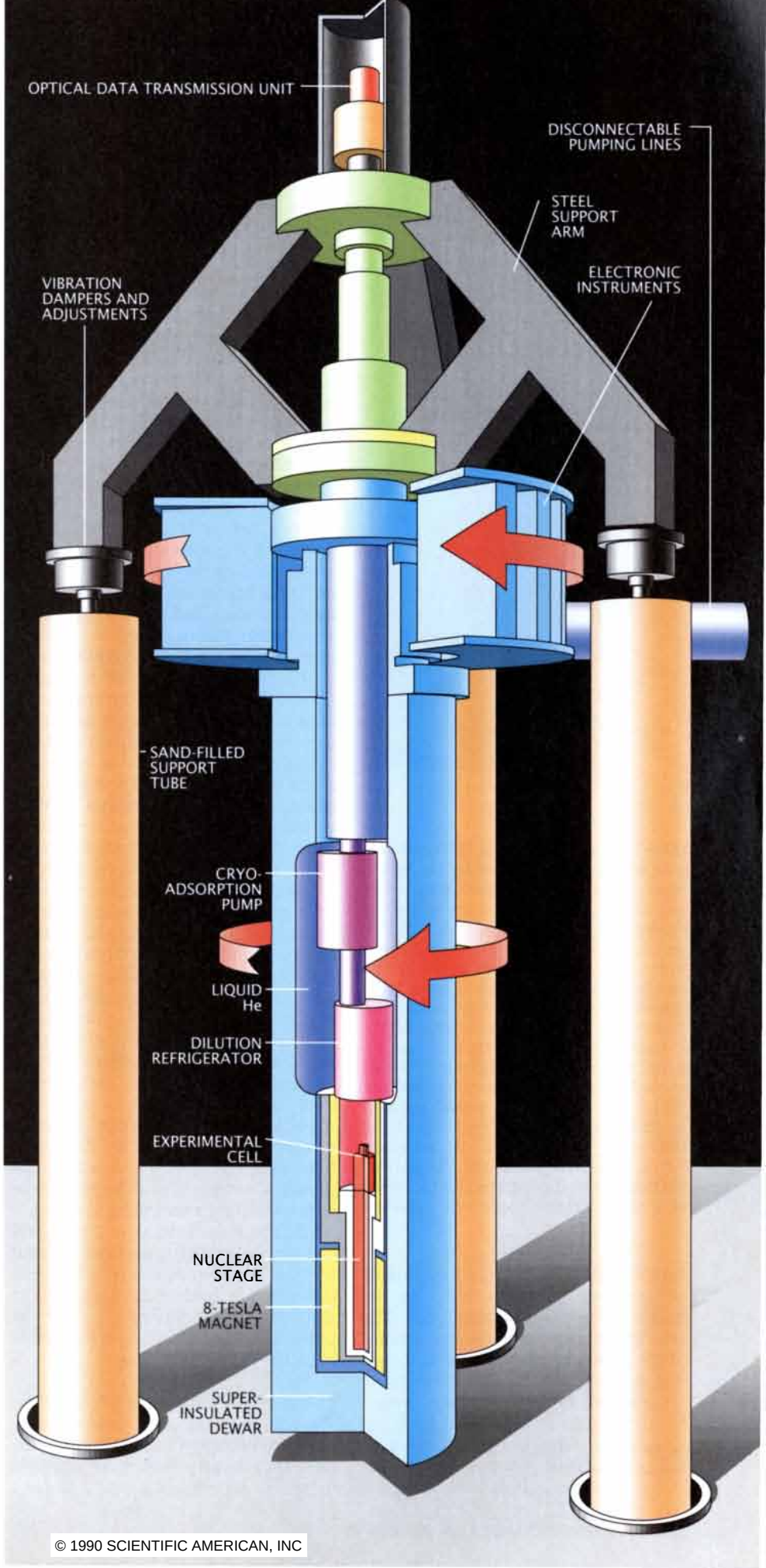
atom from one energy state to another state of nearly equal energy and dissipate a fluid flow. Helium liquid in the ground state, however, cannot be shifted into a different state by low-velocity collisions. There is no mechanism for energy dissipation.

Superfluidity in ^{3}He has a somewhat different character. Its atoms contain an odd number of neutrons and so an odd number of particles in sum. Thus, they are fermions and are unable to condense into a common ground state. As a result, ^{3}He cannot become superfluid as easily as its boson sibling can. Instead, at a transition temperature roughly 1,000 times lower than that of ^{4}He, a weak attraction between ^{3}He atoms begins to make itself evident. Atoms with equal and opposite momenta tend to form pairs in which the two particles orbit each other at a distance. These pairs (called Cooper pairs after Leon N. Cooper, now at Brown University, who originally proposed an analogous pairing of electrons to explain superconductivity) are bosons—their half-integer angular momenta add up to an integer value. Therefore, they can condense to a common ground state and form a superfluid.

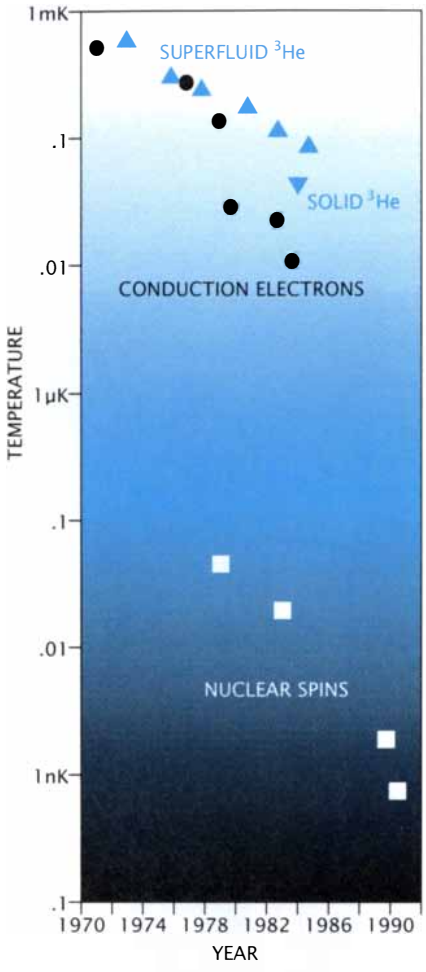
Indeed, they form two superfluids, ^{3}He-A and ^{3}He-B. In the A phase the nuclear spins of the two atoms tend to lie perpendicular to the axis of orbital motion, whereas in the B phase the correlation is more subtle.

Because all pairs of ^{3}He are in the same state, the relations between spin and orbital motion are associated not only with individual pairs but with the superfluid as a whole. Superfluid ^{3}He thus has directionality, rather like a liquid crystal; it can be aligned by external factors, such as magnetic fields, liquid flow or surfaces. The spatial arrangement of these directions in the liquid is known as the texture. (Atoms of ^{4}He have no spin and so no special directional properties; superfluid ^{4}He thus has no texture.)

The behavior of superfluids differs from that of conventional fluids not only in degree but in kind. One notable anomaly manifests itself if one tries to rotate a superfluid. A normal liquid in a bucket that is



ROTATING CRYOSTAT creates vortices in superfluid ^{3}He. The three-meter-high apparatus, located at the Helsinki University of Technology, can spin at rates as high as 30 revolutions per minute. It contains not only the liquid helium but also experimental sensors and a multistage cooling system.



LOW-TEMPERATURE RECORDS shown above have been attained in ^{3}He, which must be cooled by contact with other substances, in the electrons of metals cooled by magnetic ordering and in metal nuclei considered by themselves. The lowest temperatures in liquid ^{3}He (around 100 microkelvins) have been achieved at Lancaster. (Hidehiko Ishimoto's group at the University of Tokyo has brought solid ^{3}He to 43 microkelvins.) The Lancaster group has also cooled conduction electrons in copper to 12 microkelvins, a record equaled by Frank D. M. Pobell's group at the University of Bayreuth. In February Pertti J. Hakonen and Shi Yin in Helsinki lowered the nuclear temperature of a silver sample to 800 picokelvins.

spinning at a constant velocity rotates at the same angular velocity as the bucket, as if it were a solid body. The velocity, and thus also the momentum of the liquid, is proportional to the radial distance from the axis of rotation.

Superfluid helium, however, cannot be made to rotate as a solid body because of its status as a quantum liquid. Uniform rotation requires that the velocity, and consequently the momentum, of the liquid increase linearly with distance from the axis of rotation. Momentum and wavelength are inversely proportional to each other, and so the quantum wave functions of atoms in the outer part of the liquid must have shorter wavelengths than those of the atoms nearer the axis of rotation. That is perfectly possible for atoms in a normal liquid because each one has its own wave function. All the atoms in a sample of superfluid helium, however, are described by a single quantum-mechanical wave function, and it is geometrically impossible to construct a circular set of peaks and troughs whose spacing decreases with increasing radius. Superfluid helium exists in a state of nonrotation with respect to the universe as a whole.

What is possible is a wave function whose wavelength increases with increasing radius. Such a pattern corresponds to the motion of liquid around a whirlpool, or vortex. The flow is fastest at the center and falls off as the radius increases. Indeed, if one rotates a container full of superfluid helium, even at a relatively low angular velocity, the stationary state of the liquid breaks down and tiny vortices form. Rotation, rather than being uniformly distributed through the liquid as in solid-body motion, penetrates the liquid along the vortex lines. The interaction among vortices and between vortices and the walls of a container creates some friction, and so the liquid is no longer completely superfluid.

The circulating flow associated with each of these miniature whirlpools repels its neighbors, so that the vortices form a regular hexagonal lattice. At typical experimental rotation speeds of 12 revolutions per minute, the distance between vortices is about .2 millimeter. (The vortex lattice in ^{4}He has been photographed directly by Richard E. Packard and his co-workers at the University of California at Berkeley.)

Vortices form easily in open volumes of superfluid, but confining the superfluid in a container filled with small particles—as might be done to demonstrate the fluid's vanishing viscosity—inhibits vortex formation. The liquid can flow between the particles without friction, but there is no space for a circulating flow to develop. This leads to a paradoxical situation: the finer the pores through which a superfluid must pass, the faster it can flow.

Superfluid vortices in ^{4}He are interesting enough; the internal structure of superfluid ^{3}He yields vortices that display even more complex behavior. Experimental study of such phenomena, however, is quite demanding. Not only must samples be cooled to a few millikelvins or less, they must also be rotated to produce the vortices. So far workers have only been able to solve this problem by rotating the entire experimental apparatus.

A large part of the data on vortices in ^{3}He has been obtained from the ROTA 1 cryostat in Helsinki, in use since 1981. It can produce rotation speeds as high as 30 revolutions per minute and temperatures as low as .6 millikelvin. An improved cryostat, ROTA 2, became operational in 1988. ROTA is a joint project between the Academy of Finland and the Soviet Academy of Sciences. Many individuals have participated in this experiment: M. Peter Berglund, Yuri M. Bun'kov, Devi Garibashvili, Pertti J. Hakonen, Olli T. Ikkala, Seppo T. Islander, Matti Krusius, Olli V. Lounasmaa, Yuri Mukharsky, Kaj K. Nummila, Jukka P. Pekola, Riita H. Salmelin, Juha T. Simola, Ladislav Skrbek, Jelil S. Tsakadze, among others. Theoretical contributions by Martti M. Salomaa, Grigory E. Volovik and their co-workers have also been decisive to the success of the ROTA project.

Four different experimental methods have been employed to explore the behavior of ^{3}He inside the rotating cryostat: nuclear magnetic resonance (NMR); the alternating-current (a.c.) gyroscope, which measures changes in the angular momentum of the superfluid; ion mobility, which acts as a sensitive probe of the fluid structure; and ultrasound, whose attenuation depends on the liquid's texture.

Most of what is known today about the effects of rotation in superfluid ^{3}He has been detected by NMR: the rotating ^{3}He is subjected to a steady magnetic field, which causes the axes of rotation of the nuclei to precess. A radio-frequency signal is employed to flip the nuclear spins. The particular frequencies that cause the spins to flip are a function of the interactions among the ^{3}He atoms.

Negative ions typically yield information about the texture of superfluid ^{3}He—the macroscopic alignment of spins and Cooper-pair orbital axes. Their motion through the fluid under the influence of an electric field depends strongly on the orientation of the field and the superfluid texture.

Similarly, the attenuation of ultrasound is a sensitive probe of the texture of ^{3}He superfluids. The advantage of ultrasound is that it can be employed in all magnetic fields. Systematic ultrasonic experiments have already been carried out in the ROTA 2 cryostat on vortices in ^{3}He-A in low magnetic

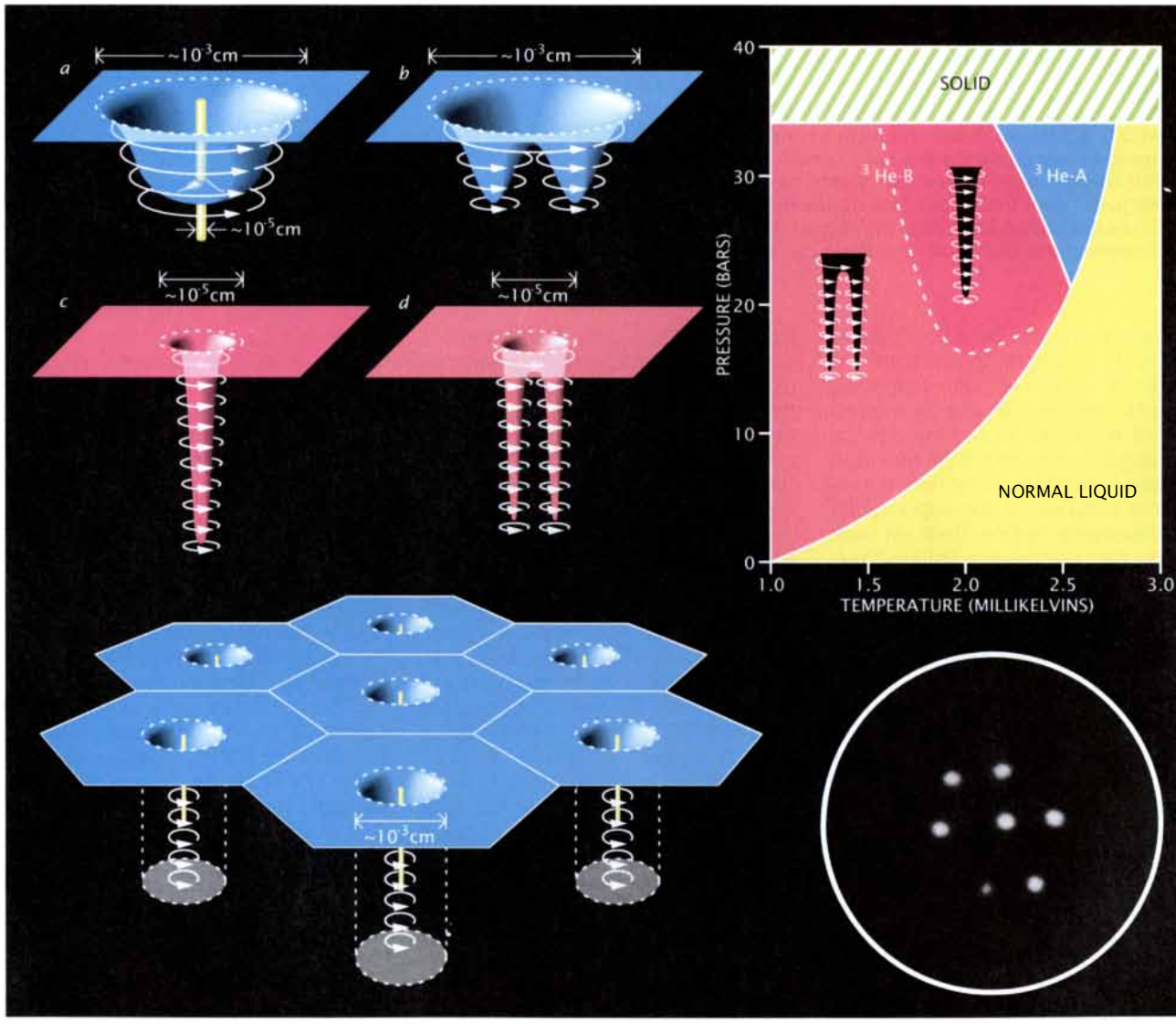
fields and in yet another superfluid phase, ^{3}He-A_1, which forms in strong magnetic fields.

The a.c. gyroscope, an experiment in which Packard participated, has been used to measure the flow properties of ^{3}He. The gyroscope consists of a horizontal torus filled with ^{3}He and plastic powder (to enhance superfluid flow) together with a drive mechanism for vibrating the torus and instruments to measure the superfluid's response.

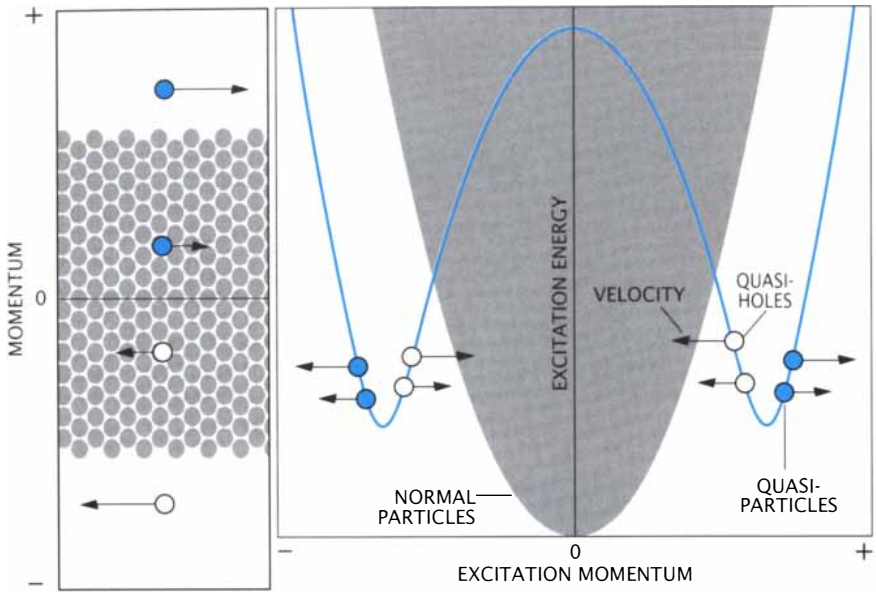
The first step in carrying out a typical gyroscope experiment is to cool the ^{3}He sample to well below the superfluid transition temperature while keeping the fluid at rest. Next the cryostat containing the torus (which holds the ^{3}He and plastic powder) rotates for about a minute at a rate between one and 20 revolutions per minute. During the five minutes following the end of the rotation, experimenters record the amplitude of vibrations around the vertical axis; these vibrations are caused by the precession of the spinning superfluid in the torus and are a measure of the angular momentum.

At low rotation speeds there is no angular momentum at all in the ring after the cryostat has been halted. When the cryostat rotates slowly, the superfluid simply slips frictionlessly through the pores of the plastic powder in the torus. Above a critical velocity of two to three revolutions per minute, however, vortices begin to form; the superfluid is dragged along and begins to rotate. An angular momentum persists in the torus after the cryostat is stopped.

One of the first experiments carried out with the gyroscope was a careful check for true superfluidity in liquid ^{3}He. The cryostat was rotated at its maximum speed to create a large angular momentum within the a.c. gyroscope; it was then brought to rest and the angular momentum measured. Af-



UNIQUE PROPERTIES of superfluid ^{3}He include the formation of at least four different kinds of vortices as the fluid is rotated. The quantum-mechanical properties of the liquid prevent it from rotating as a whole in the way that normal fluids do. A phase diagram (*upper right*) shows the conditions under which vortices form. ^{3}He-A can sustain vortices with either single cores (*a*) or double cores (*b*). The type of vortex that forms depends on the cooling history of the sample. The single-cored vortex is discontinuous: a minuscule thread of ordinary fluid runs through its center. The B phase also supports single-cored (*c*) and double-cored (*d*) vortices. The diameters of the ^{3}He-B vortices are much smaller than they are in the A phase, and both B-phase vortices are discontinuous. The fluid flows that make up individual vortices tend to repel each other, so that the vortices arrange themselves in a stable hexagonal lattice (*bottom*). Richard E. Packard of the University of California at Berkeley has photographed such a lattice in ^{4}He, which supports only one type of vortex (*lower right*).



UNPAIRED ATOMS in liquid ^{3}He form quasiparticles and quasiholes. Most atoms are bound in superfluid Cooper pairs (*gray*). Unpaired atoms have holes associated with them—empty states that would be occupied by the other atom in the Cooper pair. When the momentum of unpaired atoms is high, they stand out and appear as quasiparticles; when the momentum is low, the atoms merge into the low-momentum background, and their corresponding holes are visible instead.

ter the cryostat had been kept stationary for 48 hours, its temperature still below the superfluid transition point, workers measured the angular momentum of the liquid in the torus again. The angular momentum of the ^{3}He-B remained constant to within the 10 percent accuracy of the experiments. The resistance to flow deduced from this study is at least a trillion times smaller than that of normal liquid ^{3}He at the same temperature.

It is impossible to prove experimentally that ^{3}He-B has no resistance to flow whatsoever, but these results show beyond a reasonable doubt that ^{3}He-B is a true superfluid, not merely a normal liquid with very low viscosity. Peter L. Gammel, now at AT&T Bell Laboratories, and John D. Reppy of Cornell University, who used a somewhat different experimental arrangement, have seen persistent supercurrents in ^{3}He-A as well.

In other Helsinki experiments, we investigated additional details of vortex behavior. The critical velocity at which vortices begin to form and at which the B-phase superfluid is dragged along by the rotating gyroscope undergoes an abrupt change at certain temperatures and pressures. At a pressure of 23 bar and a temperature less than about 1.7 millikelvins, the critical velocity is 7.1 millimeters per second, whereas at a slightly higher temperature it is only 5.2. It appears that this sudden change in properties manifests the formation of different types of vortices in ^{3}He-B. The Helsinki group has discovered four different vortex types in superfluid ^{3}He, two in ^{3}He-A and two in ^{3}He-B, in contrast to the single kind that exists in ^{4}He.

In the A phase of ^{3}He, one of the vortex types is singular—it has a discontinuity in its core where the flow velocity changes direction abruptly—whereas the other type of vortex, which has a double core, is continuous. In the B phase both vortex types are singular—there is a discontinuity in the velocity field at the center. Complex theoretical analyses, first by Erkki V. Thuneberg of the University of Helsinki and then by Salomaa and Volovik, indicate that the vortex that forms at a lower critical velocity has a single, symmetric cylindrical core around which fluid flows, whereas the vortex that forms at a higher critical velocity has a double core.

Even when it is stationary, ^{3}He contains excitations. These excitations are associated with atoms that are not linked in Cooper pairs. Associated with each unpaired atom is a shadow particle—a "hole"—represented by the empty state of the atom it would have been paired with had the state been filled. These excitations combine the properties of a particle and a hole. At high momenta the particlelike properties dominate, and at low momenta the holelike properties dominate. An excitation thus is called either a quasiparticle or quasihole.

Much of the experimental data on the ballistics of quasiparticles in superfluid ^{3}He has been gained from the nuclear cooling cryostat built by Tony M. Guénault and one of us (Pickett) at the University of Lancaster. This apparatus, in operation since 1980, can cool liquid ^{3}He to around 100 microkelvins, where thermally generated excitations are scarce. Among those who have contributed to this work are John Carney, Kees Castelijns, Kenneth Coates, Shaun Fisher, Christopher Kennedy, Vepan Keith, Ian Miller, Simon Mussett, Gregory Spencer and Martin Ward. The nuclear cooling stage of this machine is unusual in that the copper cooling element is immersed directly in the liquid ^{3}He specimen, providing very good thermal contact.

Investigations of the samples cooled in this cryostat have been carried out by means of an extraordinarily simple yet versatile device (first developed by Mervyn Black, Henry Hall and Keith Thompson): a fine strand of superconducting wire bent into a semicircular loop and anchored at both ends [*see illustration on opposite page*]. If this wire is placed in a low-intensity magnetic field, then a current flowing through the wire will feel a force, and the wire will experience a sideways push.

An alternating current of the correct frequency can make the wire oscillate at its natural resonant frequency. Furthermore, as the wire moves in the field, it generates a voltage proportional to its velocity. The wire can be set in motion by sending a current through it and the response then observed by looking at the resulting voltage. This simple device has become the universal probe at very low temperatures in the Lancaster laboratory.

At low velocities the wire moves through the superfluid virtually without energy dissipation. The only friction comes from internal effects in the wire and its associated circuitry and from collisions with quasiparticles. The amount of damping is therefore proportional to the number of excitations in the liquid.

Because the number of quasiparticles changes with temperature, the wire can immediately be used as a thermometer. To be able to measure the temperature of the liquid directly at the lowest temperatures is obviously very important. It is almost impossible to get any other thermometric material into good

thermal contact with the liquid ^{3}He at 100 microkelvins, because the density of the excitations—particles the thermometer can measure—in the superfluid is comparable to a very high vacuum at room temperature.

In addition to being almost the only device capable of measuring ^{3}He temperatures directly, the wire-loop thermometer is also quite sensitive. The damping falls some five orders of magnitude between the temperature of the superfluid transition and the lowest temperatures to which liquid ^{3}He can be cooled.

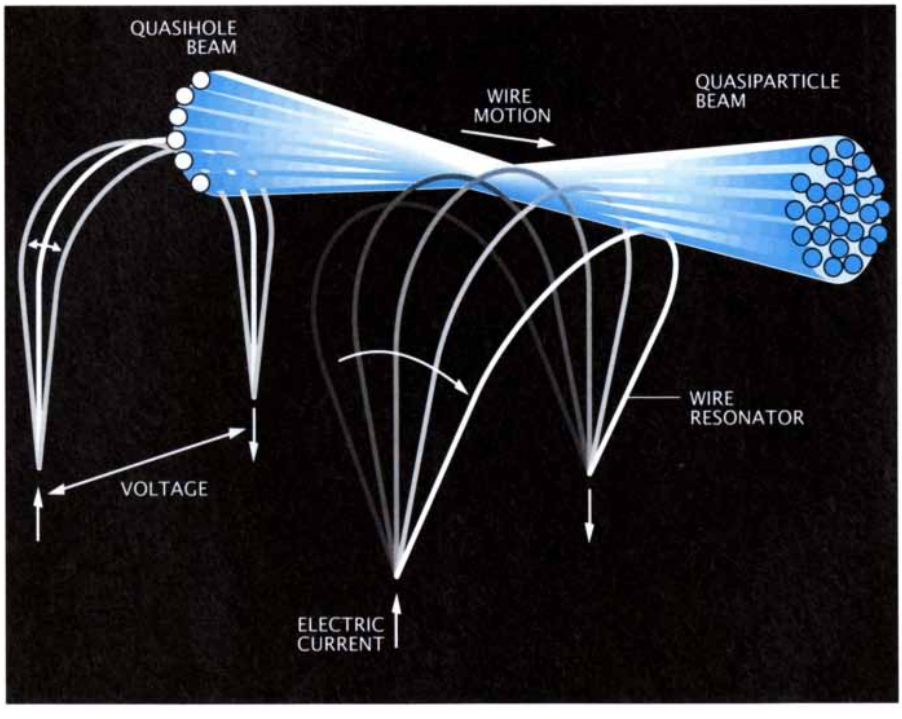
Even more important than the ability of the wire loop to determine the temperature of liquid ^{3}He is its potential for probing the structure of the liquid. Atoms in superfluid ^{3}He are bound in Cooper pairs; when the loop's maximum velocity exceeds about 10 millimeters per second, the wire can provide enough energy to break a pair into two atoms, or quasiparticles. At the lowest temperatures and low velocities, the wire's motion through the liquid is virtually frictionless. Once the wire reaches the critical velocity, however, the frictional force rapidly builds up by orders of magnitude, although the velocity increases by only a few percent. Because the change in damping is so catastrophic at the critical velocity, any anomalous flow of liquid around the wire (which would alter the wire's apparent speed) will markedly change the point at which damping builds up.

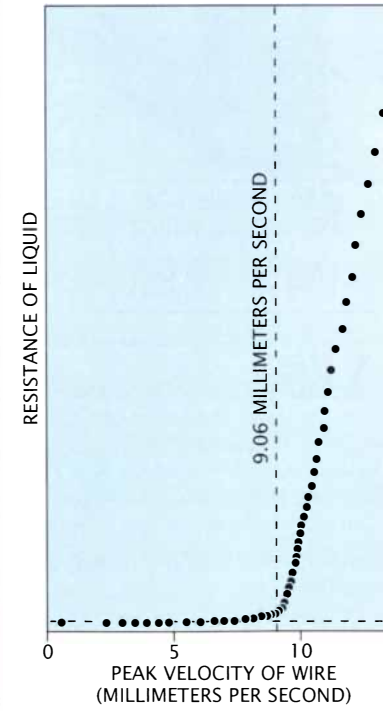
Pair breaking also provides a controllable source of artificially produced quasiparticles and quasiholes. The simplest picture of the pair-breaking process, developed by Canadian physicist Philip Stamp, suggests that the wire acts as a moving searchlight, emitting a beam of quasiparticles forward and a beam of quasiholes rearward. Not far below the superfluid transition temperature a large fraction of the particles is unpaired, and the mean free path between collisions is very short. Any quasiparticle "wind" will rapidly be scattered and dissipated by collisions with quasiparticles or quasiholes already present in the fluid. Yet if the temperature is reduced to one tenth of the superfluid transition temperature, only one in a million particles will be unpaired, and the likelihood of collisions will be so low that particles in the wind could travel for a kilometer or more without a collision.

Experiments at low temperatures have confirmed the basic accuracy of this picture. When a second wire is immersed in liquid ^{3}He, quasiparticles and quasiholes emitted by the first wire exert a force on the second wire, setting it in motion and generating a voltage. The second wire experiences a force directly proportional to the number of excitations striking it. The number of particles in the wind is in turn proportional to the energy dissipated by the first wire. Essentially all of the energy delivered to the first wire is converted into excitations, because there is no other mechanism for energy dissipation. We have also been able to confirm that the beam is narrow by looking at the angular distribution of the emitted quasiparticles.

Some puzzles still remain. Because the wire is moving back and forth, the pulsed beam of excitations emitted should consist of alternating bursts of quasiparticles and quasiholes. When a quasiparticle is scattered from a surface in a normal process, its momentum should simply be reversed, so that it applies a push to a reflector. A quasihole, in contrast, because its momentum and velocity point in opposite directions, applies a pull when reflected. Nevertheless, the detector wire experiences a push for bursts of either quasiparticles or quasiholes.

To see why this should be so requires a deeper understanding of the nature of particles and holes in ^{3}He. The concept of a hole arises from the nature of the lowest-energy level, or ground state, of a system of particles. In the lowest-energy state of a system of fermions, for example, particles fill all the states up to a certain energy lev-





SUPERCONDUCTING WIRE LOOP set in motion by current and magnetic field breaks up superfluid Cooper pairs to create beams of quasiparticles and quasiholes (*left*). A second loop can detect the resulting quasiparticle wind, whose motion yields data on the structure of the superfluid. Pair breaking increases rapidly as the wire exceeds a critical velocity (*right*).

el, determined by the number of particles, because each fermion must be in a different state. All higher-energy levels are empty. Such a ground state is what field theorists call a vacuum, because, as long as all the low-level states remain filled and no particle is boosted to an unfilled level, nothing can interact with it.

If a single fermion is removed from among the filled states and put in some higher-energy state, the situation changes markedly. The particle in the higher-energy level can now interact with various forces, and it leaves behind an empty quantum state—a hole. The particle and the hole behave in substantially different ways. Push a particle, and it moves away. Its momentum and energy increase or decrease together. Holes, however, do the opposite. Push a hole, and it approaches you. The momentum of a hole decreases as its energy increases, and vice versa. A hole behaves as if it had negative mass—indeed, it is a missing particle, so in a sense it does indeed have negative mass.

Unpaired particles in superfluid ^{3}He are particularly interesting. The Cooper pairs making up the superfluid part—the ground state—of the liquid consist of coupled particles with opposite momenta. As a result, unpaired atoms are coupled with a *hole* of opposite momentum or, if one prefers, an empty state where a particle of opposite momentum would properly be. This leads to very unusual behavior.

For a normal particle, the relation between energy and momentum is simple. Both rise and fall in step. The situation for ^{3}He quasiparticles is not so straightforward. An unpaired atom whose momentum is high stands out because other high-momentum states are empty, whereas the associated hole (a state without an atom in it) is indistinguishable from other empty high-momentum states. The particle-hole combination looks exactly like a real particle, and its energy increases with momentum. An unpaired atom whose momentum is low, in contrast, is indistinguishable from the myriad of paired low-momentum particles; it is the low-momentum hole (moving in a direction opposite to that of the particle) that stands out. And the hole's energy increases as its momentum falls. Between these two extremes is a point where the energy of the particle-hole combination falls to a minimum and its velocity falls to zero.

The direction of a quasiparticle's velocity at low momenta (when it appears as a hole) is opposite to its direction at high momenta (when it appears as a particle). As a result, a quasiparticle that enters a region where there is a force opposing its motion will gradually lose energy until its velocity reaches zero. Its hole properties then begin to dominate, its velocity reverses and it retraces its path. In effect, the force smoothly converts the quasiparticle into a quasihole, and vice versa. This process, which has no analogy in the scattering of normal particles, is called Andreev reflection after Aleksander F. Andreev of the Institute for Physical Problems in Moscow, who first suggested the mechanism in the context of superconductors.

Andreev reflection may account for the fact that the second wire in the quasiparticle-beam experiment senses a push from both quasiparticles and quasiholes. When quasiparticles are converted to quasiholes by Andreev reflection at the second wire, the wire experiences a push; the wire is also pushed when quasiholes are converted to quasiparticles. This is unlike the normal process, where the two types of excitation produce opposite effects.

The two-wire device does more than simply demonstrate the bizarre behavior of quasiparticles and quasiholes. It provides all the components needed to study the dynamics of quasiparticles in superfluid ^{3}He. It has a source and a detector, and the whole system operates at a temperature of about 100 microkelvins.

Laboratory studies of the behavior of superfluid ^{3}He may eventually yield insight about forms of matter found nowhere on the earth. It is conjectured, for example, that the neutron matter (neutronium) in rapidly rotating pulsars is superfluid, even though the temperature in neutron stars is about 100 million kelvins. Neutron matter clearly cannot be studied in the laboratory, but it may be possible to mimic its behavior by means of rotating superfluid ^{3}He or ^{4}He. Neutrons, like ^{3}He atoms, are fermions, and it is believed that neutronium becomes superfluid by the same Cooper-pair mechanism operating in ^{3}He. Only detailed theoretical calculations can tell whether the correspondence between superfluid ^{3}He and neutronium is sufficiently close for such models to yield useful results. If so, experiments will be performed on ^{3}He with neutron stars in mind.

What are the chances of finding other superfluids on the earth? One strong candidate is a dilute solution of ^{3}He in superfluid ^{4}He. Depending on the pressure applied, solutions can be made containing up to 10 percent ^{3}He. At some sufficiently low temperature, the ^{3}He atoms in the solution should form Cooper pairs and become superfluid. Despite investigations by several laboratories, no such transition has so far been observed. The density of ^{3}He atoms in a solution of this kind is very low, and the interactions between them are quite weak. Estimates of the transition temperature lie in the nanokelvin regime, far below the 80 to 100 microkelvins to which dilute solutions of ^{3}He in ^{4}He have so far been cooled.

Such a superfluid could open up entirely new realms of atomic behavior. Not only would the ^{3}He atoms become superfluid, but they also would do so in a superfluid solvent. The new system would comprise two interpenetrating yet independent superfluids. Such a two-component superfluid is bound to have even more bizarre behavior than the single-component ones now known.

Furthermore, theory suggests that two different kinds of Cooper pairs could form in a dilute solution of ^{3}He. The dominant type in any given solution would depend on the concentration of ^{3}He. At high concentrations, pairs would form with the nuclear spins of the two atoms parallel, as in pure ^{3}He. At lower concentrations, however, pairs with opposing spins should form instead. At some intermediate concentration the two kinds may coexist side by side, yielding a three-component superfluid.

The experimental verification of such a possibility may lie far in the future, because such a transition may take place only at temperatures well below those to which liquid helium can be cooled at present. Nevertheless, there is little doubt that those temperatures will eventually be reached.

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Sustainable Agriculture

Traditional conservation-minded methods combined with modern technology can reduce farmers' dependence on possibly dangerous chemicals. The rewards are both environmental and financial

by John P. Reganold, Robert I. Papendick and James F. Parr

For nearly four decades after World War II, U.S. agriculture was the envy of the world, almost annually setting new records in crop production and labor efficiency. During this period U.S. farms became highly mechanized and specialized, as well as heavily dependent on fossil fuels, borrowed capital and chemical fertilizers and pesticides. Today the same farms are associated with declining soil productivity, deteriorating environmental quality, reduced profitability and threats to human and animal health.

A growing cross section of American society is questioning the environmental, economic and social impacts of conventional agriculture. Consequently, many individuals are seeking alternative practices that would make agriculture more sustainable.

Sustainable agriculture embraces several variants of nonconventional agriculture that are often called organic, alternative, regenerative, ecological or low-input. Just because a farm is organic or alternative does not mean that it is sustainable, however. For a farm to be sustainable, it must produce adequate amounts of high-quality food, protect its resources and be both environmentally safe and profitable. Instead of depending on purchased materials such as fertilizers, a sustainable farm relies as much as possible on beneficial natural processes and renewable resources drawn from the farm itself.

Sustainable agriculture addresses many serious problems afflicting U.S. and world food production: high energy costs, groundwater contamination, soil erosion, loss of productivity, depletion of fossil resources, low farm incomes and risks to human health and wildlife habitats. It is not so much a specific farming strategy as it is a system-level approach to understanding the complex interactions within agricultural ecologies.

In 1980 the U.S. Department of Agriculture (USDA) estimated between 20,000 and 30,000 farmers—about 1 percent of the nation's total—were practicing nonconventional agriculture, most of which could now be termed sustainable. Today some experts estimate that the figure may have doubled or tripled. Farmers who practice soil conservation and reduce their dependence on fertilizers and pesticides generally report that their production costs are lower than those of nearby conventional farms. Sometimes the yields from sustainable farms are somewhat lower than those from conventional farms, but they are frequently offset by lower production costs, which leads to equal or greater net returns.

To understand the rationale for sustainable agriculture, one must grasp the critical importance of soil. Soil is not just another instrument of crop production, like pesticides, fertilizers or tractors. Rather it is a complex, living, fragile medium that must be protected and nurtured to ensure its long-term productivity and stability.

Healthy soil is a hospitable world for growth. Air circulates through it freely, and it retains moisture long after a rain. A tablespoon of soil contains millions of grains of sand, silt

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HEALTHY SOIL, essential to agriculture, is a complex, living medium. The loose but coherent structure of good soil holds moisture and invites airflow. Ants (*a*) and earthworms (*b*) mix the soil naturally. *Rhizobium* bacteria (*c*) living in the root nodules of legumes (such as soybeans) create fixed nitrogen, an essential plant nutrient. Other soil microorganisms, including fungi (*d*), actinomycetes (*e*) and bacteria (*f*), decompose organic matter, thereby releasing more nutrients. Microorganisms also produce substances that help soil particles adhere to one another. To remain healthy, soil must be fed organic materials such as various manures and crop residues.

and clay and has a vast expanse of internal surface area to which plant nutrients may cling. That same tablespoon of soil also contains billions of microorganisms, including bacteria, actinomycetes, fungi and algae, most of which are principal decomposers of organic matter. Decomposition results in the formation of humus and the release of many plant nutrients. The microbes also produce sticky substances called polysaccharides that glue soil particles together and help the soil to resist erosion.

Another essential activity that takes place in the soil is the fixation of nitrogen. Certain bacteria in the soil or in the roots of plants (most notably legumes) convert atmospheric nitrogen gas into fixed forms of nitrogen that plants and other organisms use to make proteins. The amount of available nitrogen strongly influences soil productivity.

One of the earliest landmarks of the sustainability movement in the U.S. is *Farmers of Forty Centuries: Permanent Agriculture in China, Korea and Japan,* by Franklin King, published in 1911. It documents how farmers in parts of East Asia worked fields for 4,000 years without depleting the fertility of their soil. This text and others of the early 20th century focused on holistic aspects of agriculture and the complex interactions within farming systems.

Yet around this same time, U.S. agriculture was in the early stages of industrialization. New technologies and scientific methods were developed to help farmers meet the growing demands of expanding urban populations. By substituting mechanical power for horses, for example, farmers could increase their grain acreage by from 20 to 30 percent, because they could plow more ground in less time and did not need to grow fodder.

Many groups and individuals continued to believe that biology and ecology rather than chemistry and technology should govern agriculture. Their efforts helped to give birth to the soil conservation movement of the 1930's, the ongoing organic farming movement and considerable related research. Nevertheless, by the 1950's technological advances had caused a shift in mainstream agriculture, creating a system that relied on agrichemicals, new varieties of crops and labor-saving, energy-intensive farm machinery. This system has come to be known as conventional farming.

As pesticides, inexpensive fertilizers and high-yielding varieties of crops were introduced, it became possible to grow a crop on the same field year after year—a practice called monocropping—without depleting nitrogen reserves in the soil or causing serious pest problems. Farmers began to concentrate their efforts on fewer crops. Government programs promoted monoculture by subsidizing only the production of wheat, corn and a few other major grains. Unfortunately, these practices set the stage for extensive soil erosion and for pollution of water by agrichemicals.

In the U.S. between 1950 and 1985, as a share of total production cost, the cost of interest, capital-related expenses and manufactured farm inputs (such as chemical fertilizers, pesticides and equipment) almost doubled from 22 to 42 percent, while labor and on-farm input expenses declined from 52 to 34 percent. During most of this period, relatively little research on sustainable agriculture was conducted because of lack of funding and public interest.

By the late 1970's, however, concerns were mounting that rapidly rising costs were endangering farmers nationwide. In response, Secretary of Agriculture Robert S. Bergland commissioned a study in 1979 to assess the extent of organic farming in the U.S., as well as the technology behind the farming and its economic and eco-

SOIL EROSION caused by water runoff has cut a deep gully in this field in eastern Washington State. Even a small amount of topsoil erosion can diminish agricultural productivity. Conventional farming methods often increase rates of erosion by depleting the organic matter that helps to preserve soil structure. Sustainable agriculture inhibits erosion by promoting the addition of organic matter to the soil and the growth of cover crops, which prevent soil from blowing or washing away.

GREEN MANURE CROPS, which are plowed under or surface-mulched instead of being harvested for sale, enrich the soil and improve future crop productivity. Legumes, such as sweet clover (shown being mulched), are very good green manures because they contribute biologically fixed nitrogen to the soil, thus reducing the need for any synthetic nitrogen fertilizers.

logical impact. The study, *Report and Recommendations on Organic Farming,* published in 1980, was based heavily on case studies of 69 organic farms in 23 states.

The USDA report concluded that organic farming is energy-efficient, environmentally sound, productive and stable and tends toward long-term sustainability. Since the report was published, it has stimulated interest, nationally and internationally, in sustainable agriculture. Its recommendations provided the basis for the alternative-agriculture initiative passed by Congress in the Food Security Act of 1985, which calls for research and education on sustainable farming systems.

The sustainable agriculture movement received a further boost last September when the Board on Agriculture of the National Research Council released another study, *Alternative Agriculture*. Although controversial, the report is perhaps the most important confirmation of the success of farms that rely on biological resources and their beneficial interactions instead of chemicals. It found that well-managed farms growing diverse crops with little or no chemicals are as productive and often more profitable than conventional farms. It also asserted that "wider adoption of proven alternative systems would result in even greater economic benefits to farmers and environmental gains for the nation."

Sustainable agriculture does not represent a return to pre-industrial revolution methods; rather it combines traditional conservation-minded farming techniques with modern technologies. Sustainable systems use modern equipment, certified seed, soil and water conservation practices and the latest innovations in feeding and handling livestock. Emphasis is placed on rotating crops, building up soil, diversifying crops and livestock and controlling pests naturally.

Whenever possible, external resources—such as commercially purchased chemicals and fuels—are replaced by resources found on or near the farm. These internal resources include solar or wind energy, biological pest controls and biologically fixed nitrogen and other nutrients released from organic matter or from soil reserves. In some cases external resources may be essential for reaching sustainability. As a result, such farming systems can differ considerably from one another because each tailors its practices to meet specific environmental and economic needs.

A central component of almost all sustainable farming systems is the rotation of crops—a planned succession of various crops growing on one field. When crops are rotated, the yields are usually from 10 to 15 percent higher than when they grow in monoculture. In most cases monocultures can be perpetuated only by adding large amounts of fertilizer and pesticide. Rotating crops provides better weed and insect control, less disease build-up, more efficient nutrient cycling and other benefits.

A typical seven-season rotation might involve three seasons of planting alfalfa and plowing it back into the soil, followed by four seasons of harvested crops: one of wheat, then one of soybeans, then another of wheat and finally one of oats. The cycle would then start over. The first season of wheat growth would remove some of the nitrogen produced by the alfalfa; the soil's nitrogen reserves would be depleted much less by the soybeans, which are legumes. Oats are grown at the end of the cycle because they have smaller nutrient requirements than wheat.

Regularly adding crop residues, manures and other organic materials to the soil is another central feature of sustainable farming. Organic matter improves soil structure, increases its water-storage capacity, enhances fertility and promotes the tilth, or physical condition, of the soil. The better the tilth, the more easily the soil can be tilled and the easier it is for seed-

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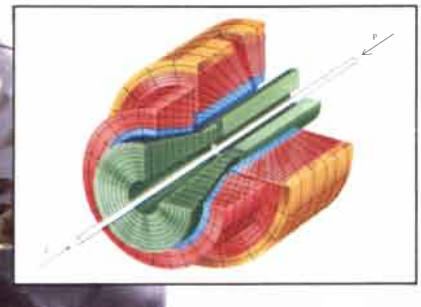

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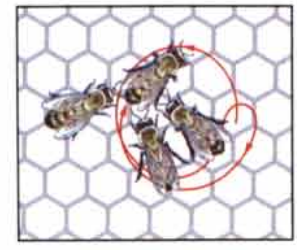

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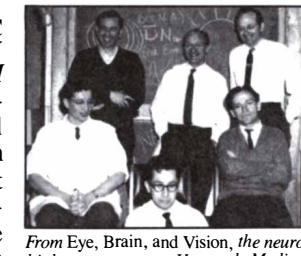

From Eye, Brain, and Vision, *the neurobiology group at Harvard Medical School, 1963, including Nobel Prize winners David Hubel, standing right, and Torsten Wiesel, seated right. Photograph by Joseph Gagliardi.*

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AN EXCITING NEW GENRE IN THE LITERATURE OF SCIENCE

LADYBUG BEETLES are natural predators of pea aphids (*above*) and other insect pests. Integrated pest management (IPM) programs now in use on many farms take advantage of natural predator-prey relationships or other biological-control mechanisms to reduce the need for chemical pesticides. Farmers who practice biological control encourage the proliferation of beneficial microbes and insects, such as ladybugs. They also make their fields generally inhospitable to herbivorous pests.

lings to emerge and for roots to extend downward. Water readily infiltrates soils with good tilth, thereby minimizing surface runoff and soil erosion. Organic materials also feed earthworms and soil microbes.

The main sources of plant nutrients in sustainable farming systems are animal and green manures. A green manure crop is a grass or legume that is plowed into the soil or surface-mulched at the end of a growing season to enhance soil productivity and tilth. Green manures help to control weeds, insect pests and soil erosion, while also providing forage for livestock and cover for wildlife.

By raising a diverse assortment of crops and livestock, a farm can buffer itself against economic and biological risks. Diversity results from mixing species and varieties of crops and from systematically integrating crops, trees and livestock. When most of North Dakota experienced a severe drought during the 1988 growing season, for example, many monocropping wheat farmers had no grain to harvest. Farmers with more diversified systems, however, had sales of their livestock to fall back on or were able to harvest their late-seeded crops or drought-tolerant varieties. A biologically diverse farming system is also less susceptible to the economic woes of a flooded market or a fall in prices for a single crop.

Controlling insects, diseases and weeds without chemicals is also a goal of sustainable strategies, and the evidence for its feasibility is encouraging. One broad approach to limiting use of pesticides is commonly called integrated pest management (IPM), which may involve disease-resistant crop varieties and biological controls (such as natural predators or parasites that keep pest populations below injurious levels). Farmers can also select tillage methods, planting times, crop rotations and plant-residue management practices to optimize the environment for beneficial insects that control pest species or to deprive pests of a habitat. If pesticides are used as a last resort, they are applied when pests are most vulnerable or when any beneficial species and natural predators are least likely to be harmed.

In practice, IPM programs are a mixed bag. They have dramatically reduced use of pesticides on crops such as cotton, sorghum and peanuts. More than 30 million acres (about 8 percent of U.S. farmland) is currently being managed with IPM programs, resulting in annual net benefits of more than $500 million. On the other hand, IPM programs have also been reduced to "pesticide management" for many crops like corn and soybeans, for which pesticide usage has actually increased significantly.

Biological-control techniques are some of the best ways to control pests without pesticides. They have been used for more than 100 years and have been commercially successful in controlling pests, especially insects, in more than 250 projects around the world. Yet USDA funds for studying them have declined.

Can sustainable farming practices make good on their promise to be ecologically stable, productive and profitable? To compare the effects of sustainable and conventional farming systems on soil productivity, one of us (Reganold), working with Lloyd F. Elliott and Yvonne L. Unger of Washington State University, conducted a study of the soil on two commercial wheat farms. One was an 800-acre sustainable farm that had been managed without synthetic fertilizers and with only limited amounts of pesticides since it was first plowed in 1909. The other was an adjacent 1,300-acre conventional farm, which had first been cultivated in 1908 but had been treated with fertilizers since 1948 and with pesticides since the early 1950's. The sustainable farm used a complex crop rotation system and practiced conservation-oriented methods of tillage, whereas the conventional farm followed a simple two-year rotation. The sustainable farm also grew legumes as a cover crop and green manure.

Because of the differences in farming methods, the soil on the sustainable farm contained significantly more organic matter, nitrogen and biologically available potassium than that on the conventional farm. It had a better capacity for storing nutrients, a higher water content, a larger microorganism population and a greater polysaccharide content. The soil also had better structure and tilth and 16 more centimeters of crop-nourishing topsoil. This topsoil difference was attributed to significantly more soil erosion on the conventional farm.

Average yields of winter wheat per acre between 1982 and 1986 were 8 percent lower on the sustainable farm than on the conventional farm. Nevertheless, the sustainable farm matched the wheat production average for the region—in fact, it yielded almost 13 percent more wheat than another nearby conventional farm with similar soils. Its ability to do so, even after almost 80 years of farming without fertilizer, may result in part from reduced soil erosion and maintenance of soil productivity.

Although conserving soil productivity is important to farmers, most of them usually select an agricultural system on the basis of its short-term profitability. Until recently conventional systems have usually appeared to be more profitable in the short term than sustainable ones. This assessment comes as no surprise, because research and USDA policy over the past four decades have promoted conventional agriculture.

Yet the long-term profitability of conventional agriculture seems questionable if the environmental and health costs currently borne by soci-

ety are taken into account. If these indirect costs were factored into the costs of conventional farm production, then sustainable systems would likely prove to be more profitable and more beneficial to society.

One of the best-known studies of the economics of sustainable agriculture was conducted by William Lockeretz, Georgia Shearer and Daniel H. Kohl of Washington University. They compared energy efficiency and crop production costs between numerous pairs of organic and conventional farms in the Midwest. Between 1974 and 1978 the energy consumed to produce a dollar's worth of crop on the organic farms was only about 40 percent as great as on the conventional farms. Although the organic farms had lower crop yields than the conventional farms, their operating costs were lower by about the same cash equivalent. As a result, the net incomes from crop production on the two types of farms were about equal every year except one.

Despite these encouraging results, some farmers who have shifted from conventional to sustainable practices have experienced short-term difficulties. Some of the problems arose because the farmers abruptly stopped applying pesticide and fertilizer to all their fields. Such radical changes can sometimes decrease yields because of severe weed problems, explosive increases in insect pests and diminished soil fertility that lasts a few years.

Researchers at the Rodale Research Center in Kutztown, Pa., have investigated the transition from conventional to sustainable farming and verified that such changes are best implemented with caution. Even a gradual change may involve small decreases in crop yields while the soil establishes a new set of chemical and biological equilibria. Farmers should change only one field at a time to avoid placing whole farms at risk. The transition is also smoother if they regularly add organic matter to the soil in the form of animal or green manures.

What are the forces that inhibit farmers from adopting sustainable methods? One obstacle is the federal farm programs, which generally support prices for only a handful of crops. Corn and other feed grains, wheat, cotton and soybeans receive roughly three fourths of all U.S. crop subsidies and account for approximately two thirds of cropland use. The lack of price supports for other crops effectively discourages farmers from diversifying and rotating their crops and from planting green manures. Instead it gives them powerful incentive to practice monoculture to achieve maximum yields and profits.

The long-term economic benefits of sustainable agriculture may not be evident to a farmer faced with having to meet payments on annual production loans. Many conventional farmers are greatly in debt, partly because of heavy investments in specialized machinery and other equipment, and their debt constrains the shift to more sustainable methods. To date, society has neither rewarded farmers financially nor given them other incentives for choosing sustainable methods that would benefit the public.

Then, too, there is little information available to farmers on sustainable practices. Government-sponsored research has inadequately explored alternative farming and focused instead on agrichemically based production methods. Agribusinesses also greatly influence research by providing grants to universities to develop chemical-intensive technologies for perpetuating grain monocultures.

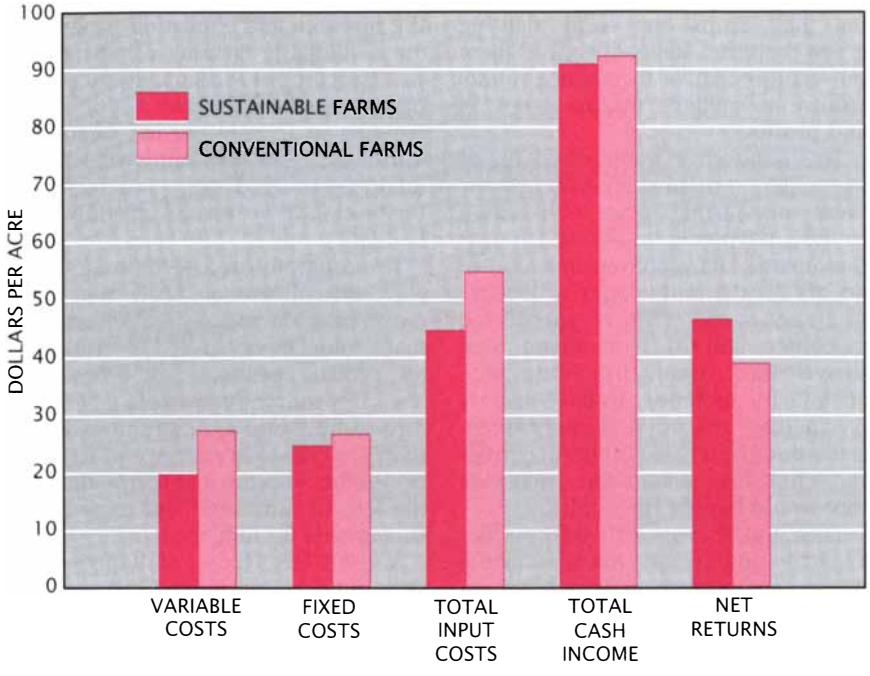
Legislative support for change in the U.S. agricultural system is growing, but financial support for sustainable agricultural projects is still only a small part of the total outlay for agriculture. Congress appropriated $3.9 million in fiscal year 1988 and $4.45 million in fiscal 1989 to implement the research and education programs on sustainable farming called for in the Agricultural Productivity Act, one part of the Food Security Act of 1985. Funding in fiscal 1990 has been the same as in the previous year—$4.45 million—which is only .5 percent of the total USDA research and education budget.

The program for low-input sustainable agriculture, or LISA, that has emerged from this federal effort has many objectives: to reduce reliance on fertilizer, pesticide and other purchased resources to farms; to increase farm profits and agricultural productivity; to conserve energy and natural resources; to reduce soil erosion and the loss of nutrients; and to develop sustainable farming systems.

A 1988 U.S. House of Representatives report, *Low Input Farming Systems: Benefits and Barriers,* recommended that Congress restructure or remove some provisions in farm-support programs, particularly those that encourage greater use of agrichemicals and that impede the adoption of low-input methods. Last year three congressional bills were introduced—two in the Senate and one in the House of Representatives—that would allow farmers to rotate crops and use other alternative methods without losing farm-support funds. All these bills are pending.

Shifting mainstream agriculture toward more sustainable methods will

COMBINATIONS OF CROPS, or of crops and livestock, make farms more sustainable by maintaining soil productivity and by reducing a farm's reliance on a single crop. On the farm shown above, the parallel strips of land have been planted on the contour of the terrain with oats (*yellow*) or corn or alfalfa (*both green*). Within each strip, crops rotate on a four-year cycle: corn (a one-year crop) is replaced by oats (another one-year crop), which is then replaced by alfalfa (a two-year crop). Such rotations improve the control of weeds, insects and diseases; they also improve the efficiency of nutrient cycling. Contour strip-cropping greatly reduces soil erosion.



PROFITS from sustainable farms can exceed those of conventional farms, according to Steven L. Kraten, formerly of Washington State University. The cash incomes per acre for the two types of farms were comparable over two years, but because the input costs of sustainable agriculture are lower, its net returns are 22.4 percent higher. Variable costs include those for fuel, machinery maintenance, seed, fertilizer, pesticide and labor. Among the fixed costs are property taxes and interest on loans.

require more than new laws and regulations; it will also require more research and public education. Universities and the USDA are slowly putting more emphasis on sustainable agricultural research. A high research priority is the development of specific cropping systems that produce and consume nitrogen more efficiently. It is essential to learn how much nitrogen is fixed by legumes under various conditions, as well as the optimum means for integrating legumes into crop rotations.

The U.S. should also step up its research efforts on other topics. More must be learned about alternatives to fertilizers and the cycling of nutrients through the agricultural ecosystem. Effective strategies must be developed for controlling pests, weeds and diseases biologically. The strategies may rely on beneficial insects and microorganisms, allelopathic crop combinations (which discourage weed growth), diverse crop mixtures and rotations and genetically resistant crops. More research should also be done on the relative benefits of various cover crops and tillage practices and on integrating livestock into the cropping system.

U.S. farmers now use only a fraction of the thousands of crop species in existence. They may benefit by increasing cultivation of alternative crops such as triticale, amaranth, ginseng and lupine, which are grown in other countries. Yet in addition to diversification, germ plasm (seeds, root stocks and pollen) from traditional crops and their wild relatives must be collected and preserved continually.

Well-managed collections of germ plasm will give plant breeders a broader genetic base for producing new crops with greater resistance to pests, diseases and drought. Today much of the germ plasm that U.S. plant breeders use to improve crops comes from developing countries.

New breeds of crops being developed by biotechnology, such as grains that fix their own nitrogen, may eventually be included in sustainable cropping systems. But neither biotechnology nor any other single technology can fix all the problems addressed by a balanced ecological approach. The success of sustainable agriculture does not hinge on creating supercrops: the system works with crops that are available now.

Better education is as important as further research. Farmers need to know clearly what sustainable agriculture means, and they must see proof of its profitability. The USDA and the Cooperative Extension Service should provide farmers with information that is up-to-date, accurate, practical and applicable to local farming conditions. Farmers and the public also need to be better educated about the potentially adverse environmental and health consequences of the pollution created by certain agrichemical practices.

One of the most effective methods for communicating practical information about sustainable agriculture is through farmer-to-farmer networks, such as the Practical Farmers of Iowa. Farmers in this association have agreed to research and demonstrate sustainable techniques on their lands. They meet regularly to share information and compare results. Because such networks have aroused growing interest and proved effective, the land-grant community should try to promote their development.

Some scientists and environmentalists have recommended levying taxes on fertilizers and pesticides to offset the environmental costs of agrichemical use, to fund sustainable agricultural research and to encourage farmers to reduce excessive use of agrichemicals. This approach is precisely how funding for the Leopold Center for Sustainable Agriculture was established by the Iowa State Legislature in 1987 as part of the Iowa Groundwater Protection Act.

Agriculture is a fundamental component of the natural resources on which rests not only the quality of human life but also its very existence. If efforts to create a sustainable agriculture are successful, farmers will profit and society in general will benefit in many ways. More important, the U.S. will protect its natural resources and move closer toward attaining a sustainable society.

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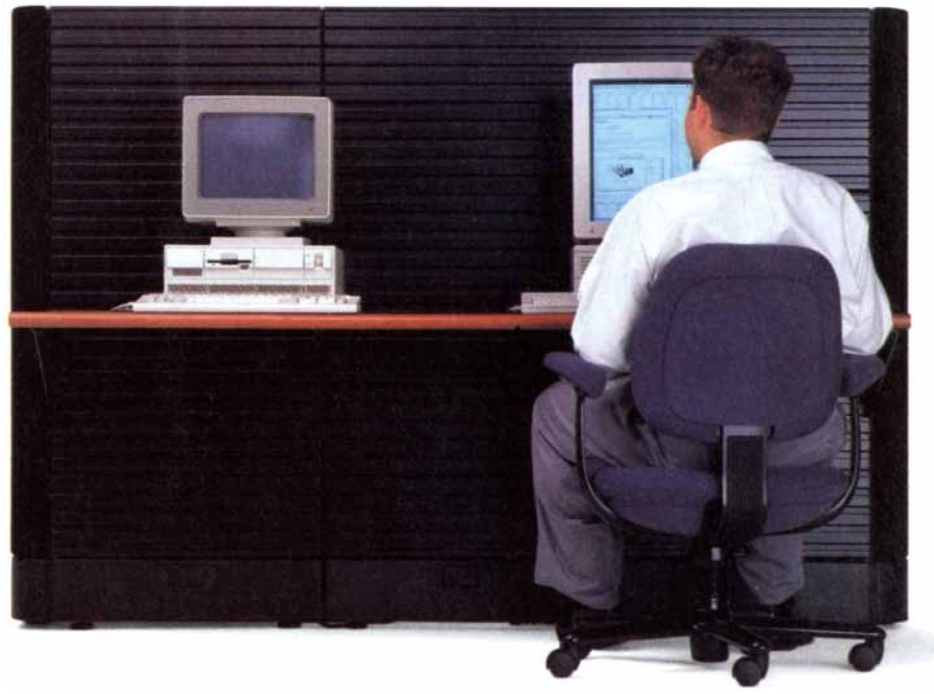

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Oliver Heaviside

An eminent Victorian mathematical physicist who despised mathematical rigor, a shy man who pilloried his enemies in print, Heaviside laid the foundations of modern electric-circuit design

by Paul J. Nahin

He was born in a London slum, he lacked a university education and he was unemployed except for a six-year stint as a telegraph clerk. Yet by virtue of his talent and sheer force of will, Oliver Heaviside became one of the leading Victorian physicists. He clarified and extended the electromagnetic theory of James Clerk Maxwell, discovered the circuit principle that made long-distance telephony possible and foresaw television, over-the-horizon radio and several aspects of Einstein's theory of relativity.

Although Heaviside was greatly esteemed by the scientists of his time, he is now almost forgotten, in part because his methods were so successful that they were written into textbooks describing the work of earlier investigators. Today, for example, many scientists simply assume that vectors describing forces were available to Newton two centuries earlier. In fact, it was Heaviside who pioneered their application to physics.

It is strange that the modern sensibility, so attuned to the colorful personality, should neglect an Englishman whose individuality stands out even in an age studded with such names as General Charles Gordon of Khartoum, Florence Nightingale, Lewis Carroll and Jack the Ripper. Oliver Heaviside was an eccentric among eccentrics, a self-made man in a self-made century.

In short, Heaviside might have been a character straight out of Dickens. The youngest of four sons of a sickly wood engraver who could barely support his family, Heaviside did, in 1850, begin his life not far from the boot-black factory that Dickens had labored in as a child. An early bout with scarlet fever left his hearing permanently impaired, cutting him off from the society of other children. That handicap molded a confrontational personality and sarcastic style that would sometimes carry him too far in his published attacks on those with whom he disagreed. Years later he recalled his youth with great bitterness, declaring that it had "permanently deformed" the course of his life.

Heaviside nonetheless did very well in school, finishing fifth among the more than 500 candidates for a College of Preceptors Examination given in 1865. The future mathematical physicist's worst grade was a dismal 15 percent score in Euclidean geometry, a curious weakness that foreshadowed his later impatience with rigorous proofs. "Euclid is the worst," Heaviside wrote later. "It is shocking that young people should be addling their brains over mere logical subtleties, trying to understand the proof of one obvious fact in terms of something equally . . . obvious, and conceiving a profound dislike for mathematics, when they might be learning geometry, a most important fundamental subject."

In any case, young Heaviside, lacking both the resources and the desire for further academic study, left school at 16, taught himself Morse code and the elements of electricity and at 18 went to Denmark to work for a telegraph company. It was to be his only paid position.

Heaviside got the telegraphy job through his uncle, Sir Charles Wheatstone, husband of his mother's sister. Wheatstone, a successful technical entrepreneur who counted William Thomson (later Lord Kelvin) and Michael Faraday among his many scientific friends, is remembered chiefly in connection with the Wheatstone Bridge, a device for gauging electrical resistance (which, however, he had no role in inventing). It must have been easy for such a man to secure the job for his nephew, who at his uncle's request had prepared himself by adding Danish and German to his other languages. For Heaviside, the move merely retraced the path that had been blazed by his elder brother Arthur, who was an employee of the Universal Private Telegraph Company until the operations of all domestic telegraph services were put under the monopoly control of the British General Post Office (GPO) in 1870.

Heaviside gained practical experience as a telegraph operator and technical troubleshooter and was promoted steadily. He returned to England and in 1871 became the chief operator in the Great Northern Telegraph Company's bureau in Newcastle upon Tyne, which handled overseas traffic. Meanwhile Heaviside had been engaged in an ambitious program of self-education in science and mathematics. His progress is charted by his first two papers on electricity, published in 1872 and 1873. The first paper employed only algebra, but the second used calculus to analyze the Wheatstone Bridge, winning a mention in the second edition of Maxwell's *Treatise on Electricity and Magnetism*.

It seems that Heaviside's encounter with Maxwell's magnificent treatise led him to quit his position in 1874 and devote himself entirely to private study. This was a momentous decision

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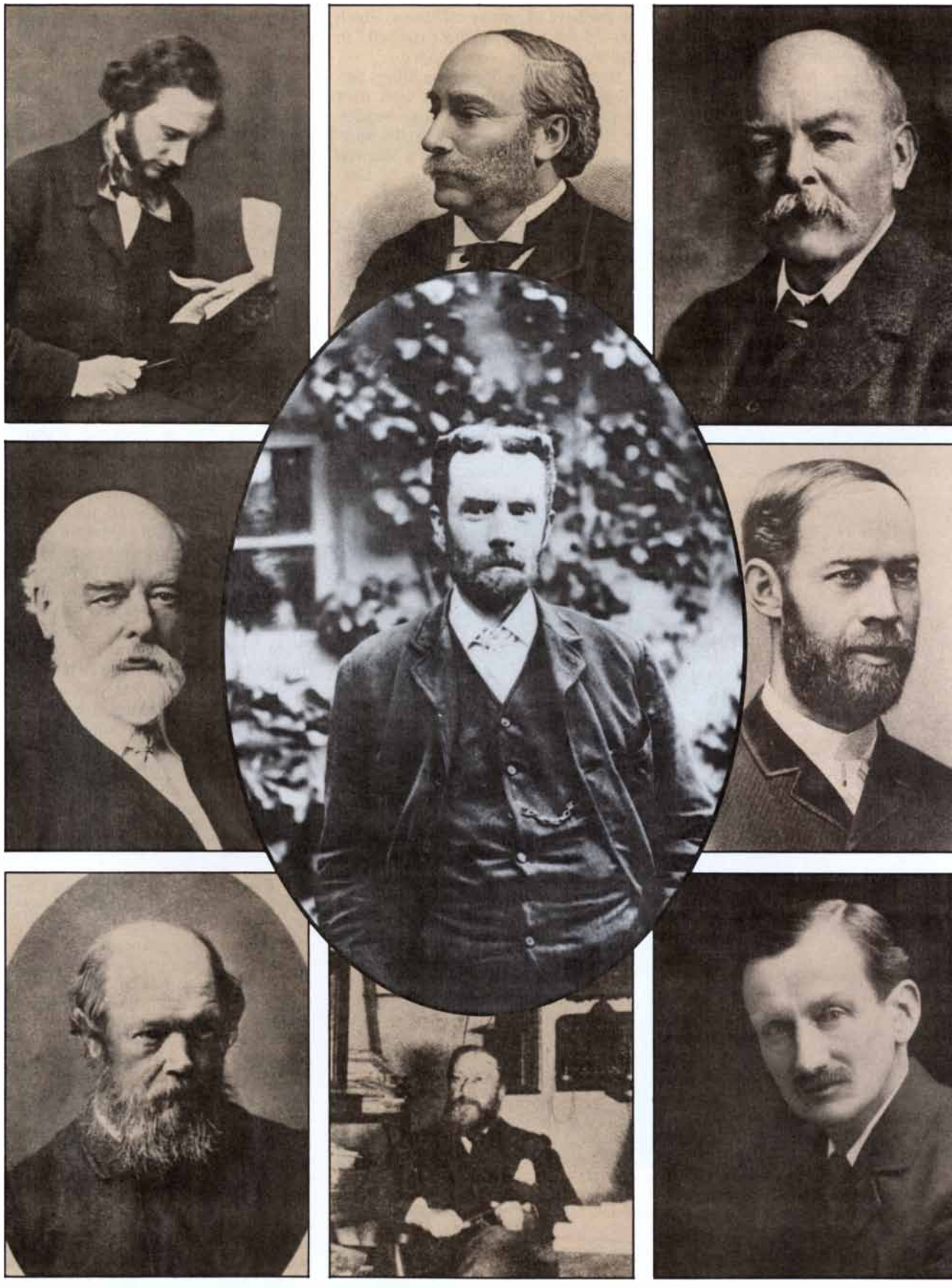


FRIENDS AND ENEMIES won by Heaviside's brilliant mind and acerbic tongue surround the physicist in this photographic montage. The friends are (*clockwise from middle left*) Sir Oliver Joseph Lodge, Lord Kelvin, Lord Rayleigh, John Henry Poynting and Heinrich Hertz; the enemies (*from left to right, bottom*) are Peter Guthrie Tait, William Henry Preece and William Burnside.

for a man of 24 years without independent means. To the great dismay of his family, with whom—and off whom—he lived, he never reconsidered his early retirement. His family humored him in his chosen routine, leaving a tray of food outside the door of his tightly shuttered room. There he worked all night and much of the day by the light of smoky oil lamps, which heated the room "hotter than hell," in the words of an acquaintance.

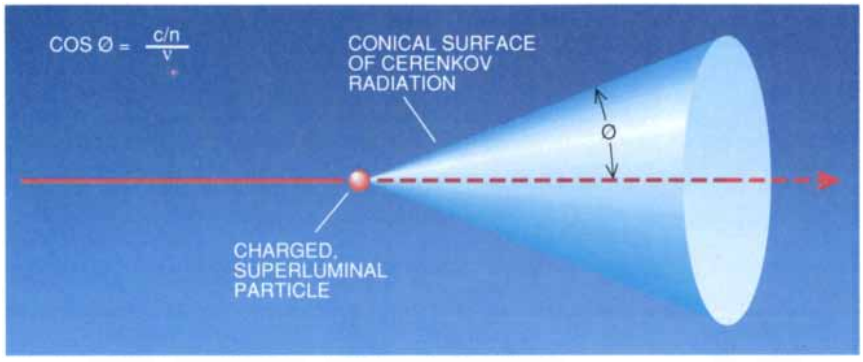
Heaviside, like the young Albert Einstein 25 years later, was won over to physics by the underlying simplicity he saw lurking in Maxwell's vastly complicated mathematics. Maxwell had demonstrated the unity of electricity and magnetism by putting Faraday's conception of the two forces as fields into mathematical form. The resulting system of equations explained many known phenomena and predicted unsuspected ones. Most important, Maxwell had predicted that an oscillating electric field in space would generate a magnetic field oscillating at the same frequency, which, in turn, would induce an electric field and so on. This "electromagnetic" wave would necessarily propagate at the speed of light, itself a species of electromagnetic radiation.

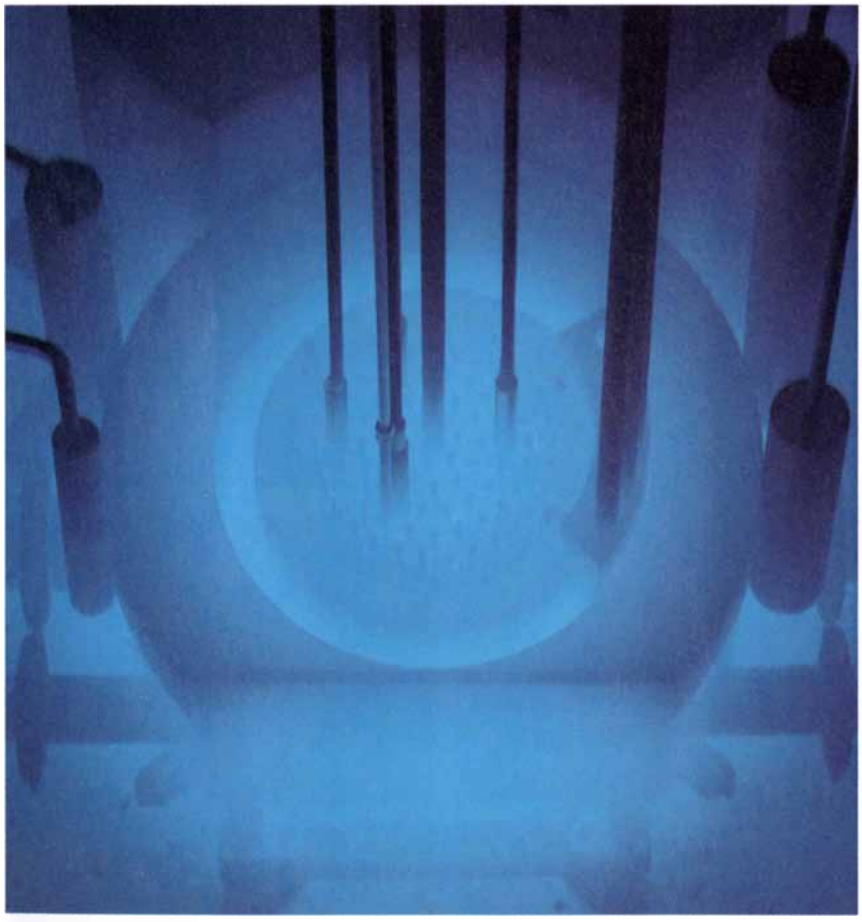
Maxwell died at 48 in 1879, nine years before the German genius Heinrich Hertz verified his prediction by detecting electromagnetic waves in space. Almost immediately thereafter Oliver J. Lodge (later Sir Oliver)—who was to be one of Heaviside's most ardent supporters—detected electromagnetic waves in metal wire. Only then did Maxwell's theory become widely accepted as the standard.

Heaviside had not required such confirmation, because he regarded the electromagnetic theory as "obviously true" on the strength of its mathematics alone, which he deemed the work of a "heaven-born genius." As he recounted his original impressions of the *Treatise* in a letter written in 1918: "I saw that it was great, greater and greatest, with prodigious possibilities in its power. I was determined to master the book and set to work.... It took me several years before I could understand as much as I possibly could. Then I set Maxwell aside and followed my own course. And I progressed much more quickly."

Heaviside vastly simplified Maxwell's 20 equations in 20 variables by squeezing their essence into two equations written in two variables (the variables described the magnetic and electric field vectors). Much of the theoretical work was done in parallel with Hertz, who graciously noted in his book on electric waves that "Mr. Heaviside has the priority." George Francis FitzGerald of Trinity College in Dublin wrote that "Maxwell's treatise is cumbered with the *débris* of his brilliant lines of assault, of his entrenched camps, of his battles. Oliver Heaviside has cleared these away, has opened up a direct route, has made a broad road, and has explored a considerable trace of country."

This was fine praise from the man who later won fame as the co-discoverer of the Lorentz-FitzGerald contraction in relativity theory [see





SUPERLUMINAL RADIATION was predicted by Heaviside decades before it was first observed as a bluish glow in the water surrounding such sources of high-energy electrons as Cornell University's Triga Mark II Research reactor (*photograph*). This so-called Cerenkov radiation results when a charged particle exceeds the speed of light in a dense medium, creating a cone-shaped electromagnetic shock wave (*diagram*). The equation (*left*) describes ϕ, the half angle of the cone, in terms of *c*, the speed of light in a vacuum, *n*, the refractive index of the medium, and *v*, the velocity of the particle. When *v* approaches *c*, the cone angle is at its greatest (about 41 degrees in water). As the particle slows, the cone collapses and finally winks out.

"G. F. FitzGerald," by Sir Edmund Whittaker; SCIENTIFIC AMERICAN, November, 1953]. For some years the reformulated equations were called the Hertz-Heaviside equations, and later the young Einstein referred to them as the Maxwell-Hertz equations. Today only Maxwell's name is mentioned.

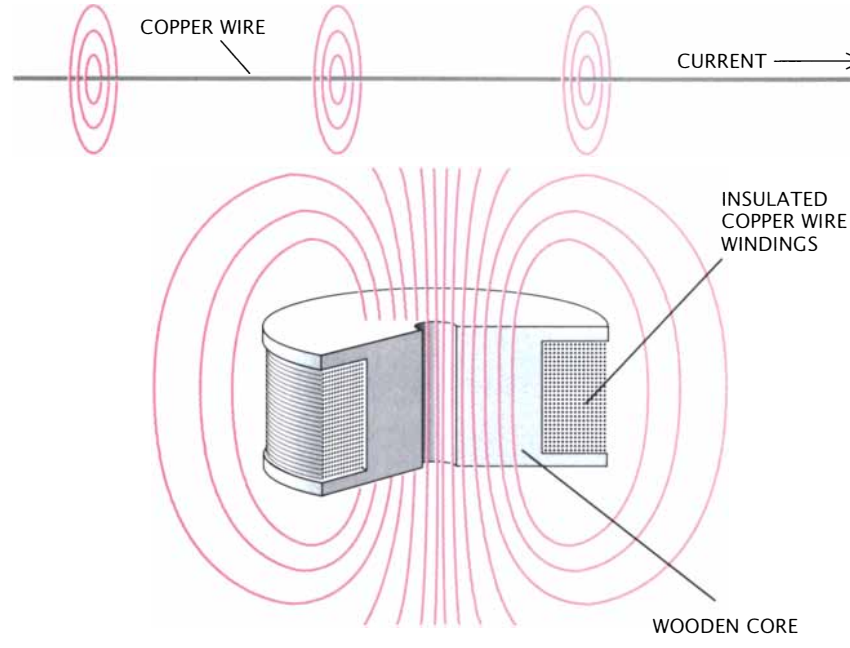
Heaviside's methods were as important as his results. Together with Josiah Willard Gibbs of Yale University, Heaviside taught vectors to the world's physicists. Vectors describe forces as directional magnitudes. One vector can represent force at a point; a system of vectors can describe a force field. Vectors can undergo the operations of arithmetic or of calculus—the differentiation of a vector system describing a magnetic field, for example, yields the vector for electric flux at any given point.

Vector operations can be quite involved, however. For example, they are not commutative: the vector product of vectors **a** and **b** does not equal **b** times **a**. But vectors are not nearly so complicated as the quaternions from which they are derived.

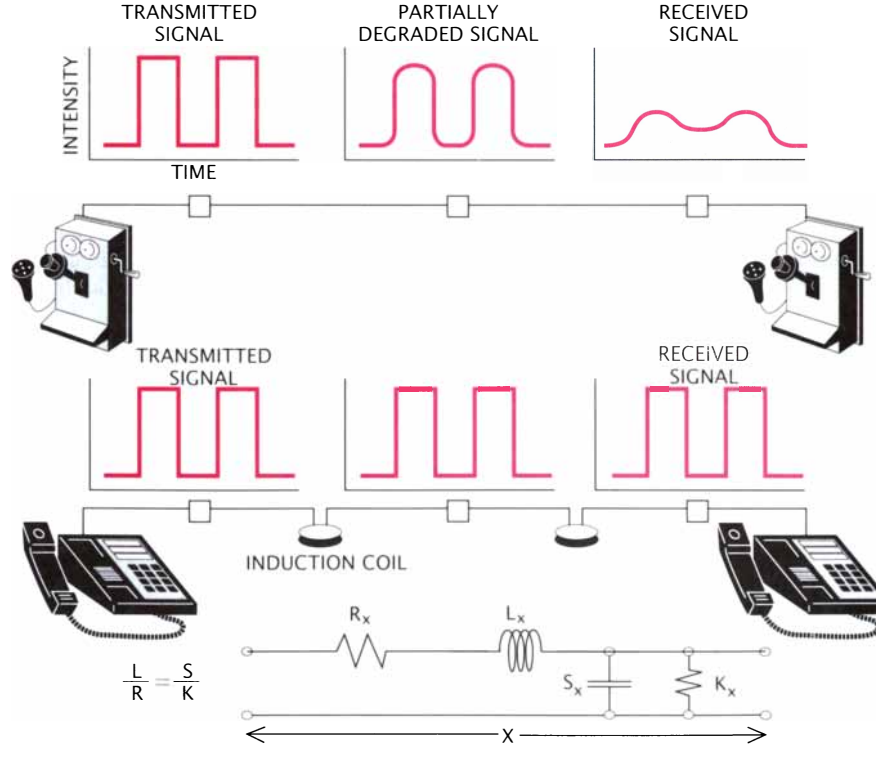
Quaternions—which add a scalar variable to the three directional coordinates—had been introduced earlier in the century by the Irish mathematician William Rowan Hamilton. They were now championed against vectors by the Scottish physicist Peter Guthrie Tait, a friend of Maxwell and Kelvin. Neither Maxwell nor Kelvin cared much for quaternions, but both were content to state their objections and move on to other matters. Tait, however, fought bitterly for the "old math," warring with Heaviside and Gibbs in numerous letters sent to the editor of *Nature*.

Heaviside's mathematics (which is now called the operational calculus) also failed to win the imprimatur of the *Proceedings of the Royal Society*, whose mathematical referee, William Burnside, rejected Heaviside's treatise for its lack of rigor. Heaviside admitted the defect, but as one who had always despised "logic chopping," he wrote, "Well, what of that? Shall I refuse my dinner because I do not fully understand the process of digestion?" Ironically, the man who had to inform Heaviside of the rejection, Lord Rayleigh, Cavendish professor of physics at the University of Cambridge, was one of the greatest admirers of Heaviside's mathematical innovations.

Vectors in the end won a victory whose scope was so sweeping that it erased the memory of their creators. Textbooks rewrote Maxwell's theory in terms of vectors, making the vec-



ENGINEERS HAD AVOIDED INDUCTION in long-distance circuits because it slows transmission. Delays occur when the magnetic field induced by a current (*top*) briefly stores, then discharges a signal's energy. But Heaviside proved that the addition of inductance to a circuit could enable it to transmit without distortion, a desideratum outweighing the slowness. George A. Campbell of the American Bell Company designed the first practical inductance loading coils (*bottom*), in which the induced field of each winding of wire reinforces that of its neighbors so that the coil supplied proportionally more inductance than resistance. Campbell's 300 test coils each added .11 henry and 12 ohms at regular intervals along 35 miles of telephone wire.



DISTORTION destroys a signal by causing its higher-frequency components to outpace its lower-frequency ones, turning a sharp pulse into a blur (*top*). Distortionless transmission (*middle*) incorporates induction loading to balance the equation (*bottom, with circuit diagram*) of inductance *L*, linear resistance *R*, capacitance *S* and leakage resistance *K*, caused by leakage between a circuit's forward and return legs.

JAMES CLERK MAXWELL (1831–1879) pioneered electromagnetic theory in an abstruse treatise that Heaviside later deemed the work of "a heaven-born genius." Heaviside quit his job at age 24 to devote himself to the extension of Maxwell's theory.

tors seem obvious and his early work seem easier than it actually was. Such unhistorical reformulation, so characteristic of the pedagogy of science, thus deprives two generations of credit, the only remuneration of a scholar.

The next major application of Maxwell's theory came in 1884, when Heaviside and John Henry Poynting described the path that electromagnetic energy follows in space. They worked in a dead heat, although Poynting got into print first, justifying the modern name of Poynting vectors. The label is punningly appropriate, too, because the vectors point in the direction of the flow of energy at every point in space.

In other ways, Heaviside pushed Maxwell's theory further than even the master himself could have dreamed. Heaviside was fascinated, for example, by what happens to charged particles when they move faster than light, and his notebooks are crammed with calculations of how such "superluminal" particles would behave. An example of superluminal conditions, which occur in dense media such as water, is the soft blue light from "swimming pool" nuclear reactors. It occurs because electrons issuing from the reactor outrace light [*see illustration on page 124*], producing an electromagnetic shock wave, much as an airplane produces a sonic boom when it exceeds the speed of sound. The shock wave is visible as light, now called Cerenkov radiation, after the Russian physicist Pavel A. Cerenkov, who won a share in the 1958 Nobel prize for his work on the phenomenon—50 years after Heaviside had predicted it.

Curiously, although current theory forbids a particle from traveling at the speed of light in a vacuum, it violates no law for a particle to exceed that speed. Some theorists speculate about particles for which the speed of light in a vacuum represents a *minimum* limit. The energy of such "tachyons," if they exist, approaches zero at infinite speeds and infinity at the speed of light. The theory of relativity would require them to travel backward in time, putting "effects" before their "causes" and thereby violating the notion of causality—which, however, is definitely not a law of physics. Heaviside knew nothing of these antichronological effects, but if charged tachyons do exist they may well be detected by the "Heaviside radiation" they should emit.

Heaviside's brilliant exposition and extension of Maxwell's theory did not pass unnoticed, for although he published most of his work in the *Electrician*, a trade journal for practical electrical engineers, it was also read by many outstanding academicians. Even the great Maxwell once published a note in it. The scientific elite, therefore, was quite aware of Heaviside's stature.

In his 1889 inaugural address as the first president of the Institution of Electrical Engineers, Thomson (now Sir William) forcibly declared Heaviside an "authority." Later that year Lodge described Heaviside to the readers of *Nature* as one "whose profound researches into electro-magnetic waves have penetrated further than anybody yet understands."

Two years afterward Heaviside was elected a Fellow of the Royal Society, his nomination supported by such men as Thomson, Lodge, FitzGerald and Poynting. The F.R.S., a great honor today, was a still greater one in 1891, before the proliferation of competing scientific prizes. In just 17 years, then, Heaviside had risen from the obscurity of an unemployed telegraphist to world fame.

It all sounds like a Hollywood movie. But in reality, Heaviside accepted his fellowship with mixed feelings, happy to be recognized but wary of being slapped down by the hands that now clapped for him. This defensive attitude can be understood in the context of the events of the previous decade, when Heaviside had engaged in many bitter controversies in which it had not always been clear who would emerge the victor.

Thomson's gracious speech to the institution had held special meaning for his audience, which had followed the controversy between Heaviside and the most formidable of his many enemies, William H. Preece, the technical expert at the GPO. A self-proclaimed "practical man" with little respect for theoreticians who cloaked their work in mathematics, Preece had strong views of how to construct a communications circuit. Heaviside published equally strong views totally at odds with Preece's, and the two exchanged sarcastic words in print. Their increasingly violent dispute raised the stakes for both men.

That a heated debate on fundamental electrical principles could be conducted as late as the 1880's might seem peculiar. Telecommunications had attained capabilities that are impressive even now and verged on wizardry at the time. Messages were re-

layed from town to town and from continent to continent on massive cables powered by gargantuan mechanisms. In fact, most of the great strides in hardware and practice had been made ad hoc, almost without the guidance of theory. The only mathematical grounding available was an analysis of the flow of very low frequency electricity through very long wires that had been done by Thomson nearly 30 years before. That theory works well at transmission rates of a few words per minute but breaks down completely at the immensely faster rates required for the transmission of speech by telephone.

The problem that cried out for a solution was how to keep a high-frequency signal from being distorted as it passes through a circuit. Some distortion is unavoidable, such as that caused by electrical resistance, which wrings energy from a signal by converting it into useless heat. Further distortion can be caused by inductance and capacitance, which briefly store a signal's energy in magnetic and electric fields, respectively. The spark that follows a toaster plug when it is pulled from the socket is the effect of inductive storage—it is energy released from a collapsing magnetic field that has been induced by an electric current. A capacitor, on the other hand, stores energy in an electric field that can persist even after it is disconnected from its charging circuit. High-voltage capacitors are what makes it so risky to poke around inside an unplugged television set.

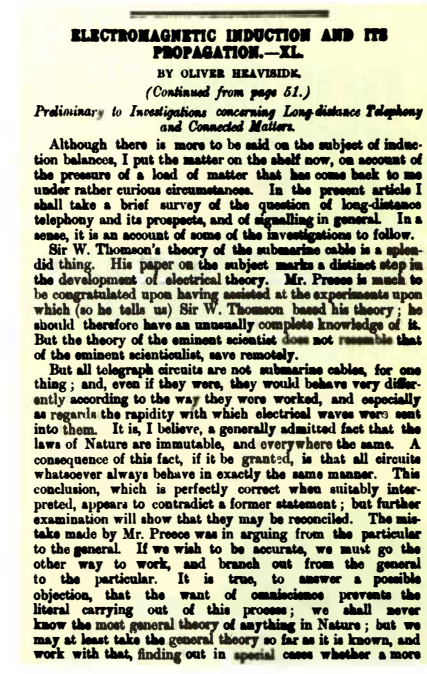
Capacitive effects accounted for most of the energy-storage effects in the transoceanic cables of the 1850's, as Thomson knew. But he also knew that, at the slow signal rates then in use, he could safely ignore the inductive effect of magnetism and the so-called leakage from resistance.

Incomplete though it was, Thomson's theory gradually acquired the status of dogma among those who were unaware of his theoretical simplifications. But those simplifications, so reasonable in the early days of telegraphy, became indefensible when applied to the faster circuits developed for multiplexed telegraphy (in which a single cable conveys several messages simultaneously) and for telephony. These circuits became subject to the disruptive effects of magnetic induction.

The first such effect was a delay in transmission resulting from the momentary storage of signal energy in the circuit's magnetic field. The time it takes energy to flow into and out of the field limits a circuit's maximum speed. In addition, the energy lost in the process attenuates the signal—the only reason Preece and others disliked induction, when they gave it any thought.

The second effect of induction was even more annoying, because it affected different components of the signal differently. A signal is merely a complex wave analyzable into a spectrum of simple sinusoidal waves, each having a particular frequency and amplitude [see "The Fourier Transform," by Ronald N. Bracewell; SCIENTIFIC AMERICAN, June, 1989]. It turns out that the higher frequencies flow along a transmission path more rapidly than do the lower frequencies and lose a greater share of their energy in the process. They therefore reach the destination ahead of time, if they prove strong enough to reach it at all.

Although the most basic telegraphy can avoid the problem by filtering out the high frequencies, this will not do for telephones. The fastest Morse code a human hand can signal has no



ELECTROMAGNETIC INDUCTION AND ITS PROPAGATION.—XI.

BY OLIVER HEAVISIDE.

(Continued from page 51.)

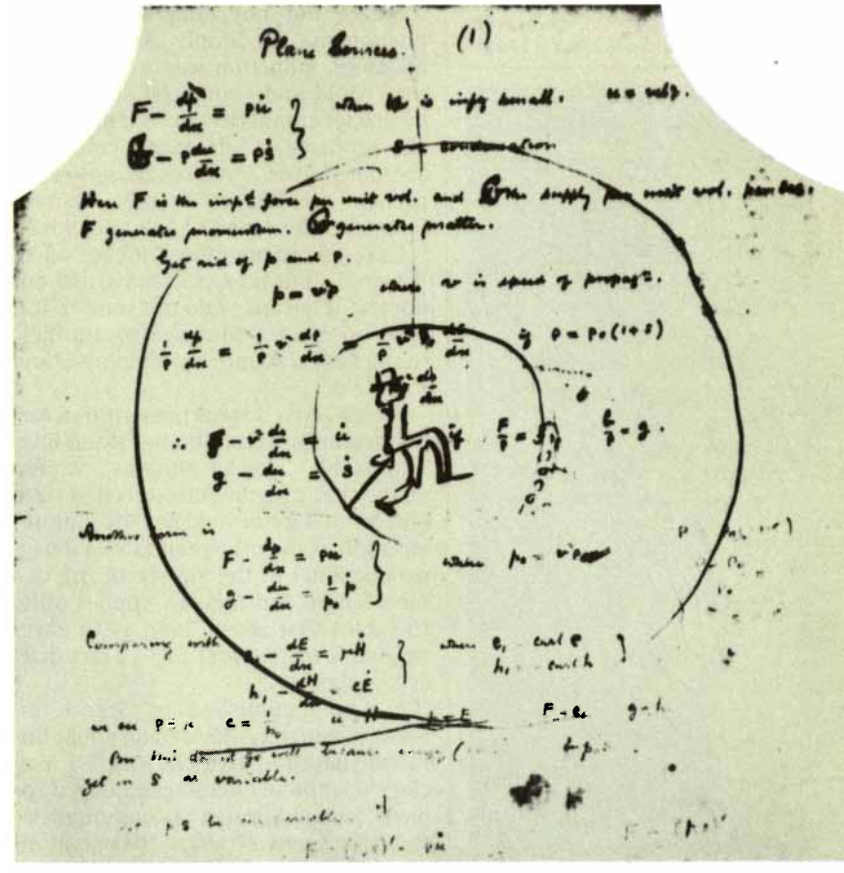
Preliminary to Investigations concerning Long-distance Telephony and Connected Matters.

Although there is more to be said on the subject of induction balances, I put the matter on the shelf now, on account of the pressure of a load of matter that has come back to me under rather curious circumstances. In the present article I shall take a brief survey of the question of long-distance telephony and its prospects, and of signalling in general. In a sense, it is an account of some of the investigations to follow.

Sir W. Thomson's theory of the submarine cable is a splendid thing. His paper on the subject marks a distinct step in the development of electrical theory. Mr. Preece is much to be congratulated upon having assisted at the experiments upon which (so he tells us) Sir W. Thomson based his theory; he should therefore have an unusually complete knowledge of it. But the theory of the eminent scientist does not resemble that of the eminent scientiticist, save remotely.

But all telegraph circuits are not submarine cables, for one thing; and, even if they were, they would behave very differently according to the way they were worked, and especially as regards the rapidity with which electrical waves were sent into them. It is, I believe, a generally admitted fact that the laws of Nature are immutable, and everywhere the same. A consequence of this fact, if it be granted, is that all circuits whatsoever always behave in exactly the same manner. This conclusion, which is perfectly correct when suitably interpreted, appears to contradict a former statement; but further examination will show that they may be reconciled. The mistake made by Mr. Preece was in arguing from the particular to the general. If we wish to be accurate, we must go the other way to work, and branch out from the general to the particular. It is true, to answer a possible objection, that the want of omniscience prevents the literal carrying out of this process; we shall never know the most general theory of anything in Nature; but we may at least take the general theory so far as it is known, and work with that, finding out in special cases whether a more

EXPOSITION OF INDUCTION LOADING is shown in this facsimile of Heaviside's original paper describing his theory in the June 3, 1887, issue of the *Electrician*.



LIGHTER SIDE OF HEAVISIDE emerges in this impromptu doodle on one of his densely packed mathematical notes. Heaviside left a number of detailed drawings that show he had inherited some of the artistic predilections of his father, a wood engraver.

essential components above 100 hertz (cycles per second); normal speech requires elements in the range of thousands of hertz. In Alexander Graham Bell's early telephones, the necessary mix of waves remained intelligible for only a few tens of miles before the signal was scrambled. An initially crisp pulse, such as one whose graph of intensity over time resembles the letter M, would soon be chewed into a blurry mess not unlike the cross section of a bald automobile tire [*see bottom illustration on page 125*].

The atmosphere disperses radio waves very little (except for the ionosphere, whose existence Heaviside was among the first to postulate), metal wire disperses them significantly and water disperses them immensely. This variance in dispersion explains why wireless radio carried speech across the oceans long before cables could be made to do so. It also explains why the U.S. Navy to this day cannot issue voice commands to its submerged submarines. The Navy has proposed to remedy the situation by building an extremely low frequency broadcasting system with an underground antenna extending over hundreds of square miles.

Preece did not understand these phenomena; he simply asserted that magnetic induction was a Bad Thing that could and should be eliminated by proper circuit design, as if an inherent property of electricity could be abolished. Worse yet, he did not comprehend why Heaviside even wanted to extend the range of the telephone. "I have one in my office," Preece once declared, "but more for show, as I do not use it because I do not want it. If I want to send a message to another room, I use a sounder or employ a boy to take it."

Preece arrived at his prescription for distortionless circuits by extending Thomson's "Law of Squares," which states that a signal introduced at one end of a circuit reaches maximum strength at the other end after a delay proportional to the square of the cable's length. But this law applies only to cables that are so long as to have negligible magnetic storage, a fact that Preece ignored.

A paper published by Preece in 1887, in which he devised an equation to calculate the greatest length for a clear telephone circuit, can be said to have impeded British telecommunications for nearly 20 years. His equation related total and per-unit resistance and capacitance, total length and a set of arbitrary parameters for circuit materials and for the geometry of the circuit. Although Preece continually fiddled with his parameters, he could never make them account for all the facts: one telephone circuit his equation ruled out by a large margin connected Boston and Chicago very well indeed.

Heaviside attacked Preece's theory three months later in the *Electrician,* stating for the first time the conditions needed to transmit an undistorted signal: the ratio of inductance to resistance *along* the circuit must be equal to the ratio of the capacitance and the leakage resistance *across* the circuit [*see bottom illustration on page 125*]. Characteristically, Heaviside larded his mathematics with malicious references to Preece as a mere "scienticulist." But what must have infuriated Preece most of all was Heaviside's suggestion that to design a distortionless circuit, one should increase induction rather than minimize it.

Heaviside imagined a device in the form of a tightly wound coil, called a solenoid, whose concentrated electromagnetism would greatly increase the circuit's inductance without adding much to its resistance. Heaviside suggested to his brother, Arthur, that the GPO build such an induction "loading coil" but dropped the idea after learning that Preece had a veto over all GPO research proposals. In this case Preece would certainly have exercised it. A patent for such a coil was taken out about a decade later by Michael I. Pupin, a professor a t Columbia University. George A. Campbell, an employee of the American Bell Company, designed the first practical coil at the turn of the century. Heaviside received neither remuneration nor recognition in the matter.

It was money that Heaviside particularly needed, for his father had died and the royalties from his massive work, *Electromagnetic Theory,* had proved disappointing. The deficit was made good by a pension the state awarded him in 1896, at the instigation of FitzGerald and other distinguished scientists.

Heaviside undertook his next public controversy without rancor, perhaps because he found himself pitted against his friend Thomson, now Lord Kelvin. The question here was the age of the earth, as calculated from models of the time it takes for the earth to radiate a presumed initial endowment of heat. Nobody realized then that radioactive decay in the core provides an active source of heat [see "The Age-of-the-Earth Debate," by Lawrence

Badash; SCIENTIFIC AMERICAN, August, 1989]. Kelvin's assumption that heat had diffused upward through all geologic layers at a uniform rate led him to put the earth's maximum age at 98 million years, far too short a period for natural selection to have done the work Darwin ascribed to it. Heaviside assumed two rates of diffusion, one for the interior and one for the crust, and estimated the earth's age as at least 300 million years. It was Heaviside's swan song: he disappeared from the correspondence columns soon after the turn of the century, moving, by 1908, to Torquay, on the southern coast of England.

There his F.R.S. and other honors meant nothing to his neighbors, who treated him as a joke. The increased isolation and the effects of age magnified Heaviside's natural sense of persecution. Beverly Nichols, a novelist who grew up next door to Heaviside's home, remembered him as a strange and embittered hermit, who signed his letters with the bizarre self-awarded title of W.O.R.M. The letters stood for nothing, except for the word they spell—Heaviside's idea of what others thought of him. Heaviside, Nichols wrote, once replaced his furniture with granite blocks "that stood about in the bare rooms like the furnishings of some Neolithic giant. Through those fantastic rooms he wandered, growing dirtier and dirtier, and more and more unkempt—with one exception. His nails were always exquisitely manicured, and painted a glistening cherry pink."

Heaviside died in February, 1925, probably as the indirect result of a fall from a ladder several months before. He lies buried in his parents' grave, his name visible on the tombstone only when the grass is closely cut. The next time you make a long-distance call and the voice on the other end comes through loud and clear, reflect for a moment on the gifted yet flawed man who made it possible.

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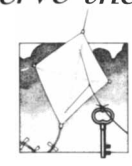
THE AMATEUR SCIENTIST

Sunspots and how to observe them safely



by Forrest M. Mims III

To the casual observer, the sun is immutable. It shines constantly with a bright white light that changes to reds and yellows only when scattered or absorbed by particles and vapors in our planet's variable atmosphere. A closer look reveals, however, that the sun is far more dynamic than the earth. Cataclysmic storms periodically erupt on the sun's surface—storms that could easily envelop several earth-size planets.

CAUTION: Viewing the sun with the naked eye or through any kind of magnifying instrument can result in severe damage to the eyes, including permanent blindness. Before you perform any of the experiments described in this column, you should follow the given instructions carefully. Children should not attempt these observations without adult supervision.

Regions of intense activity on the sun's surface are somewhat cooler than the area that surrounds them. For this reason, active regions appear dark when viewed against the hotter and therefore more brilliant solar disk. These active, dark regions are known as sunspots. Now is an excellent time to observe them, for it is only a few months past the peak of one of the most turbulent periods of solar activity ever recorded [*see illustration on opposite page*].

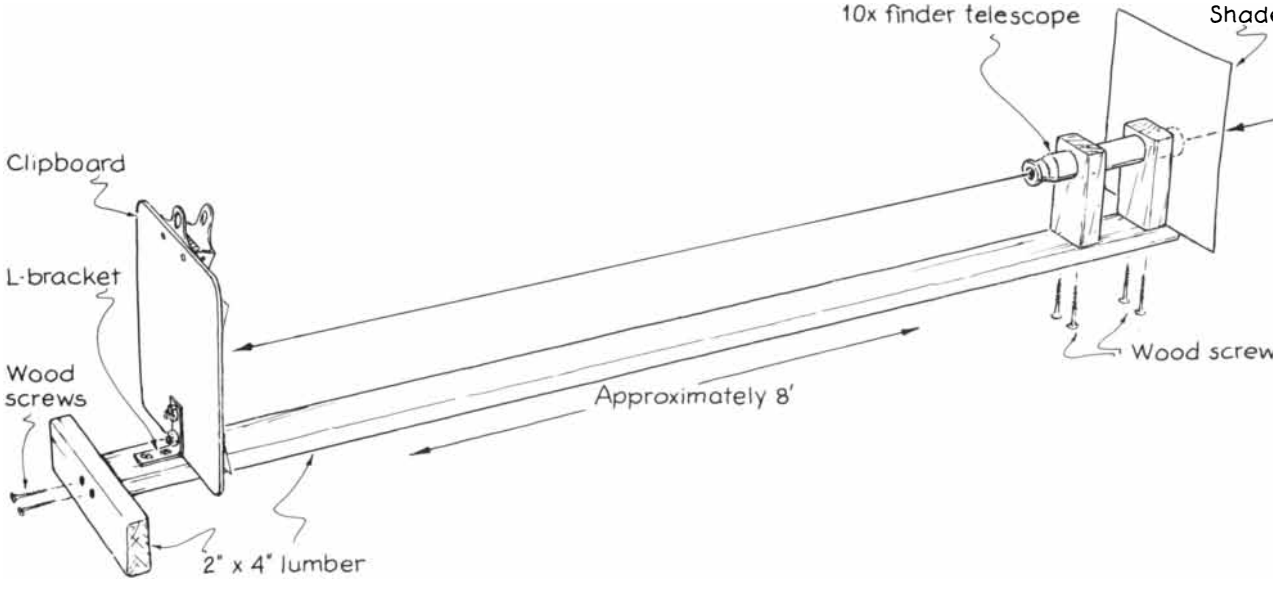
Some spots cover such a large fraction of the solar disk that they can be seen without magnification. Indeed, more than 1,700 years before the invention of the telescope, Chinese astronomers observed sunspots without the assistance of a magnifying device. Although I have long been aware of such ancient reports, not until March, 1989, did I personally look at sunspots without a special telescope. In separate accounts on the same day, two acquaintances informed me that they had seen a large spot on the sun while driving to work. The sun was low on the horizon, and they were able to view it safely through a layer of fog.

By the time I received these reports, the fog had long since vanished. I therefore drove to a nearby welding store and purchased a filter plate that is designed for an arc-welder's helmet. Within a few minutes the store's staff and I were outside looking at a large group of sunspots through plates of welder's glass.

Serious sun watchers will recall this unusual group of some 50 spots by its formal name, region 5395. Thanks to widespread media coverage, the rest of us will remember region 5395 as the cluster of spots that gave rise to a solar flare, which in turn caused a spectacular, luminous display in the night sky over most of the Northern Hemisphere. This display, known as an aurora borealis, appeared as far south as the Florida Keys and Cancún, Mexico.

When an aurora appears that far south, you can be sure that someone, somewhere, wishes it had not. That is because the increased solar activity that generates the aurora can have many deleterious effects on and near the earth. The orbits of satellites, particularly those in low orbit, can be altered; radio communications can be disrupted; and electric power grids can be subjected to power swings and even blackouts.

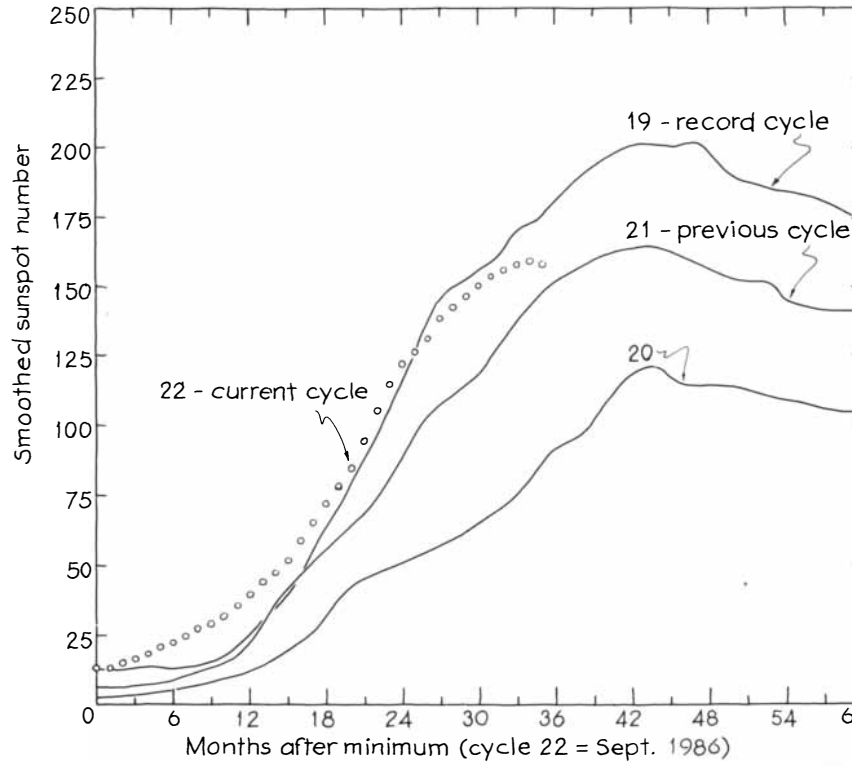
Region 5395 caused more than its fair share of such mischief, a compilation of which was prepared by Joe H. Allen of the World Data Center A for



A home-built solar observatory

Solar-Terrestrial Physics in Boulder, Colo. Power fades or outages occurred in New Mexico and New York. Six million residents of Quebec Province went without electricity for nine hours or more on March 13. These blackouts cost power utilities a total of 187 million kilowatt-hours.

Sunspot region 5395 was also responsible for many problems with broadcast systems. The earth's upper atmosphere usually refracts radio signals, but it absorbs them when it is bombarded by intense solar radiation. The opposite is true for higher-frequency signals: they propagate far beyond their usual range. During the lifetime of region 5395, these effects provided many interesting experiences for both amateur and professional operators of radio-communications systems. The effects also explain why some homeowners in California complained that their radio-controlled garage doors were mysteriously opening and closing on their own. That phenomenon was apparently caused by a nearby Navy transmitter. The station had shifted operation to a new frequency, because its standard frequencies were rendered useless by the effects of the sun on the ionosphere.



The current solar cycle compared with previous cycles

Despite all the trouble that sunspots cause, they can be a pleasure to watch. And you can gain a better appreciation of the dynamic nature of the sun by observing it daily for a month or so. You will find this project informative and considerably more convenient than those conducted by the professional and amateur astronomers who study stars other than the sun. Whereas these investigators often stay up all night in pursuit of their quarry, you will be able to observe the sun anytime during the day. You can even watch through haze or smog or from any room that has a window facing the sun.

The simplest and fastest way to look for large spots is to look at the sun directly through a suitable filter, as I first did during the appearance of region 5395. It is absolutely essential that the filter attenuate the sunlight to the proper degree. Welder's filters are rated according to the amount of light they transmit. The darkest available filter has a rating of 14. It transmits 2.7 times less light than a number 13 filter, which transmits 2.7 times less light than a number 12 filter and so on. Only a number 14 filter provides enough protection for your eyes against direct sunlight.

Welder's filters are available in at least two sizes: five by 10.8 centimeters and 11.4 by 13.3 centimeters. The small filter provides a pocket-size solar observatory that you can carry with you to check for large spots during traffic jams, lunch breaks and hikes. The large filter, which will fit in a coat pocket or purse, provides somewhat more comfortable viewing since it shades most of the face. I paid $1.95 for a small filter and $4.40 for a large one. Since some welding stores do not stock filters with a shade darker than number 12, it is a good idea to call first.

Some welding stores stock plastic filters coated with a metallic film. Although these filters have the same attenuation factor as glass filters marked with the equivalent shade number, a scratch in the metallic coating can allow the transmission of damaging rays. For this reason, a glass filter is a better choice.

No matter what kind of welder's filter you purchase, under no circumstances should you attempt to use such a filter in conjunction with a telescope or binoculars! These instruments gather more than enough light to damage your eyes, even if they are protected by a filter. Furthermore, a glass absorption filter placed between your eye and a telescope's eyepiece can be shattered by the intense heat caused by the magnified image of the solar disk.

The sun appears yellow or yellowish-green through a glass welder's filter and gold through a plastic filter. The glass filter can be tilted to increase its attenuation, a helpful adjustment when attempting to discern small sunspots. If your first glance discloses no obvious spots, look at the edge of the sun and then the entire disk. If visible spots are present, one or more may pop into view when you shift your view back toward the full disk. Indeed, that is precisely what happened when I stepped outside in the course of typing this paragraph. A first look revealed a clear solar disk. After shifting my field of view around several times, suddenly two large spots appeared on opposite sides of the sun's equator.

A large welder's filter will let you try a viewing-enhancement trick I serendipitously discovered. While watching the sun through the filter, tilt the top side of the filter away from your forehead until a blue patch of sky is reflected into your eyes [*see illustration on next page*]. A blue field will now be superposed over and around the solar disk. Because the filter is tilted, the sun will appear dimmer. The reflected skylight will contract the pupils of your eyes, thereby making the sun appear dimmer still. In my experience this technique greatly enhances the visibility of sunspots.

This rather primitive observation method can be more rewarding than it might at first seem. Since we are still near the peak of the current 11-year

sunspot cycle, you might have the opportunity to watch the progress of a major sunspot group. In late August of 1989, for example, my pocket-size observatory revealed a very large spot on the sun's east limb. Three days later the spot had grown into two giant spots connected to each other—a fact that confused even professional astronomers. At first the two spots were assigned separate names, regions 5669 and 5671. When astronomers analyzed the magnetic structure of these two regions, however, they found the spots were indeed a single massive sunspot group. So regions 5669 and 5671 were combined and designated region 5669.

This highly unusual sunspot group was the source of several major bursts of radio waves, light waves and X rays. I followed region 5669 for nearly two weeks until it rotated over the sun's west limb. One morning a few minutes after sunrise, I had a rare opportunity to see region 5669 through a thick haze and ordinary sunglasses.

Region 5669 was so large and its geometry so unusual that I wanted to examine its structure in greater detail. I therefore used a pair of binoculars to project a clear image of the solar disk onto a sheet of paper. The easiest way to implement this method is to mount the binoculars on a camera tripod. Some camera stores sell an adapter that will let you mount many kinds of binoculars on a tripod.

Under no circumstances should you look through the binoculars while attempting to aim them at the sun! Nor should you sight along the side or top of the binoculars. Instead, place a lens cap over one of the two apertures, and point the binoculars in the approximate direction of the sun. Then adjust their position while watching their shadow. When the shadow has the smallest profile, the binoculars are almost properly aligned. At that point, move them slightly until a faint image of the solar disk appears in the shadow. Align the binoculars until the disk is nearly centered in the shadow. When it is, place a cardboard light shield over the front of the open lens in order to shade the image of the solar disk and make it much brighter. Then place a white sheet or card 20 to 30 centimeters away from the binoculars, and carefully focus the binoculars for the sharpest image.

The projection method of viewing sunspots can be implemented with most binoculars and telescopes and is by far the safest method. It is important, however, to realize that curious children might attempt to look through the eyepiece of an instrument pointed at the sun. You must therefore supervise children (and adults who should know better) who are near any optical instrument that has been aimed at the sun. For even the briefest glimpse at the solar disk through a small telescope can cause a permanent and significant loss of vision. You should also be aware that binoculars or telescopes fitted with a reticle can be damaged if they are used to project solar images. The intense, focused light from the sun can burn cross hairs and melt plastic reticles.

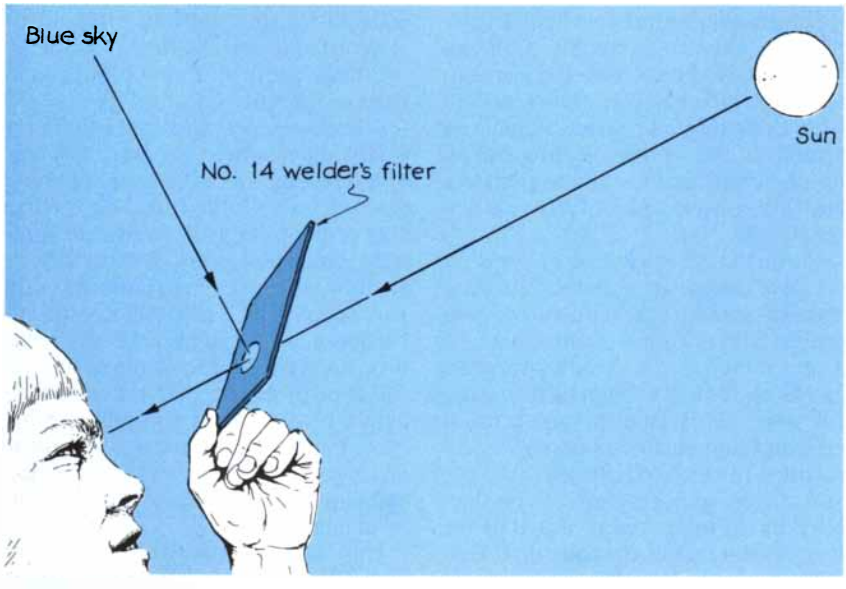
If you have a small telescope, you can easily assemble a permanent solar-projection observatory. Two years ago Vicki Rae Mims, my teenage daughter, did just that. Vicki constructed her system from scrap lumber, a clipboard, a cardboard shade and a small 10-power telescope. A finder telescope from a larger telescope will work fine. You may also purchase a small telescope from a supply company, such as Edmund Scientific Company (101 E. Gloucester Pike, Barrington, NJ 08007). Vicki's observatory is illustrated on page 130. For your own solar observatory, you might want to increase the distance between the telescope and the clipboard in order to enlarge the projected solar disk.

To operate your observatory, you should lean the telescope end of the device against a fence or on one of the rungs of a stepladder. Remove the cardboard shade from the telescope, and move the ground end of the observatory toward or away from the support until the telescope's shadow is centered on a sheet of paper held fast by the clipboard. The telescope will now be pointed approximately at the sun. You can then make fine adjustments until the solar disk is centered on the sheet of paper. Then replace the cardboard shade to brighten the image of the sun.

With this simple projection system, you can track the movement of spots across the solar disk. You will first need to center the disk on a sheet of paper held by the clipboard. Mark several points around the perimeter of the projected image, and then draw a circle through the points. You may wish to add a system of coordinates or a grid pattern so you can better specify the location of interesting spots. Provide places for the date, time and comments. Make this sheet of paper your master chart, and copy it.

To record the movement of sunspots accurately, you should make your observations at the same time each day. This schedule guarantees the sun will be oriented in the same way each time you observe it. If your daily schedule will not permit this, align the system, and watch for a few minutes as the sun's image drifts across the chart. If necessary, rotate the clipboard or the entire observatory so that a sunspot moves along or parallel to a previously drawn grid line.

Eventually you should find the approximate north pole on the solar disk. At local apparent noon in the Northern Hemisphere, celestial north is at the top of the sun. The actual north pole will be within 26 degrees of celestial north. If a scene viewed through your



Reflected blue sky may enhance the visibility of sunspots

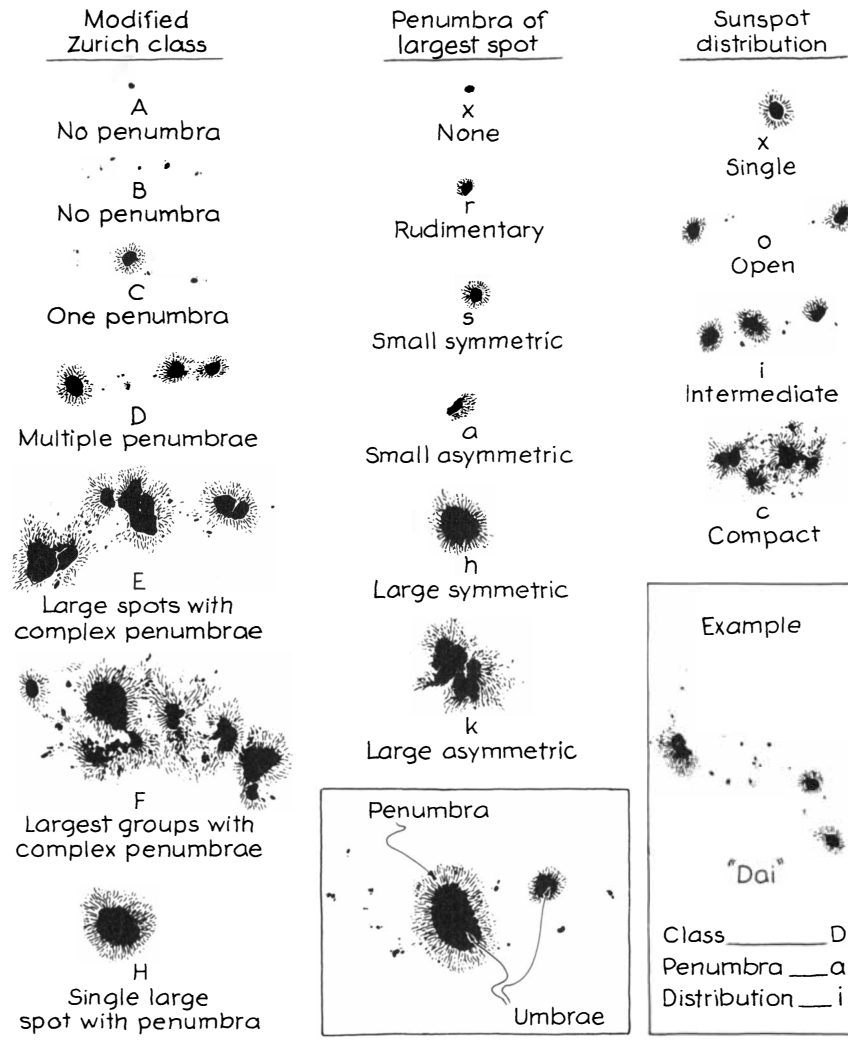
telescope's eyepiece is inverted, the top of the projected image of the sun at noon is north. If not, the top of the projected image is south.

For four months Vicki made almost daily observations of sunspots using this system. She measured the rotation of the sun by tracking several spots and groups completely across the solar disk. Vicki observed that some spots moved across the solar disk faster than others, a difference that occurs because the gases at the solar equator rotate more rapidly than the gases toward the poles.

While observing projected sunspots, periodically move the paper back and forth. This technique will help remove the effects of the paper's surface texture and bring out details you might have missed. Although the images you see can be saved with the help of a camera or video recorder, many amateurs prefer to mark the sunspots with a pencil, as Vicki did. Doing so lets you indicate small spots that might be missed by film or a video camera. But, unless you have an automatically guided telescope, you have to work fast. If there are many spots, you will have to realign the telescope periodically to make sure the solar disk stays superposed over the outline on the paper.

Serious watchers may prefer to monitor the sun with an astronomical telescope that allows either projection or direct viewing. Direct-viewing instruments are usually equipped with metallic-film aperture (not eyepiece) filters. An instrument of reasonable quality will reveal that the central dark portion, or umbra, of some sunspots is surrounded by a lighter region known as the penumbra. You may also be able to classify sunspots and sunspot groups according to their size and appearance. One classification system is described in the illustration on this page. You may wish to consult the references that follow for additional information and safety precautions.

Whether or not you elect to pursue a regular program of sunspot observations, you will find many other ways to keep up with the latest developments on the sun. A brief summary of current solar conditions and related geophysical activity is broadcast at 18 minutes past each hour by radio station WWV. The message is updated every three hours. You can receive WWV on a shortwave receiver at frequencies of 2.5, 5, 10, 15 and 20 MHz. Because WWV continually broadcasts precision-time measurements, you can set your watch while waiting for the latest solar-activity update. If you do not have access to a shortwave receiver, the WWV message is also available by telephone. The number is (303) 497-3235.



The McIntosh system of sunspot-group classification

The Space Environment Services Center in Boulder operates an experimental Public Bulletin Board System (PBBS), which will send current information and forecasts about solar activity to a personal computer equipped with a modem. You can access the PBBS by dialing (303) 497-5000. (To access the system, you will need to know that the protocol is an eight-bit data word with one stop bit and no parity at either 300 or 1,200 baud.)

Another excellent way to keep up with solar events is to subscribe to the *Preliminary Report and Forecast of Solar-Geophysical Activity*. This weekly publication gives highlights of solar and geomagnetic activity and forecasts activity for the next 27 days. The official sunspot number is reported, and a complete list of X-ray and optical flares is given. Of particular interest are the graphs comparing the current solar cycle with previous cycles. If you cannot find the report at a nearby technical library, you can purchase a subscription from the Space Environment Services Center, NOAA R/E/SE2, 325 Broadway, Boulder, CO 80303-3328. The price for U.S. subscribers is $37 per year.

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BOOKS

Dust in the wind, Dürer's eye, computer views, the 30,000-quill defense, life's minerals

by Philip Morrison

AEOLIAN DUST AND DUST DEPOSITS, by Kenneth Pye. Academic Press, Inc., 1989 (paperbound, $17.50).

The deep roadcut near Natchez, Miss., is eye-catching. Five feet of leached soil cap the section; below that lies a 30-foot layer of almost featureless smoothness. That is loess, a remarkably uniform mixture of fine-grained clay and silt without coarser content, not even an occasional string of pebbles. The geologic maps of the region are persuasive: such layers are found along a wide band that lies just eastward of the Mississippi, all the way north to St. Louis. The thickness of the loess declines quite smoothly as one probes for it farther and farther east from the river; it is as thick as 25 meters near the bluffs of the riverbank, whereas 30 miles east of the river the layer is only a meter or two thick, and beyond that it is hard to find. The deposit has been dated, too, by radiocarbon and other methods.

Even a tyro is persuaded by the experts' proposed origin of the loess on the Mississippi's east side. The time was the glacial past, during the recent icy maximum some 11,000 years ago. The agent was a prevailing wind from the west that could stir the dusty valleys. The source of the fine grains was the exposed and drying sandbars of the seasonally water-starved channels of Old Man River, blown free and replenished annually with new glacial outwash gravels and fines. The typical grains were large enough to settle out after being carried at most a few hours in moderate winds; grains some 30 microns in diameter were trapped locally by vegetation and surface roughness. Those were dusty days, possibly unprecedented in earth history.

Now both plot and loess thicken. The Rhine and the Danube basins, the valleys of the great rivers of central Asia, the Argentine pampas of the River Plate all show good-size loess deposits. But the stuff is widespread far beyond the riverbanks. Perhaps 10 percent of the land area of the earth is at present covered with loess—in Alaska, the midwestern U.S. and around the world in a dozen regions as far-flung as New Zealand. Loess covers more than a million square kilometers of central China, where it lies many hundreds of meters thick and forms the yellow earth of the Central Kingdom, fertile, shifting and insecure.

Large volume means long times, and a long time sees many changes. There is reworking and waterborne secondary deposition; glacial epochs have come and gone during the two million years fixed by the magnetic dating of deep Chinese loess. The Tibetan and Tien Shan uplands are far broader and endure longer than any river valleys. The average rates of loess emplacement in China are tenfold lower than the record rates along the lower Mississippi. Most loess properties vary during the long deposition period. Colder climates mean greater amounts of dust; warmer, wetter periods yield one or two orders of magnitude less dust. Two million years ago the sea was lower, the winds stronger, the winters colder and drier. There was less vegetation to trap the copious dust of the wide, cold deserts. In China the dust traveled about a few hundred miles, tenfold farther than along the Mississippi.

Only one example of loess older than a few million years is cited, a lithified deposit from the ancient Precambrian of northern Norway. Maybe we do not distinguish wind-borne loess very well within that rich watery record; maybe loess was often too fragile to be preserved; maybe it was not formed on a large scale before recent times. We do not know; the doubt is a bit unsettling.

Dust in today's dusty world has many sources. A summary of them opens the text. The main source of particles beyond micron size is the stirring of sediments by wind; finer ones come mostly from the conversion of acid gases, natural and industrial. The elaborate census of dust particles by size, by mineral, chemical and magnetic composition, even by the presence of oxygen isotopes, is well reported. The Sahara is currently

the world's major source of dust. Statistics of Sahara dust, occasionally windborne all the way to England, are shown along with Beijing dust from Mongolia; they are similar, of medium grain size. Much coarser grains formed the local dust collected on a hotel balcony during a Kansas dust storm; much finer Sahara dust made it across the Atlantic to Barbados. Plenty of fine dust is found in cores taken from the ocean bottom and from the polar ice caps, but the amount is less than that deposited on land by an order of magnitude and more. Like lightning, dust is continental.

You have to know about winds to understand airborne dust. Dust devils, little thermal tornadoes without rain clouds, come in all sizes; dust devils half a mile high have been observed to last seven hours above the Bonneville Salt Flats in Utah. Dust storms are routinely reported by weather stations worldwide as judged by eye—the days when visibility drops below one kilometer because of dust. The record appears to rest with a central Iranian desert station: one of every four or five days during the year is darkened by dust. Such visibility implies a dust content of hundreds of micrograms of particles per cubic meter. A rough estimate suggests that the weather along the Mississippi banks was like that during the 10,000 years of loess formation.

In the 1930's the wind-eroded dust from the drought lands of the Dust Bowl was remarkably mobile. Reportable dark days came twice a week for four months of the year. On a severely dusty day "any semblance of normal activity was out of the question. Homes, barns, tractors and fields were buried under drifts up to 25 feet high.... Dust obscured the sun for several days.... Across the room an electric light might look no brighter than the tip of a cigarette. Everything in the house—even food in the refrigerator—was covered with dust."

This modest summary of a vast literature claims not to be comprehensive, but it brings perspective to many environmental issues of today. Though here and there rather technical, it is overall good reading for the general reader and an up-to-date guide to those who would delve deeper into the dust of the earth.

ALBRECHT DÜRER AND THE ANIMAL AND PLANT STUDIES OF THE RENAISSANCE, by Fritz Koreny. Little, Brown and Company, 1985 ($75).

Master Dürer wrote: "For, verily, 'art' is embedded in nature; he who can extract it has it." This high-quality catalogue celebrates a small number of Dürer watercolors and brush paintings; they are in the famous Albertina collection in Vienna and a few years back were the focus

of a probing and joyous exhibition there. Many people know the works by name and in modern reproduction: consider the *Hare,* the *Large Piece of Turf,* the *Nosegay of Violets,* the *Stag Beetle* and the *Iris,* among others.

Dürer rendered with stunning effectiveness whatever he saw: the glowing "upper side of the outstretched left wing of a young blue roller" (a bird now seen only in southern Europe but then well known across the Alps), the big stag beetle, showy and symbolic, or more everyday wonders such as the dandelion, plantain, saxifrage and yarrow recognizably growing in one piece of turf. He wove these real sights, sometimes explicitly, into powerful visions of an imagined world, where many of them are accompanied by winged spirits, musical angels, grave knights or a Madonna radiant among a "multitude of animals"—creatures at once symbolic and mundane.

The faithful visual representation of nature as it appears—of course modulated by the artist's recording mind and the instruments that disciplined his hand—is close to a precondition for natural science later articulated by the 17th-century pioneers. But in Dürer's day even the great pictorial herbals of the 16th century were still to come; Brunfels, Fuchs and Gessner would faithfully and systematically record the plant kingdom from nature, for the first time counting on wide circulation of their images in print. A Gessner iris is shown here for comparison with Dürer's. Although Gessner's painting shows sensitivity, it portrays the iris with a general, even didactic, intention. Dürer's is also the "summary of an iris," the critic-author says, but it conveys vividly the experience of looking at a single flower.

Dürer had precursors, a few nearby and many in the distant south: the Florentines, for example, had for a long time looked sharply at their world the better to evoke the next. He had followers, too, mainly delayed. Much of the devoted scholarship that marks this study has gone to find the few who came before him and to clarify the many works of those who, by the end of Dürer's century, had copied, forged, imitated or simply transformed Dürer's images of nature (often including the "AD" of his monogram). Along the way Koreny has found reason to exclude the well-known muddy piece of turf, the popular but hesitantly drawn violets and a touching young owl from the list of works that are truly from Dürer's hand.

Dürer's mastery, like Leonardo's, served natural science and art simultaneously. Thereafter the two realms drifted apart. Scientists still share the Renaissance aim of extracting meaning from its natural matrix, but the meaning they find now has lost its intimacy as science has extended its perceptual tools. Even artists today hardly cluster around direct and clear inspection, however charged their work may be with insight. All the same, one busy green enclave does remain after four centuries: flowers and birds and mammals (though not much else) are still brilliantly represented as through inborn senses.

This whole work, beautifully printed in West Germany, is a pleasure, a book whose detailed critiques image by image engage a general reader by their breadth, candor and precision.

VISUALIZATION: THE SECOND COMPUTER REVOLUTION, by Richard Mark Friedhoff and William Benzon. Harry N. Abrams, Inc., Publishers, 1989 ($49.50).

Twenty views of Mount Shasta fill one spread of this engagingly accessible book of well-interpreted images. That fine peak stands sharply central in all the pictures as we circle the mountain more or less at its summit. Yet there was no circumnavigation of the mountain behind this set of images; there was not even a camera. The richly detailed three-dimensional scene was gathered on one pass by a high-orbiting shuttle, whose radar recorded the scene twice, from two points many miles apart. The two digital records were cross-correlated by computer, until a number of statistically matching areas within the textural richness of the eroded mountainside were found. The horizontal disparity of viewpoint could be computed nicely at many places, and the radar-scene pair was then built up into a 3-D stereo model of the peak, all in stored bits.

The radar gazed on Mount Shasta from a vantage 100 miles above the surface of the earth. Geometric transformations are easy, if tedious, in this austere universe of zeros and ones. The observer was imagined at summit height and at suitable distances from it, and the mountain posed as if on a rotating pedestal; once acceptably complete, the final image was photographed frame after frame from the color video screen. (The processor was dutifully instructed to color forests green and rocks gray on the basis of some unstipulated radar cue, so the reader should not count on fidelity of color.) Subsequent pages show five dramatic monochromes of the sparsely canyoned moon Miranda, which were prepared by many of the same methods. Those data came not from an orbit high over California but from *Voyager 2* penetrating the Uranus system nearly two billion miles away; we may surmise that Mount Shasta was a warm-up for the image masters of the Jet Propulsion Laboratory.

With no higher technical level and little more detail than the single account above, the authors have arrayed a gallery of images, about 140 of them in color, to exemplify their comprehensive overview of visualization techniques. Although the prodigious computational tasks involved justify the computer-centered title, the authors have wisely set the discussion in the much wider context it demands, always with apt visible examples.

The book opens with an essay on human visual perception, making the point illuminated long ago by Sir Richard L. Gregory (who wrote the book's foreward), that perception is as active for us as it is for the computer. We ourselves steadily compute as we watch, often at a preconscious level. The eye is no mere camera; it is intelligent. Edwin H. Land's retinex theory of color perception is described, and the complex cues by which we are able to see in three dimensions are explained. A Matisse self-portrait is shown in two ways to bring out the distinctions between the shape we see with acuity and our judgment of color, which is geometrically cruder.

One chapter is a simple treatment of digital data as captured by extensions of everyday vision, holography, radar, magnetic resonance imaging and more. The power of coding makes it possible to intervene with false color, swift geometric change, contrast stretching, edge emphasis and multiple-image processing. We see what can be done with pixels point by point, as in "paintbox" image reconstructions, and with object-based systems—fundamentally mathematical representations of whole forms at once.

The invocation of the word "algorithm" opens us to ambitious synthetic visions, the elaborate ray tracing and fractal generation of scenes that never actually existed, from skyscrapers to still-life poses of luscious fruit. There is one frame from a now celebrated animated film of 1984, *The Adventures of André & Wally B.* Here a whole forest of evergreens is created by moving points according to specific trajectories that sweep upward to branch and then twig out to match statistically the eye's textural grasp. After such "procedural amplification" the 20,000 input bytes that set the stage grow to 60 million for the pleasing final image. We take leave of the book by sampling some of the rich combinations of imaging methods now appearing so rapidly, like those of Mount Shasta and simulated crowds of fast-colliding molecules. Such images embody the swiftly growing "emergent technologies" with which the book and the decade close.

The senior author, a skilled science journalist, has made work in this field during the entire 1980's into something of a personal chronicle. Computer-savvy readers will find many of the individual explanations and examples here less than novel, yet they will enjoy the breadth of scene and profit from the pervasive sense of intellectual unity. For the less initiated reader, these nontechnical pages open on and simplify an epistemological revolution, one that already holds major territory within contemporary thought.

THE NORTH AMERICAN PORCUPINE, by Uldis Roze. Smithsonian Institution Press, 1989 (paperbound, $29.95).

People who live near woodlands may view these spiny animals as familiar pests, yet many residents would not kill one, for they hold that a porcupine is "almost the only animal an unarmed man lost in the woods can capture for food." We all know its legendary defense, that bristling coat of quills. Here a naturalist offers a firsthand account of the porcupines he has watched, counted, caught, feared and admired. For more than a decade he has worked in a lonely woods on the Catskill slopes, coming to understand porcupines by the dozens. The variety, power and pleasure of modern natural history shines brightly in this book. Long and sympathetic watching, radio tracking, chemical analysis, safe anesthesia, an improvised bola to pluck leaf samples from the high branches of linden trees and a brilliantly successful lure are all part of this Queens College naturalist's ingenious and peaceable arsenal of inquiry into the lives of porcupines.

First, on defenses. The slow-moving animal bears 30,000 sharp quills: big, loosely attached guard hairs, spongy, light and stiff. Erected in random directions to make a true phalanx in frontal defense, the long quills spear whatever passes within a critical distance of their white shafts and black tips. Sharp end out, many quills are suddenly transferred from prey to predator by the momentum of an incautious approach. The porcupine tail bears short, black quills, which are wielded in defense by a split-second tail slap. The quills may well bury themselves wholly beneath the victim's skin on contact.

A dead porcupine is inviting food; yet one frozen corpse found in the woods was untouched despite many carnivore tracks around it. In death as in life the beast is respected. Only the agile weasel-like fisher preys regularly on porcupine. The fisher bites the animal's unprotected face, circling to penetrate the guard again and again; after about half an hour of such biting, the weakened porcupine can be turned over to expose its vulnerable belly.

Toward the end of summer, porcupines feast on apples and other fruit

Quills are fatal to many animals and sometimes even to humans. The microbarb at the tip of the quill acts as a ratchet, so that the implanted quill migrates forward under random bodily motions, to go anywhere, to penetrate—often fatally—vital organs and will sometimes even pass through the body. The author recounts his own experience: one tail quill penetrated his clothing, burying itself in the muscle of his upper arm. A few days later it emerged, having ratcheted its way to his forearm like some "mole of the flesh" but beautifully clean.

Why do the quills rarely cause infection? Because they bear a greasy coating that is a growth-inhibiting antibiotic mix of fatty acids. But why protect a quill victim from secondary infection, only to punish it with internal injury? Because one frequent victim is the porcupine itself: falling heavily out of a tree, it can be wounded by its own quills.

Porcupines use their quills only in extremis for strategic defense, after other methods have failed. The animals are easy to see by night, for they bear the black-and-white pattern that stands out best in the dark. They are easy to hear, for they produce an ominous, shivery tooth clacking as you approach. They are easy to smell, for they emit a goaty, pungent signal scent, probably from a special hairless region of skin, exposed when the tail is lifted. Ignore those three warnings, and you dare the quills.

Porcupines are considered to be pests because they gnaw and mar all kinds of human property near or in the woods. Even Roze confesses that he once clubbed a porcupine or two for rasping insistently at the plywood wall of his new cabin (a two-foot belt of chicken wire eventually stopped them). Plywood is a common bait for porcupine: cabins, outbuildings, implements all bear their marks. Vehicle underbodies attract them, too. The nutrient they seek is the sodium ion, a hunger shared with all other herbivores. But porcupines fear little, and so they will freely come to a cabin wall of plywood rich in the sodium of its antifungal impregnation, to human tools that bear the salt of the sweaty user and to vehicles dusted with salt stirred up from the anti-ice treatment of the roads.

Roze describes his early encounters with hungry porcupines. A varying palisade of gnawing sticks outside the cabin was well watched by the nighttime resident within. "I felt trapped inside a bass viol as the house vibrated under their powerful teeth." Controls showed that it was only sodium the porcupines wanted; their demand was strongly seasonal, and in spring the visitors that binged were overwhelmingly female. Not all these matters are yet clear.

What is plain is that herbivores, feeding on plants that have neither nerve nor muscle, face potassium overload and sodium starvation, a ratio that can reach 500 to 1. Mammalian kidneys cannot discriminate between the two ions very well, and so scarce sodium is excreted along with surplus potassium. Long ago it was noticed that porcupines often

feed on the yellow water lily, which is a thousandfold richer in sodium than the average plant. Porcupines also scavenge for and chew on the bones of old kills in the woods and will occasionally ingest the odd ant while feeding on vegetation. How do they retain sufficient salt? There may be an internal intestinal pool of sodium in porcupines, as there is known to be in moose. "I have not felt justified in killing porcupines to pursue this study," Roze writes.

Porcupines climb to live; they feed on bark, twigs, leaves and fruit. By winter the animals slowly starve on a meager diet of chewed bark and twigs in the dormant forest. Their weight falls; many die. They must derive their energy from the slow metabolism of cellulose, and, like ruminants, they possess symbiotic intestinal bacteria that hydrolyze the abundant glucose polymer.

Come spring porcupines feast on bursting new buds, rich in protein. First they visit sugar-maple buds, then the young leaves of beech, then of ash. There is method here: the tannins that are a deciduous tree's chemical defense accumulate during growth and imbue the leaves with a bitter taste. It is the buildup of such tannins that seems to press the porcupines to new sources. By midsummer they feed on acorns and beech seeds, and at harvest time they feast delightedly on the little apples of the forest.

In their own way, porcupines manage the forest itself. They take bark from the trees' upper branches but not from the trunk. After many years the result is a little grove of "witch trees": old, shortened trees with baroquely twisted branches, best seen in the leafless season near porcupine dens.

There is plenty more to porcupine life, and much that is puzzling about the evolution of these animals. But for the backyard naturalist, this is an agreeably rich little book, clearly on the side of the porcupines. For the author, each animal is "a teacher, a storyteller of the woods, a complexifier and adorner of the world."

ON BIOMINERALIZATION, by Heinz A. Lowenstam and Stephen Weiner. Oxford University Press, 1989 ($57).

We know it in our bones: the mineral kingdom shares with the living ones a frontier more convoluted than any road that winds across the mountains of Transylvania. In this comprehensive yet compact volume, two investigators, one a geologist at Cal Tech and the other a biologist at the Weizmann Institute of Science, present a wide view of the tangled discipline. Their focus is on tangible end products: the ions, macromolecules and crystals that are organized by cells within the five kingdoms of life.

The systematic lists and classes that are the skeleton of this treatise are striking. About 60 biogenic minerals, from calcite, galena and fluorite to potassium fluorosilicate, are found among more than 50 phyla—from tiny blue-green cyanobacteria to intricately biomineralized chordates such as human beings. Half a dozen chapters review the findings in group after important group; three or four chapters address process, special function and evolution. Paleontology is, after all, written in biomineral remains as commonly as history is read from characters marked on stone, clay and paper.

We can only sample the wide coverage provided by this book. Most scientific readers are familiar with the magnetic-field sensors of black iron oxide made by certain mud-dwelling bacteria and are aware of the case made for similar magnetite grains in animals ranging from honeybees to salmon. It was recognized in the 1960's that subtropical underwater limestone ledges were actually abraded and undercut by little chitons, strange articulated mollusks that graze on the organisms on and just below the rock surface. Lowenstam was the first to realize that there had to be some hardener in chiton teeth; limestone does not cut limestone.

In fact, chitons have hardened their teeth with magnetite. The teeth grow in row after row, assembly-line fashion, so that we can watch over the entire mineralization process. During maturation each tooth forms as a composite of three localized minerals. Mollusks as a group are the champions of biominerals: the mother-of-pearl layers that pleasure the eye and show a high specificity of shape, size and mineral type.

Single crystals of calcite show a wonderfully characteristic cleavage, a trait that was a stimulus to the founders of crystallography. Every sea-urchin spine is a single crystal of magnesium-rich calcite that will regenerate after fracture. A particular crystal axis is invariably aligned along the long radial axis. The spine form is smooth, without crystal facets on a microscopic scale, yet crystalline atomic order is complete. On a scanning electron micrograph the spine shows glassy fracture surfaces and so resembles a worked flint. Sea-urchin spine seems a subtly composite material, with the "hardness and order of crystals, but not their brittleness."

How is organic form given to biocrystalline products? In the simplest cases they grow as familiar mineral microcrystals within a tiny bag of cell membrane. The space where the crystals will grow is

sequestered from the overall medium, where the ions necessary for growth are often rare. Pumping mechanisms arrange for concentration, and nucleation may be enhanced on the custom-built surfaces. Consider the unicellular diatom. It is enclosed by elegantly perforated and carved plates of silica that are preformed by a dance of various organelles within the cell. The well-formed armature on which the silica is deposited is produced inside the cell; it ends up outside in maneuvers that remain obscure. The result is near magical form, which, no matter how beautiful, is still gross and disorderly on the molecular scale, where chemistry happens.

One group of microplankton constructs beautiful skeletons of strontium sulfate. But the strontium ion is so rare in seawater that when these organisms die, their skeletons dissolve quickly, unlike those of their more commonplace calcium carbonate relatives. Freshwater snails that normally construct shells of calcium carbonate were experimentally grown in water enriched with increasing amounts of strontium. Eventually, a snail with a shell made entirely of strontium carbonate was produced; to undertake so much inorganic chemistry seems no trick for the expert biomineralizing cell.

What happened toward the end of the Precambrian period when animals with hard parts first appear in the fossil record? Such causal questions are at best tentatively answered; there is some attraction in the notion that new amino acids arose that depended on molecular oxygen for their synthesis. That may have led in turn to the evolution of structural glycoproteins such as collagen and eventually to animals with hardened parts. Controlled biomineralization itself may have begun much earlier, because some domain-size magnetite crystals are two billion years old; they were possibly bacterial products.

The famous red-black layers of the banded-iron formations might—or might not—be the earliest signs of biomineralization of some complexity. Like the bacteria that act as nuclei around which ice crystals form, the alternating bands might have been induced by the temperature changes that affected the outside surfaces of bacteria.

Thus are X-ray diffraction, electron microscopy, elemental analysis, powerful infrared spectroscopy and the growth of our understanding of macromolecules building a remarkable bioscience and powerful resource out of the studies of curious Victorian microscopists. A well-illustrated survey by these two authors would make a fine popular natural history, worthy of our times.

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ESSAY

Of ladders, cycles and economic growth

by Ralph Gomory

A major scientific advance is at last achieved. Engineers refine it through successive stages until it can be embodied in a useful new device. This is the "ladder paradigm" for the evolution of technology into product. If the ladder paradigm sounds familiar, it should; it dominates our view of the relation between science and manufacturing. Yet technology can also reach the marketplace as an incremental improvement, introduced as one generation of a product succeeds another. This is the obscure "cycle paradigm." Simple? A small distinction? Perhaps. And yet by failing to make it, managers and policymakers commit strategic errors that hurt the competitiveness of U.S. firms.

The ladder paradigm shapes our thinking because it makes both good history and good journalism. Bell, the Wright brothers—their careers give the pattern substance. During World War II radar and the science-led, science-developed process of creating the atomic bomb reinforced the concept. The transistor stands as a more recent example. It was the result of decades of fundamental scientific research that eventually yielded a practical device. A series of rapid developments then led to the manufacture of the first chips and to the foundation of a major new industry.

The ladder paradigm describes the start-up of an industry or the launch of a product. The cycle paradigm provides the right approach to planning the evolution of an existing product. It mandates repeated, incremental improvement in each generation. By implementing the cyclic process, manufacturers have been able to pack an increasing number of components in a square centimeter, so that today a chip can contain several million elements. Such achievements make good computers but not good mythology.

That is unfortunate because the cycle paradigm has implicit in it several realities that are dangerous to ignore but powerful if recognized and exploited. First of all, the length of the cycle is very important. Suppose two companies having access to the same technology are manufacturing a product, one product generation after another. One company can bring the product from design to market in three and a half years. The other can do it in two years. Presume further that both products reach the market in 1990. Clearly, the technology embedded in the product with the shorter cycle will be more advanced, providing a competitive lead, even though both companies have access to the same technology. A short cycle time has another advantage: it permits faster response to changing market conditions.

The cycle paradigm demands discipline. It does not welcome lightning strokes of creativity. A new idea has to be well developed, and it has to be presented at the right time, not part way through a cycle. Consequently, the cyclic process often seems resistant to outside ideas. This frequently accounts for charges of insularity and jeers that play on the "not invented here syndrome."

A look at Japanese manufacturers shows that they are fully aware of the realities that the cycle paradigm dictates. They design a product so that it can be easily made. In fact, design and manufacturing teams often work together. Japanese manufacturers have achieved very short cycles, and they carefully time the introduction of new technology.

Yet our perception, distorted by the ladder paradigm, misreads the situation. The press, for example, tends to emphasize the advanced-technology programs that Japan's Ministry of International Trade and Industry sponsors. Such programs are useful in the early stages of development. But it is the successful execution of cycle strategies, not ladder strategies, that has created the deciding Japanese margin in such industries as automobiles, semiconductors and consumer electronics.

What we do not know can indeed hurt us, in several ways. It can cripple the formulation of adequate public policy. High-temperature superconductivity illustrates the point. At least 10 years will pass before such technologies can become economically significant. It seems plausible that applications capable of transforming society and the economy in major ways lie even farther in the future. During this time knowledge inevitably diffuses throughout the world, so the advantage gained from discovering the phenomenon is lost. Yet when this undoubtedly great scientific achievement was announced, meetings were called in Washington that the president attended, Congress enacted legislation and committees were set up to advise the government. All of this activity assumed a close tie between basic discovery and industrial supremacy, which unfortunately does not exist.

High-definition television has evoked the same response from policymakers. Yet it would be more useful to look at this technology as part of the continuum of TV products. The question is not whether to get into HDTV, it is whether to get back into making television sets. The misperception has its roots in the confusion between ladders and cycles. The only way that you can enter HDTV is to build a major manufacturing capability, back it with a strong R&D program and start the cycle churning. R&D alone will not do it. The market for TV devices does not invite entry from the outside with a new technology. It is an ongoing market, not a new one.

The ladder paradigm distorts the national view in other ways. Take investment in R&D. We note aggressive Japanese action in this area and assume that the appropriate response is to mimic our rivals. Again the picture is "you put R&D in here, and the product pops out there." That's a very different picture from the one you actually encounter if you are developing products cyclically. In cyclic development the income from sales of the product funds both current expenses and R&D for the next product generation. A fixed fraction of this stream, as much as 8 to 10 percent, would be committed to R&D. In this cyclic world a successful product generates more R&D, an unsuccessful product less. It is not easy to persuade managers to find money from other sources to bolster R&D for a losing product.

A high dollar level of R&D can create a successful product. Such high levels can also be the consequence of product success. Yet if we think "ladder," we will automatically ascribe a competitor's success to intense R&D and respond in the same manner. Such a response overlooks the fact that in the cyclic world R&D is not an independent variable.

The paradigms of ladder and cycle are not incompatible. Companies need a mix of new and mature products. In our thinking we need to understand the cycle as well as the ladder paradigm so that we can excel at applying either strategy. As long as we ignore these realities, the U.S. economy's ability to compete and grow will suffer.

RALPH GOMORY is president of the Alfred P. Sloan Foundation. He retired in 1989 as senior vice president for science and technology, the IBM Corporation.

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