SCIENTIFIC AMERICAN

APRIL 1988
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Vaccines for autoimmune disease?

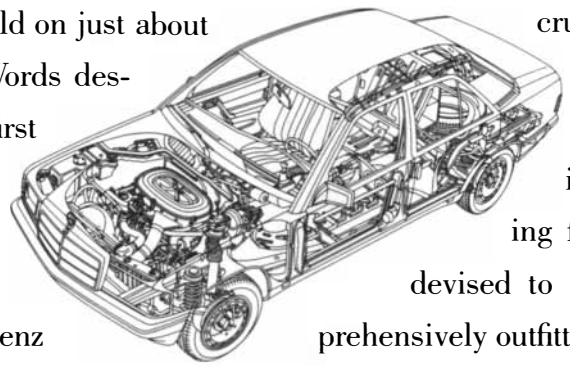
Energy-efficient buildings: the $50-billion saving.

How black holes could power quasars.

***The computer** serves as a musical instrument in* Répons, *a composition for chamber orchestra by Pierre Boulez.*

THE MERCEDES-BENZ 190 CLASS: THE AUTOMOBILE EVERY SPORTS SEDAN WANTS TO BE WHEN IT GROWS UP.

It has been written that the Mercedes-Benz 190 Class "...will challenge some of the finest sporting sedans in the world on just about any road you choose."* Words destined to leap to life the first time you choose a likely road and storm it in a 190 Class sedan.



But Mercedes-Benz engineers have never believed in building one-dimensional automobiles. The 190 Class repays your investment—and separates itself from today's legions of single-minded sports sedans—by promising infinitely more for your money than occasional moments of driving nirvana.

Such as a permanent sense of automotive integrity. Proceeding outward from a steel vault of a body structure, through technology that system for system may be the most fully developed in the automotive world, to fit and finish that prompted *Car and Driver* to ask, "Why is it that Benzes fit together better than anything else in the world?"

Producing, in turn, an aura of driving civilization unique not only among sports sedans but among all automobiles. Matching such exploits as triple-digit test-track maximums with velvety running smoothness. Blending sports car cornering power with a gentle ride. So reducing friction between airstream and automobile at cruising speeds that wind noise is all but obsolete.

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The 190 Class: proof that your automotive judgment can be very grown up, while your automotive enthusiasm remains very young.

Engineered like no other car in the world

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SCIENTIFIC AMERICAN

April 1988 Volume 258 Number 4

DEPARTMENTS

THE COVER painting depicts a programmable electronic device as an integral part of an orchestral ensemble (see "Computers in Music," by Pierre Boulez and Andrew Gerzso, page 44). The device routes audio signals from instrumentalists to a processing unit (which stores, manipulates and recalls digitized sound waveforms) and then on to speakers. In this way instrumental sounds can be transformed as soon as they are produced by human musicians.

THE ILLUSTRATIONS

Cover painting by Ted Lodigensky

Page	Source
44–45	Ian Worpole
46	Andrew Gerzso (*top*), Ian Worpole (*bottom*)
47	Ian Worpole
48	By permission of Universal Edition, Vienna
49–50	Ian Worpole
53	Yaakov Naparstek and Dorit Gurfel
54–55	Joan Starwood
56	Ritta Stanescu, Hôpital des Enfants Malades, Paris
57–60	Joan Starwood
69–77	Javier Romero
79	Einhorn Yaffee Prescott
80–85	Gabor Kiss
89	James Kilkelly
90–91	Gabor Kiss
92	James Kilkelly (*top*), Gabor Kiss (*bottom*)
93	Gabor Kiss
94–100	George Retseck
103	Pacific Whale Foundation
104–107	Patricia J. Wynne
109–110	Courtesy of Howard M. Lenhoff and Sylvia G. Lenhoff
111	Richard D. Campbell, University of California at Irvine (*top*); Tom Prentiss (*bottom*)
112	Courtesy of Howard M. Lenhoff and Sylvia G. Lenhoff
113	Courtesy of M. Archinard, Musée d'Histoire des Sciences, Geneva
114	David K. Donald
115	Michael Goodman
116	Michael Goodman (*top*), Jearl Walker (*bottom*)
118–121	Laurie Grace

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Q. Would you buy a pair of shoes from this man?

A. Thousands of Lands' End customers do, for reasons this interview makes clear.

Above is a rare photo of Jim Jennings, the "old shoe dog" who governs the buying and selling of Lands' End shoes. Rare, because Jim is seldom caught in repose. But Carol Sadtler, one of our resourceful creative people, cornered him one day, and what follows are excerpts from an interview that may lead you to rethink whatever prejudice you may have against ordering shoes from a catalog. Even ours.

Carol: *How long have you been in the business, Jim? And how does that affect your buying shoes for your customers?*

Jim: Let's see... about 20 years, I guess. When you've been around that long, you see a lot of companies come and go. You get to know the good, reliable ones. The ones that make the Lands' End kind of shoe.

Carol: *And what kind of shoe is that?*

Jim: The kind of shoe that goes with the clothing we sell. Not "high fashion", or a "hot seller". But classic. We offer casual shoes, as you know, and a very controlled line of dress shoes. Always in style. And as well made as possible.

Carol: *What steps do you take to get that kind of quality?*

Jim: Extra steps, frankly. When we look at a shoe, we'll see what we can add to it to give it more quality. Like a leather lining instead of vinyl, so the shoe wears longer and breathes better. Or a wool lining instead of acrylic in a pair of slippers. Or we'll add a better sole.

(JIM PAUSES, RUMMAGING AROUND IN SOME SHOE BOXES AND COMES UP WITH A PAIR OF LANDS' END "DUSTY BUCKS".)

Here's a perfect example. We took these traditional Bucks. Nice suede leather, but the rubber soles wore out in a big hurry. And they were heavy. So we added a lightweight Vibram® sole, with a real tough skin to make it long-lasting. Now, instead of a Buck, we give you a Buck-and-a-quarter.

Carol: *They warned me about your puns, Jim. Let's get serious again. I'm told you visit manufacturers quite often. Right? What do you look for?*

Jim: Actually, as a company we probably do make more factory visits than most. That's really the only way to maintain quality. You just can't run our business from an "ivory tower". And when we do visit, we look to see how things are organized. And at how many points the shoes are inspected. After a while, you can tell how neat and careful the work is at every step.

Carol: *Do you literally look over a handsewer's shoulder?*

Jim: You bet. You look to see how neat and even the stitches are.

Carol: *That kind of quality control must take a lot of travel.*

Jim: It does. But we're fortunate in having built up a very strong domestic structure of suppliers. Which means for the customer that we can keep an eagle eye on quality, and keep the shoes they want in stock too.

LANDS' END® DIRECT MERCHANTS

Carol: *But you buy shoes overseas, too?*

Jim: Yes, indeed. We go where we can get the best shoe. Italy, for example, for the fine leathers and excellent craftsmanship for some of our dressier shoes.

Carol: *How do you do all these extra things and still keep prices as low as they are?*

Jim: We have several things going for us. We don't operate on the normal 50% retail mark-up. We're direct merchants, with no middlemen to raise costs. Also, we order in large quantities. And we have long-standing relationships with our suppliers, which helps.

Carol: *What would you say to the person who hesitates to order shoes from a catalog because of fit?*

Jim: We make an extra effort to standardize sizes within our offerings. We've used the same lasts—which determine fit—for ten years or more in many of our shoes. And we fit-test a shoe on 20 to 25 people before we offer it.

Carol: *Gee, you seem to have things all worked out. Don't you have any problems?*

(LONG PAUSE. JIM LAUGHS A LITTLE NERVOUSLY. FINALLY, HE ANSWERS.)

Jim: Frankly, the hardest thing to do is managing the variety of sizes and colors we offer in each style. We try our darndest to fit everybody, and that means we have to keep track of something like 1,863 offerings.

Carol: *That ought to keep you busy. And your customers happy.*

Jim: Well, Carol... that's the idea!

* * * * *

It is, indeed. Whether it's Lands' End shoes you're buying, or any one of our other catalog items. All quality offerings, all priced to reflect remarkable value, all GUARANTEED. PERIOD.®

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LETTERS

To the Editors:

"Why is Mars too cold, Venus too hot and the earth just right?" Because earthlings are asking the question [see "How Climate Evolved on the Terrestrial Planets," by James F. Kasting, Owen B. Toon and James B. Pollack; SCIENTIFIC AMERICAN, February].

VERA C. RUBIN

Carnegie Institution of Washington
Department of Terrestrial Magnetism
Washington, D.C.

To the Editors:

We found "Technology in Services," by James Brian Quinn, Jordan J. Baruch and Penny Cushman Paquette [SCIENTIFIC AMERICAN, December, 1987], to be comprehensive, informative and enlightening. The authors are very clear about the importance of technology to the services industry and also about how services can contribute to manufacturing and the economy as a whole. What was almost entirely missing, however, was an appreciation of the critical role that manufacturing plays in providing state-of-the-art products for the delivery of those services. The absence of such a discussion helps to perpetuate the dangerous myth that the U.S. economy and indeed services (at least those on the leading edge) will be able to flourish without a strong industrial base.

Part of the problem lies in the definition of services. Although several reasonable definitions of the services sector were presented in the early parts of the article, the authors go on to use the term "services" to encompass virtually everything. For example, an automobile delivers transportation and convenience: services. Yet the automobile industry is not part of the economic sector called services. A cabdriver driving a car delivers a service. Driven by its owner, however, an automobile is not necessarily a service. Similarly, a computer disk is a manufactured item and not a service, although computer disks may be used in the services sector.

Nearly all the examples given in the article indicate the importance of the services sector to the technology embodied in manufactured goods or to the goods themselves. But, curiously, the authors leave out any discussion of the role these products play in the delivery of services. It is difficult to imagine a globally competitive transportation system, for example, that did not include state-of-the-art equipment, such as aircraft, computers and software for scheduling flights. A more balanced view is needed of the growing interdependence of technology, services and manufacturing.

Although the authors have correctly discussed the large and growing importance of the services sector, it should be pointed out that one of the major economic problems in the U.S., namely the trade deficit, is not likely to be helped much by an increase in internationally traded services. The trade balance of services is slightly positive, but their magnitude in international trade is comparatively small and is likely to remain so for the foreseeable future. The trade deficit will be solved only by exporting more U.S.-made goods or importing fewer foreign goods. Doing so will require a major commitment of resources and talent, because many U.S. companies have already lost their lead in research, development and the commercialization of new products and processes. Leading-edge services have an important role to play in that revitalization.

DANIEL BERG

DANIEL ORNE

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Troy, N.Y.

To the Editors:

I suggest that the authors of "Technology in Services" overestimate the ability of services to "sustain...increases in real income and personal wealth" because they neglect some peculiarities of the service economy.

They state that the "revenue [a] service brings to its producers" can be compared with capital and labor inputs to measure productivity in a services industry. This is true for an individual transaction but not necessarily for the industry as a whole. If I hire a lawyer and win a lawsuit, my lawyer's labor is productive from my point of view, but if we all hire lawyers and sue one another, we are playing a zero-sum game: the lawyers' labor accomplishes a redistribution of wealth but does nothing to increase the total wealth of society.

The legal profession is not the only one that is distributive rather than productive of wealth. Suppose we could double the productivity of the world's advertisers, lobbyists, investment advisers, bureaucratic regulators, ministers, soldiers, defense contractors, salesmen, entertainers, tax accountants and dress-for-success consultants; how, if at all, would this increase total wealth?

An additional feature of the service economy is its tendency to dissipate improvements in productivity by increasing procedural complexity. I imagine that the process of choosing a president, buying a house, entering a child in school, applying for a job, judging the Olympics, selecting a government contractor, checking into a hospital or administering a Federal tax code is more complicated than it was 50 years ago. But an increase in procedural complexity is not in itself an economically productive achievement.

FELIX GODWIN

New Market, Ala.

To the Editors:

Throughout the article we tried to maintain clearly the definitional differences between "services industries" and "services" that might be provided either by services industries or by product manufacturers. We also emphasized the high interchangeability and interdependence of manufacturing and services activities. We stress the services component of manufacturing primarily to increase awareness of the ways in which services can substitute for products and vice versa. Often manufacturers can lower costs, increase value added and diversify product offerings most effectively through such substitutions.

Contrary to the views of Professor Berg and his colleagues, however, it is conceivable that a highly effective services sector could be maintained by importing and utilizing products and associated technologies manufactured abroad. For many services industries domestic manufacture of product technologies is not essential, even though it is highly desirable from an economic point of view. Today many producer-services industries sell, advertise, distribute, maintain or support foreign-made products. Clearly the most favorable economy is one that combines indigenous manufacturing and services.

We explicity stated that trade in

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- Shinsegae Department Store Co., Ltd.
- Hotel Shilla Co., Ltd.
- The Joong-ang Daily News
- Samsung Medical Systems Co., Ltd.
- Samsung Hewlett-Packard
- Samsung Data Systems Co., Ltd.
- Koryo General Hospital
- Samsung Lions Co., Ltd.
- Samsung Foundation of Art & Culture

services, as it is currently measured, is not likely to "come close to covering current merchandise trade deficits." Services technologies can contribute enormously to decreasing merchandise trade deficits, however, by lowering domestic manufacturing costs, increasing quality and improving value added. We point out that much of the value added in manufactures (whether they are sold abroad or not) derives from services activities such as design, marketing and so on. And the effectiveness with which those goods are presented abroad depends heavily on services. Decreasing trade barriers in services and normalizing regulation and disclosure requirements for services trade can greatly help trade in both manufactured goods and services.

We do not believe the scenario presented by Mr. Godwin is real. A manufacturing economy that produced only beads to be swapped between producers would not increase wealth either. Lawyers can increase real wealth in the economy if their actions encourage doctors to perform more effectively, force companies to design products with an eye to their environmental impacts, or protect the rights of individuals to the fruits of their creative activities. Increasing the productivity of advertisers would presumably lower the costs consumers pay for products; better investment advisers lower risks and hence the cost of capital for producers; an efficient defense establishment lowers national costs, and so on.

Godwin seems to blame complexity on the services economy. Complexity itself, however, is largely an outgrowth of modern technology and its complex feats. Society has come to expect government, private entities and other individuals to protect it from unwanted side effects (air pollution, medical disasters, safety hazards) of these new technologies. It is this desire for new forms of protection that has led to some of the complexities Godwin indicates. We suggest that economic growth through increased manufacturing requires a services support system to add value, distribute, market and maintain the products *and also* to protect the public against the often unwanted side effects of such production. This is not a zero-sum game.

JAMES BRIAN QUINN

JORDAN J. BARUCH

PENNY CUSHMAN PAQUETTE

SCIENCE/SCOPE®

Hughes Aircraft Company designed and built a probe for the Galileo Mission, which is expected to unlock the secrets of Jupiter, providing scientists with data about the planet's atmosphere. Scheduled for launch from the Space Shuttle in late 1989, Galileo will employ a solid-fueled Inertial Upper Stage rocket, aided by gravity assists from Venus and Earth, to boost itself from the Shuttle's orbit to the giant planet. Once Galileo is within reach of outer Jupiter, the Hughes-built probe will be released into the Jovian atmosphere. During its 60-minute descent to the surface, the probe will continually broadcast scientific data back to Galileo, which will then transmit the information to Earth.

Revolutionary "smart skins" will integrate avionics and sensors directly into the skin and structure of future aircraft and space vehicles. As part of the U.S. Air Force's Project Forecast II, Hughes is working with the USAF Avionics Laboratory to develop concepts and applications for a new generation of avionics. Systems using these technologies will provide levels of performance, reliability, and fault tolerance not possible in current conventional avionics systems.

A new circuit design complex will help Hughes microchip designers develop advanced radar and communications systems for military applications. The Microwave Monolithic Integrated Circuit (MMIC) Design Center will include cell libraries and computer-aided design workstations and will be located in the new gallium arsenide (GaAs) microchip production facility. Location of MMIC design and GaAs production in the same facility will benefit the design activities, as MMIC chip development requires repetitive design-processing cycles with quick turnaround. The MMIC program is designed to support all microwave and millimeter wave systems with the latest state-of-the-art technology.

A newly developed system significantly speeds up the measurement of digital data generated by modern radars. The Automated Radar Monitor (ARM) system uses a computer and special interface hardware. It replaces expensive, time-consuming manual special test equipment (STE) hardware panels currently used. ARM can collect high-speed digital radar data, analyze it, and display it on several computer terminals simultaneously. The cost of the ARM system, developed by Hughes, is approximately one-third that of the STE it replaces.

Hughes is seeking experienced engineers and scientists to further develop advanced spacecraft systems and components for communications satellites. Openings are in the fields of: software, computers, and data processing systems; electrical components; microwave/RF communication systems development; on-board spacecraft electronics and control systems; satellite design, integration, propulsion, and electrical power system development; spacecraft manufacturing, systems test and evaluation; GaAs applications R&D. Send your resume to Michael Martinez, Hughes Space & Communications Group, Dept. S2, S4/A300, P.O. Box 92919, Los Angeles, CA 90009. Equal opportunity employer. U.S. citizenship required.

For more information write to: P.O. Box 45068, Los Angeles, CA 90045-0068

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"A MAN SHOULD DO THREE THINGS IN HIS LIFE AND DRIVING THIS CAR IS ONE OF THEM."

THE NEW BMW 750iL.

The BMW 750iL has been greeted by the European press as "the superstar of the luxury class" and "not just a milestone in German automotive history, but its crowning achievement."

It was a well-known American automotive editor, however, who offered the spirited appraisal quoted on the opposite page.

Back when mighty Duesenbergs and Bugattis ruled the roadways, he explained, it was said that every man should enjoy three experiences in life: planting a tree, raising a son, and driving a 12-cylinder car.

The new flagship of BMW's 7-Series, he reports, makes the third endeavor more satisfying than ever imagined.

When you sit in the hand-stitched leather driver's seat, you command not merely an abundance of power but a seamless, unhesitating flow of power that never raises its voice above a whisper.

Your mastery of the most unruly roads is assured by the 750iL's even weight distribution and stable aerodynamics combined with a patented fully-independent suspension and gas-pressure shocks.

The car is long, spacious, and uncannily quiet. Its amenities are astonishing—a cellular telephone, for example, is standard equipment—and it evinces a level of workmanship that is elsewhere close to extinction.

Your authorized BMW dealer can confirm the truth of this by arranging a thorough test drive of the 750iL.

The noblest transformation that 4,235 pounds of steel, aluminum, glass, and leather have ever undergone.

THE ULTIMATE DRIVING MACHINE.

50 AND 100 YEARS AGO

SCIENTIFIC AMERICAN

APRIL, 1938: "Two research chemists of the pulpwood industry have put ordinary bacteria to work producing power from the sulfite waste liquors of pulp mills. Many years ago it was definitely proved that the formation of marsh gas (methane) was caused by the action of tiny anaerobic bacteria that fermented the cellulose contained in decaying swamp vegetation. If this was so, reasoned the research men, could not the same bacteria be used to generate methane from the organic material in waste sulfite liquors? The methane produced could then be burned to generate electric power."

"The altitudes of the northern lights have been skillfully measured in Norway by a number of observers connected by telephone, who took photographs at the same instant from different places a measured number of miles apart. A simple calculation determines the altitude of the aurora. About 60 miles is the most common result. Sometimes the tops of the streamers may be 250 miles above the earth."

"In the light of its astounding capacities, in the light of its protein nature, and viewed against the background of all distinctly non-living arrangements of atoms and all living organisms, the virus molecule must for all time appear to be a transition form between non-life and full-flowering life—but a form vividly more alive than not."

"By a new process of electroplating, developed in England, metals may be deposited on molded plastic articles to produce decorative or protective effects. Copper, brass, nickel, chromium, silver and rhodium have been successfully applied. This new finish permits many articles to be made of plastics of light weight that hitherto have been die cast."

"If you look in any chemistry text book that is not just fresh off the presses, you will find a table of the chemical elements that ends at uranium, number 92. That is the way the chemical elements, building stones of everything around us, were first arranged back in 1871 by Mendeleeff, the Russian, and Meyer, the German, to form the periodic table. Yet science has now discovered not one but at least four 'transuranic' elements. Little wonder they were not discovered earlier, for the discovery was dependent upon creating them first, and this was done only through the use of neutrons, discovered in 1932."

SCIENTIFIC AMERICAN

APRIL, 1888: "The number of women of our country who have undertaken and are carrying on business enterprises successfully are not a few, and they increase every year."

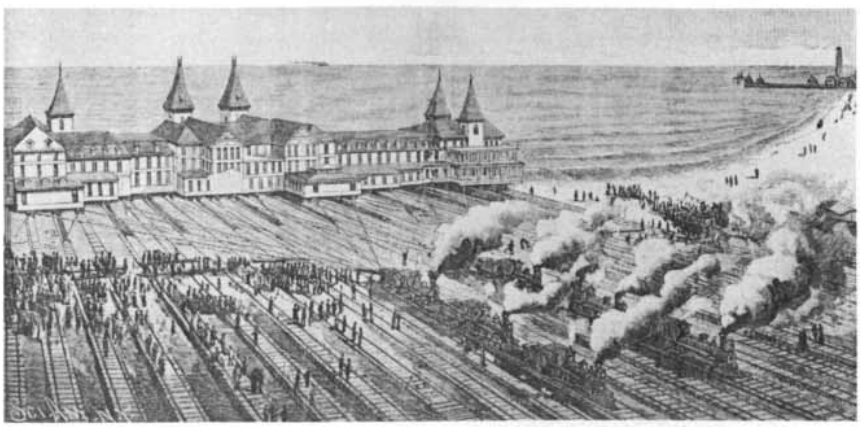
"Almost every newspaper from Australia has something to say about the rabbit plague in that colony. And now comes a similar wail from China, stating a danger threatening that empire. A recent number of the Peking *Gazette* contains a memorial to the Emperor from the Governor of Uliassutai stating that, owing to the appearance of swarms of rats, it has been found necessary to alter the routes of the government courier in three of the postal stations in the Khalkha region of Outer Mongolia."

"The fury of the chemical world is the element fluorine. It exists peacefully in company with calcium in fluorspar, and also in a few other compounds; but when isolated, as it recently has been, it is a rabid gas that nothing can resist. In uniting with sodium, potassium, calcium, magnesium and aluminum the metals become heated even to redness by the fervor of its embrace. Even the noble metals, which at melting heat proudly resist the fascinations of oxygen, succumb to this chemical siren."

"The government administration of the new metropolitan railroad in Berlin has devoted considerable attention to the subject of diminishing the noise of trains passing over the viaducts and bridges, which, of course, form the principal portion of the road. Where the rails on a metal bridge rest on wooden cross ties, or on timbers running longitudinally, the sound is less than where they are secured directly to the metal, and it may be still further diminished by placing cushions of felt or rubber under the timbers before bolting them to the bridge construction."

"The conservator of the museum at Bergen, Norway, Mr. Frithjof Nansen, intends very soon to investigate the interior of Greenland. For making the journey over the ice or snow he means wholly to rely on the use of the Norwegian snow shoes, long narrow strips of wood (ash as a rule) on which great distances can be traversed in an incredibly short time."

"We illustrate in our present issue the moving of the Brighton Beach Hotel, one of the great buildings of Coney Island. For many months there has been a marked tendency on the part of the water to wear away the sandy beach upon which the building was erected. It was evident that unless some preventive measures were taken, the house would be undermined and carried away. The plan was to place the hotel upon a number of freight cars, resting on parallel tracks, and to draw it where wanted by locomotives."



The Brighton Beach Hotel is moved away from the sea

AN ENGINE SHOULDN'T BE FORCED TO COMPENSATE FOR ITS FUEL.

FUEL MUST BE AN EXTENSION

It used to be an engine was a relatively simple machine.

But as the automakers have squeezed more and more performance and efficiency out of fewer and fewer cubic inches, engines have reached remarkable levels of sophistication and precision.

Fuel injectors are run by microprocessors and feed gas through clearances as small as 2/1000".

A new device, called a knock sensor, has been introduced to compensate for octane deficiency. When it hears a knock, its computer retards the spark, eliminating the knock. But at the expense of an immediate drop in power.

Even the most advanced engine is still at the mercy of the weather. On a hot day, gasoline can evaporate in the fuel lines before it ever gets to your engine. In cold weather, your car may not start or accelerate because the gasoline doesn't vaporize enough.

All of which leads us to conclude that the more sophisticated the engine is, the more sophisticated the fuel must be. And why engines designed to aerospace tolerances should have a fuel that's equally exacting.

OF THE ENGINE.

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THE AUTHORS

PIERRE BOULEZ and ANDREW GERZSO ("Computers in Music") have been collaborating since 1980 on the theoretical and practical aspects of the use of computers in music. Boulez is director of the Institut de Recherche et Coordination Acoustique/Musique (IRCAM), president of the Ensemble InterContemporain and professor at the Collège de France. He studied composition at the Paris Conservatory and became musical director of the Renaud-Barrault theater company in 1946, a position he held for 10 years. In 1954 he began organizing the Petit Marigny and Domaine Musical concert series, dedicated to contemporary music. From 1960 to 1963 he was a professor of musical analysis and composition. Boulez has been the principal guest conductor of the Cleveland Orchestra, the principal conductor of the BBC Orchestra and music director of the New York Philharmonic. Gerzso, a flutist, coordinates research on computer-aided composition and scientist/composer interaction at IRCAM. He obtained a bachelor's degree in music at the New England Conservatory and a master's degree at the California Institute of the Arts. From 1974 to 1976 he studied at the Royal Conservatory in The Hague. Since 1977 he has held various positions at IRCAM.

IRUN R. COHEN ("The Self, the World and Autoimmunity") is Mauerberger Professor of Immunology at the Weizmann Institute of Science in Israel. Born and raised in Chicago, he got his medical degree at Northwestern University. After doing an internship and spending two years at what then was called the Communicable Disease Center in Atlanta, he completed a residency in pediatrics at the Johns Hopkins Hospital. He moved in 1968 to the Weizmann Institute, where he has been ever since, except for a period in the early 1970's when he helped to establish a medical school at the Ben-Gurion University in Beer-Sheva. Cohen and his family have built, and help to run, a children's library and cultural center dedicated to the memory of Cohen's first-born daughter, Michal, who died in a car accident at the age of 17.

RICHARD H. PRICE and KIP S. THORNE ("The Membrane Paradigm for Black Holes") have collaborated since Price was a graduate student of Thorne's. Price is now professor of physics at the University of Utah, where he went in 1971 as assistant professor. He holds a bachelor's degree in engineering physics from Cornell University and a Ph.D. from the California Institute of Technology. His main research focus is relativistic astrophysics, but he has recently begun to collaborate with workers in engineering design on the problems of micromechanical devices. Thorne is William R. Kenan, Jr., Professor and professor of theoretical physics at Caltech, where he received his undergraduate degree in 1962. He earned a Ph.D. from Princeton University in 1965 and spent a postdoctoral year there before going to Caltech as a research fellow in physics. This is his third article for SCIENTIFIC AMERICAN.

ARTHUR H. ROSENFELD and DAVID HAFEMEISTER ("Energy-efficient Buildings") are professors of physics at the University of California at Berkeley and at California Polytechnic State University respectively. Rosenfeld, who has a doctorate from the University of Chicago for work done under Enrico Fermi, is also director of the Center for Building Science at the Lawrence Berkeley Laboratory. He founded the LBL's research program on energy-efficient buildings. Hafemeister was a science adviser to the U.S. Senate from 1975 to 1977, working on energy legislation. He spent the next two years as a special assistant in the U.S. Department of State and was a visiting scientist at the LBL from 1985 to 1986. The authors thank their colleagues Sam Berman, Steve Selkowitz, Seth Zuckerman and Evan Mills for their great help in preparing the article.

PHYLLIS B. MOSES and NAM-HAI CHUA ("Light Switches for Plant Genes") share an interest in plant biology. Moses this year became an acquisitions editor for Academic Press, Inc. She got a bachelor's degree in biology at Johns Hopkins University in 1977 and a Ph.D. in molecular genetics from Rockefeller University in 1983. She continued there on a National Science Foundation postdoctoral fellowship and moved to the National Research Council in 1985 to work on agricultural-science policy. Chua is professor and head of the Laboratory of Plant Molecular Biology at Rockefeller. He received his bachelor's degree at the University of Singapore in 1965 and his doctorate in biology from Harvard University in 1969. He has been at Rockefeller since 1971.

FRANCK LALOË and JACK H. FREED ("The Effects of Spin in Gases") both study spin-polarized quantum fluids. Laloë, an investigator at the École Normale Supérieure in Paris, is the coauthor of a textbook on quantum mechanics and an amateur clarinetist. Freed is professor of chemistry at Cornell University, where he has been since 1963. He obtained his undergraduate degree at Yale University in 1958 and a Ph.D. in chemical physics from Columbia University in 1962; he then spent a year at the University of Cambridge. He has been a visiting professor at several universities around the world.

BERND WÜRSIG ("The Behavior of Baleen Whales") is associate professor of marine biology at the Moss Landing Marine Laboratories of California State University. He got his doctorate in behavior and ecology from the State University of New York at Stony Brook in 1978 and did postdoctoral work at the University of California at Santa Cruz before joining Moss Landing. Würsig has studied whales in the Arctic for the past eight years. This is his second article for SCIENTIFIC AMERICAN.

HOWARD M. LENHOFF and SYLVIA G. LENHOFF ("Trembley's Polyps"), who are married, collaborated on the English translation of Abraham Trembley's 1744 *Mémoires* on the hydra. Howard Lenhoff is professor of developmental and cell biology at the University of California at Irvine and has done research on virtually every phase of the hydra's life history. He received a Ph.D. in enzymology at Johns Hopkins University in 1955 and has pursued his investigations at several institutions, including the Carnegie Institution of Washington, the University of Miami and the Weizmann Institute of Science in Israel. Sylvia Lenhoff is director of the Office of Relations with Schools and Colleges at Irvine and an adjunct member of the department of developmental and cell biology. She was graduated from Goucher College with a degree in history and in 1954 was a Woodrow Wilson Fellow at Radcliffe-Harvard, where she earned a master's degree.

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SCIENCE AND THE CITIZEN

Intelligence Test

Can the U.S. monitor cuts in strategic nuclear missiles?

Ronald Reagan, who has lambasted past arms treaties for lacking "effective" verification provisions, has lately been forced to swallow his own medicine. Many arms-control experts accuse his administration of neglecting verification in its desire to gain an arms pact before his term expires.

The criticism will probably not block ratification of the intermediate-range nuclear forces (INF) treaty signed by President Reagan and Mikhail S. Gorbachev at their summit meeting last December, mainly because the treaty is thought to have little military significance. It would eliminate missiles, most of them based in Europe, with a range of between 300 and 3,400 miles; only some 4 percent of the 50,000 warheads the U.S. and the U.S.S.R. possess would be deactivated.

Concerns about verification pose a much greater threat to a proposal, under discussion at the Strategic Arms Reduction Talks (START) in Geneva, that would cut stockpiles of strategic (long-range) nuclear weapons in half. Reagan and Gorbachev have both expressed a wish to sign a START agreement by the end of this year. Strategic weapons, which include missiles based on submarines and on land, are the most expensive and destructive ones in the superpowers' arsenals.

"With START you'll have more military incentive to cheat," says Sidney N. Graybeal, a former official of the U.S. Arms Control and Disarmament Agency and now a consultant to the Pentagon. He points out that keeping track of the numerical limits imposed by a START agreement will be much more complicated than verifying the INF pact, which bans all medium-range missiles and their supporting infrastructure outright. If the START pact limits such easily concealable weapons as ballistic missiles based on trucks and railroad cars or cruise missiles based on ships and submarines, Graybeal remarks, verification will be even more difficult.

The INF treaty has been hailed because it calls for a limited number of on-site inspections of designated missile-production facilities. The U.S. has long insisted that the best way to achieve foolproof verification is through far more extensive "anytime anywhere" inspections; nevertheless, American negotiators rejected a Soviet proposal to include them in the INF agreement. Paul A. Stokes, who manages verification research at the Sandia National Laboratories, recalls that U.S. officials "suddenly got worried about the risks involved" in allowing the Soviets to examine any facility they choose.

Many experts, even within the Administration, say the value of inspections has been greatly overrated. Manfred Eimer, assistant director of verification and intelligence at the Arms Control and Disarmament Agency, asserts that anytime-anywhere inspection will result in either "a denial of access or the opportunity to determine that you made a mistake and nothing was there. It may have some political benefit, but for verification it isn't the answer to any problem I know of." Nevertheless, he says, the latest START proposal calls for anytime-anywhere inspections.

Numerous so-called cooperative measures that might complement inspections have been proposed. These include limiting weapons to designated zones, "tagging" them with transmitters and installing unmanned sensors at weapons facilities. Yet there has been no systematic study of how these techniques can be applied to a START pact, according to Milo D. Nordyke, who directs verification research at the Lawrence Livermore National Laboratory. "All of it is a top-of-the-head, back-of-the-envelope kind of thing," he remarks.

Eimer points out that cooperative measures can only control weapons and facilities the Soviets willingly expose. "That is an important component," he acknowledges, but "intelligence systems have to make sure nothing is going on in the rest of the Soviet Union." The U.S. intelligence network includes satellites, planes and other systems that remotely monitor the U.S.S.R.; published reports suggest the annual intelligence budget exceeds $16 billion (the exact figure is classified). But Eimer suggests that verification sometimes falls through the cracks. "I can't always get the intelligence community to give proper weight to verification," he says.

Last November the U.S. House of Representatives Permanent Select Committee on Intelligence issued a report blaming the Administration for this state of affairs. The report states: "The executive branch has failed over the years to develop a comprehensive architecture for directing, prioritizing and properly funding arms research and development of new technologies for arms control monitoring." Dave McCurdy, a Democrat from Oklahoma who serves on the intelligence committee, recalls hearing testimony on potential verification technologies that "would blow your socks off" but that were not being developed. "More and more requirements are being placed on intelligence," he observes, "but our assets are leveling off." He adds: "I'm a little concerned about the Administration's rush to get a START agreement."

Others suggest U.S. intelligence indeed is, or soon will be, up to the task of monitoring a START pact. Jeffrey T. Richelson, an intelligence consultant at the National Security Archives, a private research organization, asserts that the Soviets would have to violate a START agreement on a "tremendous" scale to gain a significant military advantage. He notes the U.S. is planning to launch satellites that will greatly improve its ability to detect such violations. One such satellite, code-named LaCrosse, will reportedly employ synthetic-aperture radar to scan the earth through cloud cover and at night.

Richard N. Perle, who recently resigned as head of international secu-

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rity policy for the Department of Defense and who is widely viewed as a staunch opponent of arms control, suggests he could accept a START agreement if it incorporates "better verification than we've had up to now." He recommends, for example, an exchange of information on weapons "so comprehensive that it is extremely difficult to falsify." But he doubts such measures can be negotiated before Reagan's term ends.

Michael Krepon, who studies arms control at the Carnegie Endowment for International Peace, points out that START negotiators have not even decided what they should limit, let alone how the limits should be verified. For this reason, he thinks the chances that Reagan and Gorbachev will sign a START pact this year are remote. "On the other hand," Krepon points out, "how often do you get a situation where the two big guys both want it?" —*John Horgan*

Pie in the Sky?

The president requests a $1.2-billion boost for civilian R&D

If the proposed budget for fiscal year 1989 that President Reagan sent to Congress in February could be counted on, much civilian research and development would be poised for halcyon days. Compared with last year's R&D budget the figure is up $1.2 billion, to $21 billion; it includes large increases for areas such as space, AIDS research and the proposed Superconducting Supercollider (SSC), a particle accelerator 52 miles in circumference. The budget stipulates a $316-million boost for basic research funded by the National Science Foundation.

Congress, however, is no more likely to take the Administration's request seriously this year than it did last year, when it killed a proposed 17 percent increase for the NSF. As a result the NSF had to delay for at least a year its program to create 15 science and technology centers at universities. In February, Erich Bloch, the agency's director, noted the growth in basic-research spending in Japan by way of comparison and said the "serious shortfall" in the level of support for the NSF was "not what we need...for a change to a knowledge-based society."

Full redress is not likely in fiscal 1989, in spite of the generous budget. Under the budget "summit" agreement reached at the end of last year, the Federal budget for 1989 can include at most a $3-billion increase in nonmilitary discretionary domestic spending. The proposed increases for research and development, together with increases for space-shuttle operations and development of the space station, exceed that figure; Congress would therefore have to make cuts in popular domestic programs to support the buildup. Congressional staff in both Houses see virtually no chance of such cuts, particularly in an election year. During a hearing on the science budget, Rep. Robert A. Roe, chairman of the House of Representatives' Science and Technology Committee, described the Administration's request as "an exercise in voodoo R&D budgeting."

Roe did promise a reexamination of priorities in research spending, which might mean better treatment for the NSF this year at the expense of other projects or agencies. The SSC seems to be the most vulnerable, both because the $363 million requested is the first major outlay for the project and because the decrease in the number of potential sites for the high-tech behemoth, now down to seven, has limited its political allure. Trapped between the Scylla of cuts in domestic programs and the Charybdis of the budget deficit, Congress will be sorely tempted to delay construction and keep the project alive on a slow drip of research funds, as it did this year.

One kind of spending many scientists would curb takes the form of earkmarked appropriations for specific university projects. Last year more than $250 million was awarded through such "pork barrel" amendments to the appropriations for the departments of Defense and Energy. The practice is deplored by the departments themselves and by most academics since projects thus funded avoid independent peer review. Nevertheless, growing financial pressures are leading some "have not" institutions to lobby their elected representatives directly, and there is no sign that Congress will prohibit the practice.

Concern about Soviet progress in space will probably ensure that the National Aeronautics and Space Administration gets a large part of the $2.5-billion total increase proposed for the agency. New items in the NASA budget include $100 million for Pathfinder, a research program to investigate technologies for manned exploration of the solar system, and $27 million for the Advanced X-Ray Astrophysics Facility, a satellite X-ray observatory.

Elsewhere the Administration has broken with convention by proposing a budget increase for the National Institutes of Health; normally it simply relies on Congress to legislate an increase on its own. The NIH increase joins a $410-million increase in spending on AIDS research and prevention. Congressional concern about the disease makes it quite likely the latter request will be met in full. In other, less emotive areas of the R&D budget the politics of a presidential-election year make prediction difficult. —*Tim Beardsley*

PHYSICAL SCIENCES

Cosmic Forgery

Can black holes, like supernovas, make elements?

Supernova 1987A recently provided spectacular proof that exploding stars forge light elements into heavy ones and fling them through space. The event finally settles the question of how the metals found in the earth and elsewhere in the solar system were originally created.

Or does it? W. David Arnett and Liping Jin of the University of Chicago's Enrico Fermi Institute and Sandip K. Chakrabarti of the California Institute of Technology propose that heavy elements may also spring from another extraordinarily powerful phenomenon: a black hole.

According to theory, matter caught in the gravitational field of a black hole often spirals violently around it before finally plunging into it. If the matter has enough angular momentum, it may form an "accretion disk" around the black hole. "You get close to the dragon's mouth," Arnett says, "but you don't quite get in."

Working with computers, the three investigators have modeled the thermodynamic conditions in accretion disks, altering such parameters as the mass of the black hole and the composition of the matter feeding into the disk. The models suggest that some accretion disks could be

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sufficiently dense and hot for thermonuclear fusion to occur.

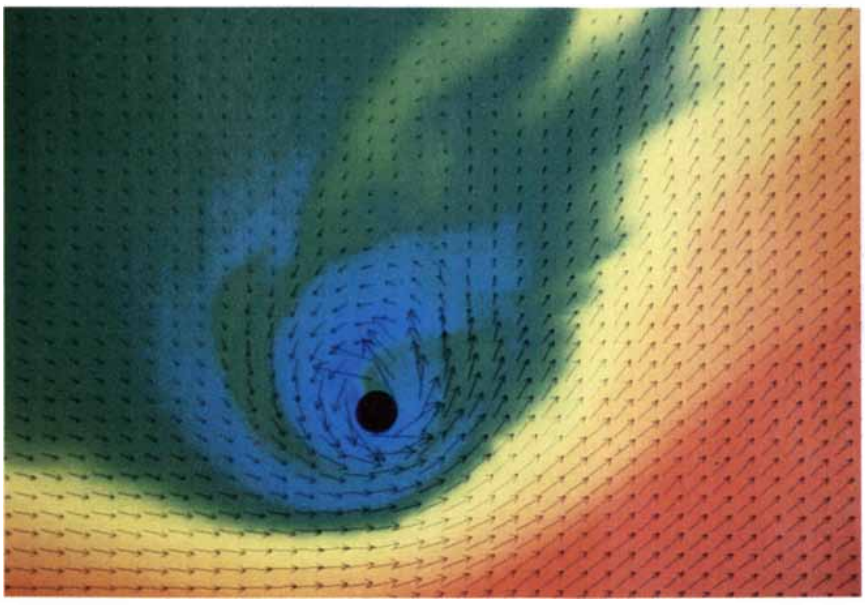
Conditions are most conducive for nucleosynthesis, the workers maintain, in the accretion disk of a relatively low-mass black hole—perhaps the remnant of a single collapsed star; temperatures at the center of the disk could rise above one billion degrees Celsius, hot enough to spawn metals. As the black hole accumulates mass, the density and temperature of its accretion disk apparently diminish. Nevertheless, the group proposes that accretion disks of even so-called supermassive black holes—consisting of a million or more solar masses and thought to exist at the heart of quasars and many galaxies—could convert hydrogen into helium and produce small amounts of heavier elements.

How are the elements forged in an accretion disk distributed through space? Some workers, Arnett points out, believe intense radiation may cause a disk to eject matter in a direction perpendicular to its plane. This hypothesis has been advanced to explain the vast "jets" spewing from some galaxies and binary-star systems. Spectroscopic data suggest that some of these jets may contain heavy elements.

Jin speculates that some of the metals observed in the solar system and elsewhere in the Milky Way may have been produced by a black hole at the center of the galaxy when it was first forming. He also says that black-hole nucleosynthesis may explain why some extremely old stars in our galaxy contain elements heavier than any thought to have been made in the big bang. Perhaps the most radical of the group's proposals is that some of the helium thought to have been forged in the early stages of the big bang was actually generated later by black holes. The cosmic abundance of helium is one of the underpinnings of the standard big-bang model.

Other investigators who have studied accretion disks are somewhat skeptical. Douglas N. C. Lin of the University of California at Santa Cruz maintains that before an accretion disk becomes hot enough to promote nucleosynthesis it will expand and cool. Bohdan Paczynski of Princeton University points out that jets—the primary observational evidence cited by Arnett, Jin and Chakrabarti—are an "unsolved puzzle." Arnett concedes "there are a number of gaps in our understanding." He contends, however, that more hard data—for example better spectroscopic analyses of cosmic jets—may help to fill in the gaps: "We need the observationists to take over." —*J.H.*

Metals such as those that enrich the solar system may spring from the maelstrom near a black hole



GASEOUS ACCRETION DISK swirls around an object with a powerful gravitational field in a simulation done on a computer by Bruce A. Fryxell of the University of Chicago. Relatively low-density gas (red) *becomes denser* (blue) *as it approaches the object.*

Deeply Moved

Convection may shape properties of the inner core

Under terra firma all is flux. Continents drift, the underlying mantle moves in slow currents of rock and the liquid metal of the outer core circulates, generating the earth's magnetic field. Now it seems that the inner core—the earth's hard kernel—may also flow. Writing in *Geophysical Research Letters,* Raymond Jeanloz and Hans-Rudolf Wenk of the University of California at Berkeley propose that certain seismological anomalies are the signature of a circulation pattern that slowly works the solid, iron-rich alloy of the inner core.

A little more than a year ago other geophysicists reported that when pressure waves from earthquakes and whole-earth oscillations penetrate the inner core, they seem to propagate faster along a pole-to-pole path than they do across the equatorial plane. The inner core, it appears, is slightly less compressible parallel to the earth's rotation axis than it is across the Equator.

Jeanloz and Wenk speculated that the explanation might involve the crystal structure of the iron in the inner core. At very high pressures atoms of iron adopt an arrangement known as hexagonal closest-packed (hcp), forming crystals that resemble tiny hexagonal tiles. These "tiles" are harder to compress in a direction parallel to their hexagonal faces than they are in the perpendicular direction. If the crystals in the inner core were aligned so that on the average their hexagonal faces paralleled the earth's axis, their properties might account for the seismological findings. The workers argue that such alignment does prevail. They think it is the result of shear forces generated by a heat-driven convective flow.

The tendency of a body of material to lose heat by convection (rather than by conduction) is expressed in its Rayleigh number, which in part indicates how readily a particle heated deep within the material can travel to the surface to lose heat. In estimating the Rayleigh number for the inner core, Jeanloz and Wenk considered such factors as its radius (1,200 kilometers), iron's thermal conductivity and rate of expansion with increasing temperature, and the amount of heat that might be produced in the inner core by radioactivity. The investigators also had to esti-

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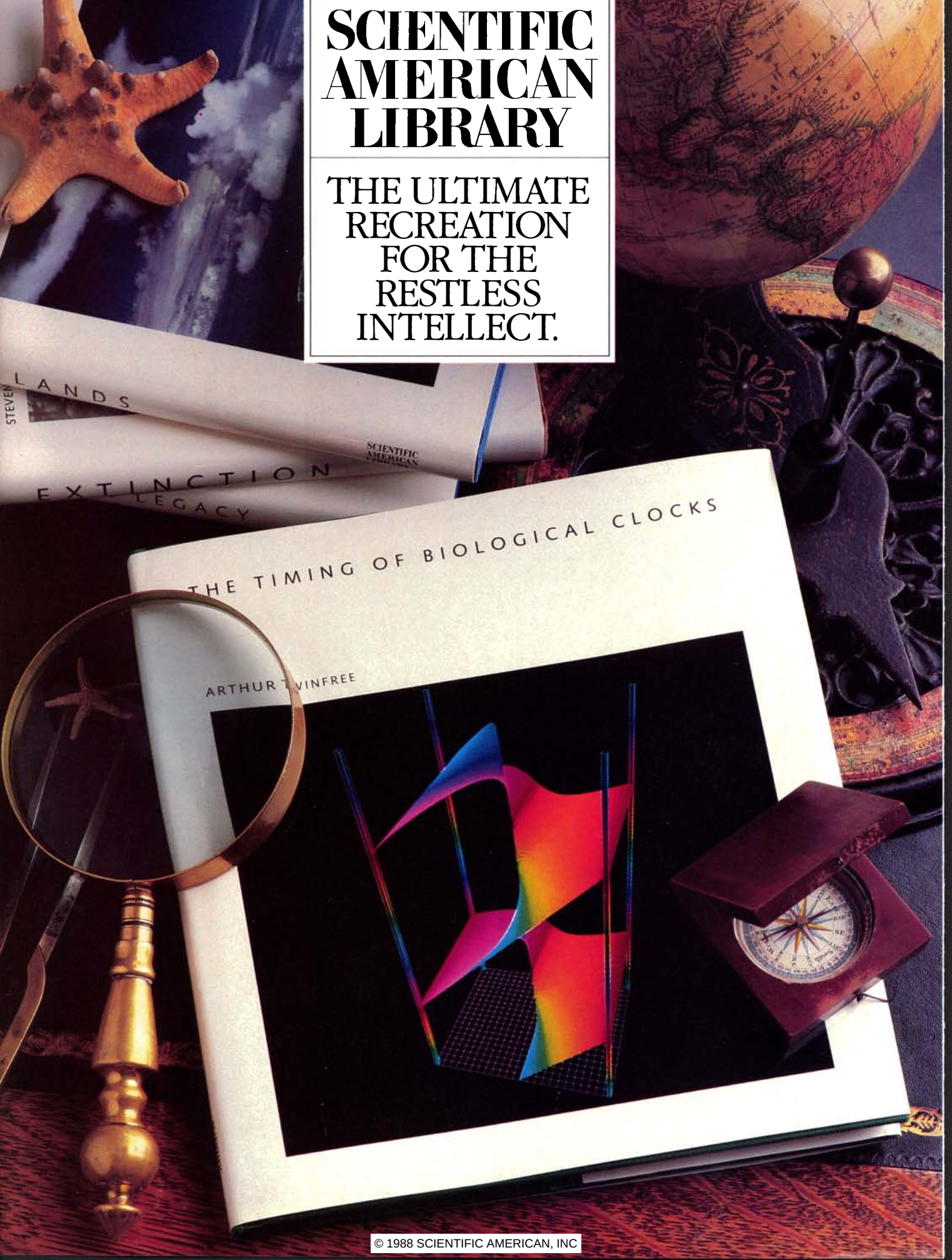
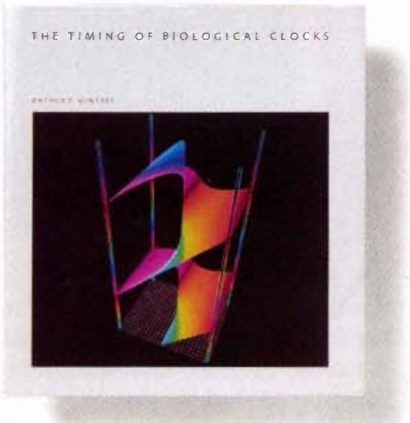


THE TIMING OF BIOLOGICAL CLOCKS

Arthur T. Winfree

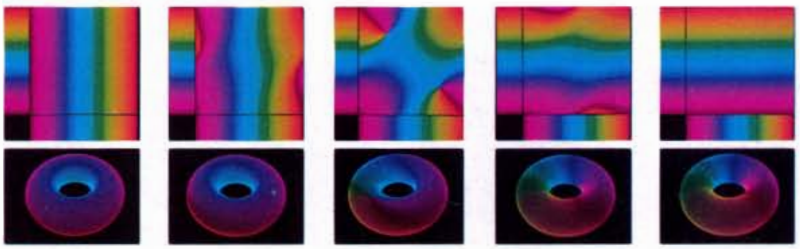


In 1931, Wiley Post flew around the world in eight days and became the first human being to experience jet lag. The fatigue and disorientation he felt happens to all of us when rapid long-distance travel knocks our "internal clocks"—our

In the early 1930s, Wiley Post used the Winnie Mae to study jet lag and its effect on pilot performance. Courtesy of the National Air & Space Museum, Smithsonian Institution.

circadian rhythms—out of kilter with local time. Arthur Winfree describes jet lag as "that disconcerting sensation of time travelers that their organs are strewn across a dozen time zones while their empty skins forge boldly into the future."

Jet lag, biorhythms, mosquito insomnia, temporal isolation experiments, the sleep movement of plants, "forbidden phases" of sleep when one cannot awake spontaneously—these are some of the many fascinating aspects of circadian rhythms that Dr. Winfree explores in *The Timing of Biological Clocks.*



Winfree's innovative use of gradient color to express the passage of time helps us visualize the biological cycles that govern the processes of life. Courtesy of Arthur Winfree.

Winfree shows that the most critical property of biological clocks is their ability to be reset on cue, enabling them to regain synchrony with a changing environment (as when we travel across

Flowering in the morning glory, as in many other plants, is timed by a circadian clock. Courtesy of Travis Amos.

time zones) or to adjust the body's 25-hour rhythm to the 24-hour solar day.

Reporting experiments on animals, plants, and single cells, he not only illustrates the principles that guide the resetting of biological clocks but reveals that each of these clocks has a vulnerable phase when a suitably intense cueing stimulus can produce a thoroughly unpredictable resetting—perhaps even annihilating the clock's rhythm entirely.

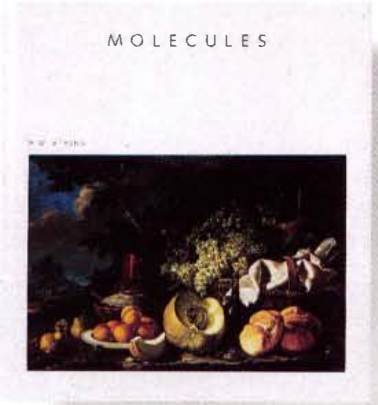
The graphics that Winfree uses are as innovative as his insights. By using gradient color rather than the conventional clock dial to express the passage of time, Winfree helps us visualize the true continuities—and discontinuities—of the internal cycles that govern the processes of life.

Has this cave salamander, living in temporal isolation, lost its circadian rhythmicity? Courtesy of Chip Clark.

Arthur T. Winfree is one of the world's foremost theoreticians of circadian rhythms. Trained as a biophysicist, Winfree received a MacArthur Grant for his work on biological clocks. Formerly at the Institute for Nonlinear Science at the University of California at San Diego, he is now with the Department of Ecology and Evolution at the University of Arizona at Tucson. Professor Winfree is also the author of the classic work *The Geometry of Biological Time* and *When Time Breaks Down,* a technical monograph on circadian rhythms.

199 PAGES, 233 ILLUSTRATIONS

P. W. Atkins



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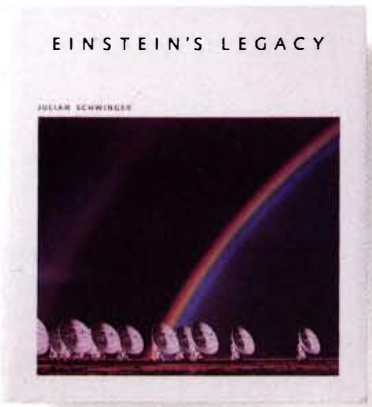
P. W. Atkins lectures in physical chemistry at the University of Oxford. He is the author of *The Second Law* (for the Scientific American Library) and the widely used textbook *Physical Chemistry,* now in its third edition.

256 PAGES, 290 ILLUSTRATIONS

Julian Schwinger



Nobel laureate Julian Schwinger tells the captivating story behind one of the twentieth century's greatest achievements, the theory of relativity.

The groundwork was laid first by Isaac Newton and then by James Clerk Maxwell. But it was left to the sixteen-year-old Einstein to glimpse, for the first time, that the unifying theories of these two giants were incompatible.

In a lively and compelling narrative, Schwinger recounts Einstein's quest for the reconciliation of the conflict—a quest that ultimately led to the unification of matter and energy and of space and time in Einstein's special and general theories of relativity.

Schwinger carries this story to the space-age experiments that have been designed to confirm Einstein's legacy—and possibly lead to a still more comprehensive theory.

Julian Schwinger was awarded the Einstein Prize in 1951, the National Medal of Science in 1964, and the Nobel Prize for Physics in 1965. He is currently University Professor of the University of California.

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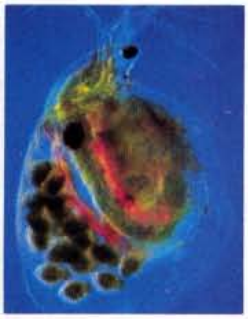

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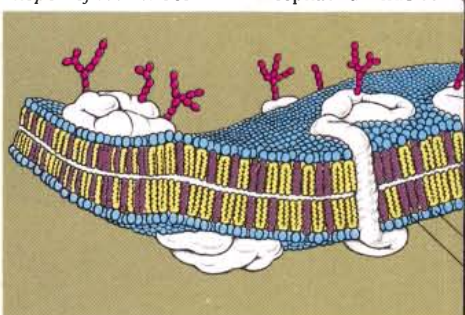

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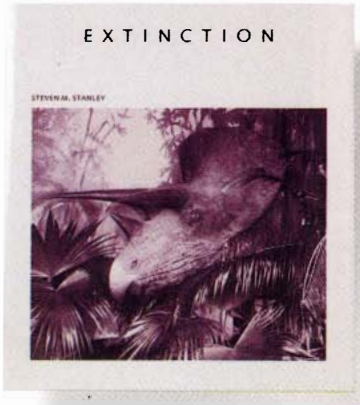
EXTINCTION

Steven M. Stanley



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Steven M. Stanley, professor of paleobiology and director of graduate studies at Johns Hopkins University, is a Guggenheim Fellow and winner of the Schuchert Award of the Paleontological Society.

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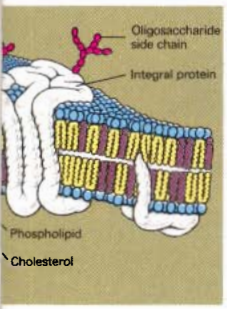

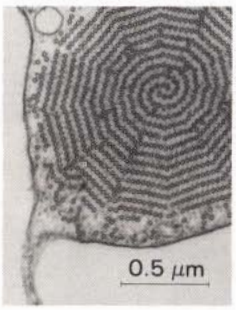

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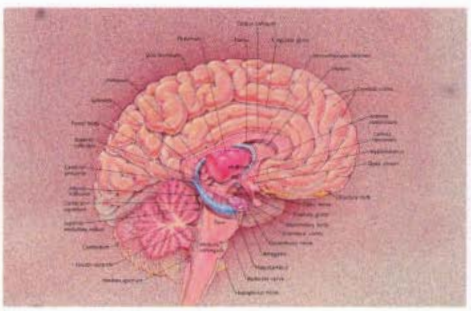

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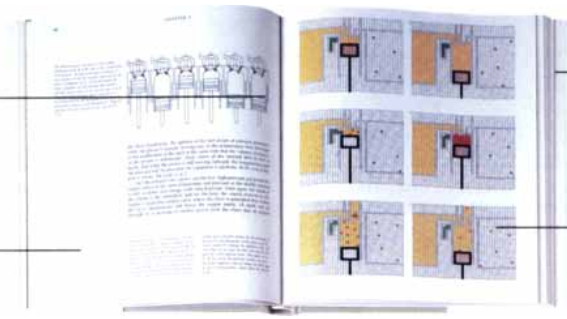

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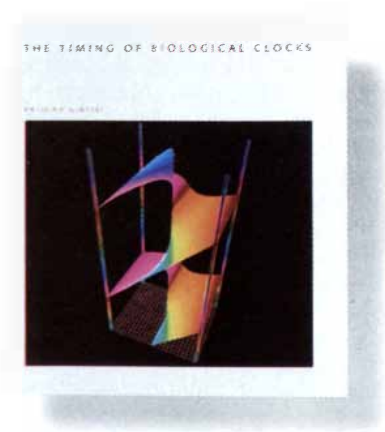

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mate the viscosity of solid iron under the conditions of the inner core: a pressure of several million atmospheres and a temperature of perhaps 6,600 degrees Kelvin. They arrived at a Rayleigh number at least 100 times larger than the value at which convection would begin in a spherical body such as the inner core.

In predicting how the convective circulation might affect crystal orientation, the workers assumed the simplest convection pattern possible: hot material wells up at one pole, loses heat as it circulates laterally to the other pole and sinks. The rate of lateral flow would vary with depth, subjecting the iron to shear.

Theoretical calculations combined with data on the behavior of metals that have a hexagonal structure at ordinary pressures suggested that the shear might align the crystals of hcp iron enough to account for the seismological results. Thus pressure waves traveling from pole to pole would tend to propagate through the crystals parallel to their hexagonal faces—the direction in which they are the least compressible—and so would propagate faster than waves following other paths.

Jeanloz and Wenk acknowledge that their hypothesis can account for the seismological observations only if the overall flow in the inner core were aligned with the earth's spin axis, which is plausible but by no means certain. Even if their analysis cannot definitively resolve the seismological puzzle, however, it casts serious doubt on the rigidity of the inner core over geologic spans of time. *—Tim Appenzeller*

Paste and Cut

A tunneling microscope can cleave molecules

When is a microscope not a microscope? When it is a knife, according to a report in *Nature* by John S. Foster, Jane E. Frommer and Patrick C. Arnett of the IBM Almaden Research Center in San Jose, Calif. With a scanning tunneling microscope (STM) these investigators have apparently made the finest cut ever. They seem to have pinned a single molecule to a graphite surface and then cut the molecule apart.

The STM can create atomic-scale images of the structure of various surfaces. It is essentially a very sharp tungsten needle whose position is minutely controlled by piezoelectric supports. The needle is held about 10 angstrom units, or a billionth of a meter, away from the surface being scanned, and a small voltage difference is established between the two. Electrons then quantum-mechanically "tunnel" through the gap between the surface and the needle at a rate that is an exact measure of the distance. As the needle follows the surface, maintaining just the right separation for tunneling to take place continuously, the current of tunneling electrons can be translated into a three-dimensional map of the surface's topography. Bumps on the map represent individual atoms.

Foster and his colleagues took advantage of the fact that the needle is not simply an accurate probe of a surface's shape; it can also deliver a very precise voltage to an extremely small area. The workers covered a graphite surface with a drop of an organic liquid called di(2-ethylhexyl) phthalate and scanned the surface with an STM. During the scanning they applied a brief pulse of relatively high voltage to the needle. Immediately afterward, scanning revealed a large lump on the surface, about the size of a di(2-ethylhexyl) phthalate molecule. The IBM workers hypothesize that the voltage pulse gave the molecule enough energy to form a chemical bond with the graphite. In other experiments they found that similar pulses could have the opposite effect, releasing a pinned molecule.

The pulses could not only capture molecules, it seemed, but also cleave them. The investigators used a voltage pulse to pin a molecule of dimethyl phthalate—a compound related to di(2-ethylhexyl) phthalate—to graphite. When they applied a pulse to the resulting lumpy shape, the shape became smaller—as if some of the molecule had been stripped off. The remaining lump was the size and shape of a benzene ring, a component of dimethyl phthalate.

The investigators stress that their interpretation, namely that the voltage pulses pinned and cleaved organic molecules, is not necessarily the correct one. They know for certain that they created molecule-size bumps on a surface and reduced large bumps to smaller ones, but the bumps could result from interactions between the needle and the graphite. If the workers are right, however, they may have opened the door to a technology for manipulation of materials on the smallest scale. *—Ari W. Epstein*

BIOLOGICAL SCIENCES

New Kinship for Old Cells

One biologist goes out on a limb to change the evolutionary tree

Teeth and bones, fossils and sediment, fragments of amber that hold prisoners from the past: such is the traditional evidence from which evolutionary origins are deduced. Not much remains of the single-cell creatures that were the earth's first inhabitants. To construct the family trees of these ancient ancestors, biologists rely on statistical comparisons of the genes in existing unicellular organisms.

One such analysis has provoked a spirited debate. Published in *Nature* by James A. Lake of the University of California at Los Angeles, the analysis challenges the firmly entrenched distinction between eukaryotes (organisms whose cells have nuclei) and prokaryotes (whose cells do not have nuclei). The two "superkingdoms" are thought to represent the primary division between life forms, a rift more fundamental than the one that separates the plant and animal kingdoms.

In Lake's tree a branch of the prokaryotes known as the eocytes is grouped instead with the eukaryotes; Lake says that, nucleus or no nucleus, the eocytes are more closely related to members of the eukaryotic clan than they are to other prokaryotes. He wants to redefine the superkingdoms according to this radical phylogeny, calling eocytes and eukaryotes the "karyotes" and dubbing all other organisms the "parkaryotes."

In the same paper Lake makes the bold assertion that his methodology has established the cell at the root of the tree: the "last common ancestor" shared by all living things. The cell, he says, probably metabolized sulfur and lived at temperatures greater than 175 degrees Fahrenheit more than three and a half billion years ago. Although hot sulfur springs have been considered a likely cradle for evolution, many of Lake's peers are skeptical of his new math and

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therefore question the scope of his conclusions.

"I'm very concerned that what he is using in constructing his trees is essentially noise," says Gary J. Olsen, a molecular biologist at Indiana University. Olsen and his colleague Carl R. Woese at the University of Illinois at Urbana-Champaign are the chief advocates of the prokaryote-eukaryote tree Lake's paper would discredit. Olsen's methodology has its own shortcomings and has not been able to specify the ancestral cell. Notwithstanding, Olsen distrusts Lake's claims. "I still don't think we know what the root of the tree is," he says. "I would love to know it, but this just isn't the way to get it."

Both camps deduce their trees from analyses of a ubiquitous cell organelle called the ribosome. Ribosomes are made in part from strands of RNA, a nucleic acid like DNA that reflects the genetic heritage of a cell. RNA consists of a sequence of molecular units called nucleotides. Biologists can infer how closely two or more species are related by comparing statistically the variations among ribosomal nucleotide sequences.

Unfortunately most standard techniques for inferring trees are plagued by unequal-rate effects, a bias introduced when species that evolve at different rates are compared. Lake's algorithm seems to eliminate these effects, but Olsen asserts that it rests on several dubious assumptions that render the analysis "phenomenally misleading."

Other investigators are more generous to Lake's methodology. "As a statistical method, it is not yet in its final form," says Joseph Felsenstein, a geneticist at the University of Washington, "but I think the basic idea underlying it is correct." He points out that objective scrutiny is probably not the sole source of rancor. "You're talking about getting credit for discovering a kingdom, so you can imagine the amount of ego invested."

Olsen acknowledges that the debate has gone beyond purely professional disagreement. "At times," he says, "it's depressing how personal it's gotten." But Lake is not daunted by the controversy; he passes it off as a natural, "extremely positive" companion to any major revision in taxonomic categorization. If nothing else, Lake's perspective may extract more rigorous methods of analysis from those who are reluctant to let him have the last word on the last common ancestor. —*Karen Wright*

Creatures of the Quarry

A remarkable fossil site draws paleontologists to Mexico

In 1964 Don Miguel Aranguty opened a flagstone quarry near Tepexi de Rodriguez, in the state of Puebla in southern Mexico. When Don Miguel, and later his five sons, found fossil remains of fish and other animals in the reddish laminated limestone, they at first gave them away as decorative curiosities. Then, in 1980, they showed samples of the fossils to investigators from the Institute of Geology at the National Autonomous University of Mexico.

Today the quarry near Tepexi, which is still being worked by Don Miguel and his family, is recognized as "potentially one of the world's most significant new paleontological finds," according to Lance Grande of the Field Museum of Natural History in Chicago. So far more than 4,000 fossils have been harvested from the 115-million-year-old limestone, including dozens of new species and families that promise to shed important new light on the evolution of numerous animal groups. President Miguel de la Madrid Hurtado has visited the site and promised national support for its exploration.

The quarry was first investigated by Shelton P. Applegate of the University of Mexico and George Callison of California State University at Long Beach, with funding from the National Geographic Society. More recently the National Science Foundation has also supported excavations there. Applegate has trained the Aranguty family as fossil spotters. When they come on a fossil, which is by all accounts quite often, they put it aside and record where it was found—"community paleontology," Applegate calls it.

The Tepexi fossil beds are unique because there are no other sites from that time—the early Cretaceous period—in North America, according to David Bardack of the University of Illinois at Chicago Circle. The early Cretaceous is of particular interest because many animal groups that are now dominant first appeared then. The site is geologically similar to the famous Solnhofen deposits in West Germany, where the best *Archaeopteryx* specimen was discovered, but the diversity and the sheer number of fossils at Tepexi (Applegate estimates about one per cubic meter) is unprecedented.

Fishes—including various preteleosts, ancestors of modern bony fishes—are the most prominently represented, with more than 30 new species. For some species the site has yielded a complete developmental series from hatchling to adult—a paleontologist's dream. There are also extinct reptiles, including lizards, a turtle, a crocodilian, a pleurosaur and a pterosaur. In addition, Tepexi has revealed many new species of invertebrates, including crabs. Even soft-bodied organisms have been found, among them anemones, sea cucumbers and a segmented bristle-bearing worm. Many of the fossils are intact and astonishingly well preserved: in some of the fish even the stomach contents can be examined. Grande

The treasures found near Tepexi will fill a gap in the fossil record of evolution in North America

FOSSIL IMPRESSION of a pipefish about 20 centimeters long was found in laminated limestone hewn from a quarry near Tepexi, Mexico. Photograph by Gale A. Bishop.

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IT'S SOBERING TO THINK THAT KIDS TAKE DRIVING MORE SERIOUSLY THAN SOME ADULTS.

thinks the site must have been a shallow lagoon with a low level of dissolved oxygen, where dead creatures would have settled undisturbed, safe from scavengers.

A museum has been built at Tepexi and more funds are being sought to develop the site. Mexico has too few paleontologists to explore the wealth of material, and so U.S. scientists are joining the effort. Applegate says he wants to "use the site to help Mexico." Key type specimens will, he insists, remain in the country. —*T.M.B.*

SOCIAL SCIENCES

The Oldest Glory

Earliest image of the Stars and Stripes is found in New Jersey

For most people the image of Old Glory is inextricably linked with those of Betsy Ross, the Continental Congress and the Green Mountain Boys. Yet there is surprisingly little evidence that the new flag was actually flown during most of the land battles of the Revolutionary War. Archaeologists in New Jersey have now turned up evidence that the flag may have been carried more widely than has previously been thought. The new evidence consists of a pair of brass plates bearing the earliest known depiction of the Stars and Stripes.

The plates were found during the excavation of a Revolutionary War site at Pluckemin in Somerset County. There, during the winter of 1778–79, Gen. Henry Knox quartered more than 1,000 troops of the Continental Artillery, the Military Stores Department and support groups. The excavation, which has been carried out since 1980 by the Pluckemin Archaeological Project, shows that the encampment was a well-supplied and well-organized military installation, in sharp contrast to the usual picture of the Continental Army.

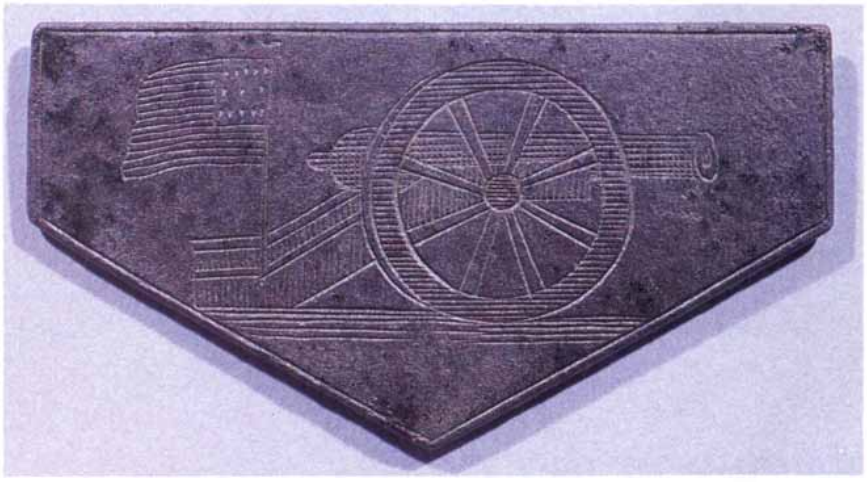
In one corner of the site, near where workshops for blacksmiths, gunsmiths and tinsmiths stood, the two plates were discovered. One was found on the surface, the other just below it. That position suggested they might have been planted recently, according to John L. Seidel of Rutgers University, director of the Pluckemin project. Consequently the plates were subjected to chemical analysis, which showed they were of the same chemical composition as pieces of brass that were excavated at the site and are certainly contemporary with the revolutionary encampment.

Each plate is about two and a quarter inches wide, just the width of the belts from which Continental troops hung their swords and bayonets. Small tabs on the back may have provided a means of attaching the plate to the end of the leather belt. On the front of the plate is an engraved image of a cannon with a flag mounted on the carriage. Although each flag has 13 stars, the unfamiliarity of the image apparently led the engraver to make mistakes: one flag has 14 stripes, the other 12.

Because the site was occupied only briefly, the plates can be dated with precision: between December 7, 1778 (when the artillery arrived at Pluckemin), and early June of the next year, when the troops moved north to begin the spring campaign. That is a period from which no images of the Stars and Stripes are known. Although the design was adopted by the Continental Congress in June, 1777, the earliest depiction of the flag (in the journal of Maj. John Ross) dates from July, 1779; the earliest extant flag was flown during the battle of Guilford Court House in North Carolina in 1781.

Indeed, many historians have argued that the flag was originally adopted as a naval ensign to identify American ships at sea, and paintings of the Stars and Stripes on naval vessels are known dating from late in 1779. The find at Pluckemin, however, suggests that the flag was also flown on land. "It seems to me that you're not going to have depictions like this unless the flag was actually in use," Seidel said. "It appears that the flag was more widely used early in the war than we have thought." —*John Benditt*

The Stars and Stripes may have flown earlier in the War of Independence than historians thought



BRASS PLATE bears the earliest known depiction of the American flag. The plate, some two inches wide, may have decorated a sword belt. It was found in the remains of an encampment at Pluckemin, N.J., that was occupied by artillery troops in the winter of 1778–79. The engraver mistakenly included 14 stripes. Photograph by Chris Burke.

Welfare's Worth

Does it act more as a trap than as a safety net?

Politicians of every genus have vilified welfare. In 1935 Franklin D. Roosevelt, the archetypal liberal Democrat, called it "a narcotic, a subtle destroyer of the human spirit." Earlier this year President Reagan, in his State of the Union Address, charged that welfare is a "poverty trap that wreaks havoc on...the family." Far from alleviating poverty, according to critics, welfare perpetuates it by fostering reliance on the state; those immersed in the "welfare culture," and even their children, are doomed never to escape.

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cized" Federal welfare program—Aid to Families with Dependent Children (AFDC)—does not conform to this view, according to Greg J. Duncan and Martha S. Hill of the University of Michigan's Institute for Social Research and Saul D. Hoffman of the University of Delaware. AFDC, Hoffman recalls, was originally created by Roosevelt to help widows whose husbands had not contributed substantially to Social Security. The program was greatly expanded, in terms of both eligibility and spending, in the late 1960's. In 1986, the last year for which figures are available, the Department of Health and Human Services provided $18 billion in AFDC grants to states, which distributed the funds to 3.8 million families, most of them headed by single women.

The investigators reviewed studies of all families who received AFDC funds between the mid-1960's and the late 1970's and found only a minority were enrolled for long periods: 30 percent were on AFDC for two years or less, 70 percent for seven years or less. These figures, the group reports in *Science,* show the program "does not foster reliance on welfare so much as it acts as insurance against temporary misfortune."

Hoffman says the studies suggest that AFDC serves a diverse clientele with varied backgrounds and needs. Recipients may require assistance after a divorce or the loss of a job, for example, or during a long illness. If a recipient has a high school diploma and work experience and has been married, she generally is enrolled for a relatively short period.

The flip side of this finding is that young, unwed mothers who lack a high school diploma and work experience are indeed likely to remain on welfare for long periods. These women, Duncan points out, account for many of the 30 percent of all AFDC recipients between the mid-1960's and the late 1970's who were enrolled for more than seven years. "They are the essence of the debate over welfare," Duncan remarks. "It's depressing to see that this stereotype does seem to hold."

To reduce the number of long-term recipients, Duncan maintains, more effort should be focused on helping these "unmarried, teen-age mothers." "The crucial first task is to get them to finish high school," he says. Job-training programs, although expensive, can also help them to obtain work, at least part time. Hill notes, however, that some states reduce the incentive to work by taking away a dollar of AFDC benefits for every dollar the recipient earns; if a mother who chooses to work must pay for child care, her net income drops. Either this practice should be given up, Hill contends, or the state should provide child-care programs.

Perhaps the brightest implication of the team's report is that even if efforts to help long-term recipients fail, their offspring are not likely to remain in the welfare "trap." The investigators found that only about one in five of the females reared in families "heavily" dependent on AFDC had become dependent themselves by the time they had reached their mid-twenties. "The stereotype of heavy welfare dependence being routinely passed from mother to child," the group concludes, "is thus contradicted." —*J.H.*

MEDICINE

Damage Control

New biological modifiers boost blood-cell production

Cancer and its treatments chemotherapy and radiotherapy often lower blood-cell counts by suppressing the bone-marrow cells from which blood cells differentiate and mature. Low blood counts also accompany some inherited disorders, and in AIDS both the disorder itself and antiviral drugs such as AZT devastate certain blood-cell populations. Because many of the cells are crucial to the immune defense, the consequence is often a severely reduced resistance to infection.

A promising way to rebuild blood-cell populations has emerged from basic research on the immune system. The research has identified and characterized glycoproteins—naturally present in minute amounts—that stimulate the proliferation and development of blood cells. It is now possible to produce these hematologic growth factors in quantity by genetic engineering. Early trials of their clinical promise are starting to produce encouraging results.

One kind of growth factor that has been extensively tested is erythropoietin, a protein that stimulates the production of the oxygen-carrying red cells. Genetically engineered erythropoietin has already been shown to boost red-cell count in patients who are anemic from dialysis treatment for chronic kidney disease, and it is now being tested in anemic AIDS patients.

Production of some types of white blood cells is stimulated by a group of proteins called colony-stimulating factors (CSF's), of which there are six known varieties. These form a command-and-control system for the immune system, stimulating marrow cells to divide and differentiate into the various specialized white cells. One CSF that is now in clinical trials is granulocyte CSF (G-CSF). It is secreted by white cells called macrophages when they encounter bacteria and causes a rapid increase in the production of granulocytes, another infection-fighting cell.

In a trial in Manchester, England, G-CSF boosted granulocyte counts following chemotherapy in 12 patients with advanced small-cell lung cancer and apparently kept them free of infection. In a more recent trial Janice Gabrilove and Malcolm A. S. Moore of the Memorial Sloan-Kettering Cancer Center in New York found that G-CSF substantially accelerates the recovery of granulocyte counts after chemotherapy in patients who have advanced bladder cancer.

At the Dana-Farber Cancer Institute in Boston, James D. Griffin and Karen Antman found that another member of the CSF family, granulocyte-macrophage CSF (GM-CSF), yielded "certainly encouraging" improvements of white-cell counts in adult sarcoma (bone cancer) patients undergoing aggressive chemotherapy. GM-CSF also improves white-cell counts in myelodysplastic syndrome, a condition that sometimes progresses to leukemia.

Given these results and the fact that CSF's seem to lack significant toxicity, Griffin says, "the big money is on whether this will translate into using chemotherapeutic drugs in new ways and at higher doses." Immune suppression often limits the maximum dose a patient can tolerate. If higher doses could be given, "it would not be irresponsible to speculate that CSF's might improve the cure rates" of some cancers, according to Fred R. Appelbaum of the Fred Hutchinson Cancer Research Center in Seattle.

CSF's may have other uses. They might stimulate the recovery of bone marrow that has been removed from

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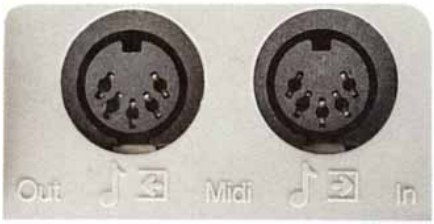

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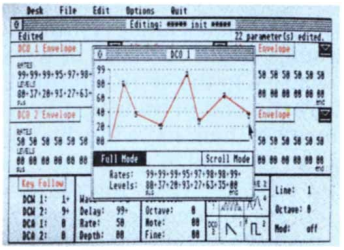

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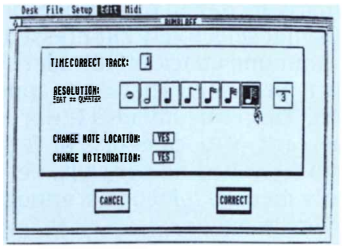

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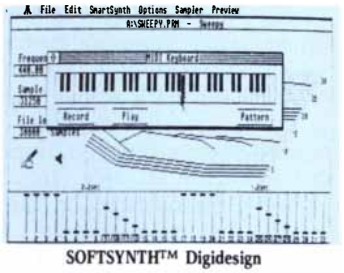

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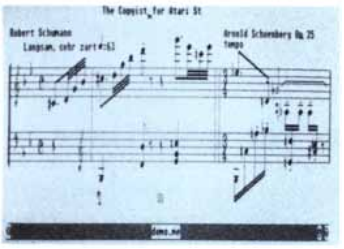

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a patient, stored while the patient undergoes radiotherapy and then replaced—a strategy employed in some leukemias. A combination of GM-CSF and other agents might also help in treating AIDS, according to Jerome E. Groopman of the Harvard Medical School, although CSF's do not stimulate production of *T* lymphocytes (the white cells that are the disease's primary target). Moore thinks CSF's could be a primary treatment for some leukemias. Leukemic cells divide incessantly, as if stuck in an early stage of development; CSF's, Moore says, stimulate some leukemic cells to complete their maturation and stop dividing. —*T.M.B.*

Virtue in Viruses

Infection paradoxically saves mice from a deadly diabetes

My enemy's enemy is my friend. This primordial logic now turns out to apply to viruses, which are generally viewed as irredeemable villains: the protein-wrapped packets of genetic material can replicate only by invading living cells, where they can alter cellular function and cause disease in the host organism. Yet recently an investigator has found a virus that attacks an internal enemy—renegade white blood cells—and so saves the host animal from developing a lethal autoimmune disease.

Michael B. A. Oldstone of the Research Institute of Scripps Clinic in La Jolla reports in *Science* that a form of lymphocytic choriomeningitis virus (LCMV) prevents diabetes in nonobese diabetic mice, which are genetically predisposed to develop the disease. The virus appears to interfere with the animals' immune system, blocking a self-destructive attack on insulin-producing cells in the pancreas. The work raises the intriguing possibility of someday exploiting viral products, just as bacterial and fungal products are used now, to fight disease.

The mice in the study are bred to spontaneously develop insulin-dependent diabetes mellitus, a disease similar to insulin-dependent (type I) diabetes in human beings. It is an autoimmune disorder: certain white blood cells known as *T* lymphocytes, which ordinarily destroy foreign invaders, instead attack the body's own cells—in this case the islet cells of the pancreas, which produce insulin. Unable to make insulin, the mice develop diabetes and eventually die. The mice begin to come down with the disease in the sixth month of life, and by the end of their first year virtually all of them have the disease.

In the early 1970's Oldstone found that a different virus interferes with the course of another autoimmune disease, lupus erythematosus, in mice. He thought the diabetes might similarly be halted by an appropriate virus that selectively suppressed the autoimmune attack on the islet cells. This is precisely what LCMV appears to do. The virus invades fewer than 2 percent of a category of *T* lymphocytes called helper cells, yet this highly focused infection is enough to prevent diabetes.

Once exposed to the virus, the mice are permanently infected and are protected from diabetes for life. Moreover, when lymphocytes from LCMV-infected mice were transferred into uninfected diabetic mice, those mice too did not develop diabetes, even though the infected lymphocytes do not release the virus into the recipient mouse's blood. On the other hand, when lymphocytes from uninfected diabetic mice were transferred into uninfected, prediabetic mice, they caused diabetes. The immune systems of LCMV-infected mice appear to remain otherwise intact, and harmful side effects (mainly the accumulation in tissue of antibody-antigen clusters) are "subtle and minimal," Oldstone says.

Oldstone now hopes to isolate the viral gene or its product—perhaps an enzyme—that is the active component in preventing the autoimmunity. He notes that such viral products not only may lead eventually to the treatment of the illness in humans, but also may "be used as probes to dissect the molecular basis of various nonvirally caused disorders."

Elliot J. Rayfield, a diabetes specialist at the Mount Sinai School of Medicine in New York, says the work may be applicable to the treatment of insulin-dependent diabetes, which strikes 1.5 million people in the U.S., "but a lot more studies need to be done first." He points out that even if an effective viral therapy could be developed, there is still a need for a better genetic marker to identify individuals who are at high risk of developing the illness. —*June Kinoshita*

TECHNOLOGY

Now There Are Three

A new kind of high-temperature superconductor is discovered

Nature's capacity to surprise is apparently not yet exhausted. Just two years ago K. Alex Müller and J. Georg Bednorz of the IBM Zurich Research Laboratory initiated a revolution in physics with their discovery of a high-temperature superconductor based on the rare-earth element lanthanum combined with barium, copper and oxygen. That material had a maximum superconducting temperature, or T_c, of 28 degrees Kelvin, and its discovery won Müller and Bednorz a Nobel prize last year. It has been only a year or so since Paul C. W. Chu of the University of Houston raised the maximum known T_c to 90 degrees K. with a second type of superconductor, which has a related structure and contains the rare earth yttrium instead of lanthanum.

Now workers led by H. Maeda at the Institute of Metallic Material Research in Tsukuba, Japan, have identified a material that defines yet another class of superconductors. The new material does not contain any rare-earth element, it has a different crystal structure from earlier superconductors and it appears to have a T_c above 100 degrees K.

Many variants of the first two types have been investigated over the past two years. Some workers have reported hints of superconductivity well above 90 degrees K., but no such observation has been independently confirmed. After word of the Japanese claims spread in late January, however, other laboratories started fabricating the new material and quickly found signs of superconductivity above 100 degrees K.

The new superconductor is composed of bismuth, strontium, calcium, copper and oxygen; various laboratories report slightly different compositions and structures. Preliminary studies at the AT&T Bell Laboratories, the Argonne National Laboratory and elsewhere suggest that, like the earlier compounds, it is a complex superlattice consisting of sheets of copper and oxygen atoms separated by planes of other components—strontium atoms, calcium atoms and bismuth oxide in this case.

Both the structural similarities and the differences between the new material and earlier superconductors are certain to tantalize theorists seeking to understand how high-temperature superconductivity works.

The new superconductor seems to have two distinct crystal phases. One of them, which has been made in pure form at the Bell Laboratories, superconducts at 84 degrees K. The other, which by late February still had not been purified, appears to have a T_c some 20 degrees or more higher. In addition, Chu has announced a variant of the basic bismuth-containing compound that also includes aluminum.

Large-scale applications of any new superconductor are still years away. Nevertheless, workers such as Angelica M. Stacey of the Lawrence Berkeley Laboratory are encouraged by the fact that the new bismuth compound (in addition to being less expensive than the earlier, yttrium-containing materials) appears to be more ductile and less easily degraded by exposure to the atmosphere than the earlier materials. It may foreshadow future variants that are still more tractable. —*T.M.B.*

Self-Destruct

A new insecticide causes insects to kill themselves

Workers at the University of Illinois at Urbana-Champaign have found a way to kill insects by turning their own metabolism against them. The method may yield a class of cheap, biodegradable and resistanceproof insecticides, according to Constantin A. Rebeiz, John A. Juvik and Carole C. Rebeiz. "Most commercial insecticides attack the nervous system," Constantin Rebeiz says, "but this one is based on a totally different phenomenon."

The insecticide's major component is delta-aminolevulinic acid (ALA), a nontoxic, biodegradable amino acid that is a building block of protoporphyrin, a metal-transporting substance necessary for energy metabolism. The other component is a synthetic chemical "modulator" that appears to accelerate the production of protoporphyrin. When the two chemicals are sprayed on or ingested by an insect, it synthesizes protoporphyrin in such quantities that its metabolism is fatally disrupted.

Prototypes of the insecticide have proved effective in the laboratory against two of the most destructive agricultural pests in the world: the corn earworm and the cabbage looper. The insecticide is particularly deadly if the insects are exposed to light, which triggers the sudden production of oxygen free radicals, poisonous molecules that have an extra electron. Most insects die within 10 seconds after exposure to light; in the dark they usually die within 48 hours, according to Rebeiz.

So far the group has successfully tested two synthetic organic chemicals as modulators: 2,2′-dipyridyl and 1,10-phenanthroline. The workers do not yet know if these modulators are toxic to humans or animals, but now they are experimenting with modulators that (like ALA) occur naturally and are known to be nontoxic. The group is also testing modulators that affect only specific insects.

A species of insect could become immune to an ALA-based insecticide, Rebeiz maintains, only if it developed a metabolism that did not require protoporphyrin—something he says is "very unlikely." —*J.H.*

OVERVIEW

Star-struck?

Impacts' role in the history of life remains contentious

Several times during the past 600 million years something so changed global conditions that a substantial fraction of all species became extinct over a relatively short span of time. In the most celebrated mass extinction, at the end of the Cretaceous period 65 million years ago, more than half of all species may have perished—probably including the last of the dinosaurs. Attempts to explain these events have engendered heated debate.

Much of the heat has been generated by a hypothesis put forward in 1980 by Luis W. Alvarez of the Lawrence Berkeley Laboratory and his colleagues. They proposed that the mass extinction at the end of the Cretaceous was caused by the impact of a mountain-size meteorite or comet. Dust lofted by the collision, Alvarez supposed, would have blotted out sunlight and prevented photosynthesis; most living things would have died within weeks.

The principal evidence was a very thin layer of clay enriched in the element iridium, found precisely at the boundary of the Cretaceous and Tertiary periods (the K-T boundary) at sites all over the world. Iridium is rare in the earth's crust but relatively abundant in some meteorites. Alvarez calculated that a meteorite 10 kilometers in diameter would throw enough iridium-rich dust into the atmosphere to account for the worldwide iridium layer.

Alvarez' theory was strengthened by the discovery of soot in the K-T boundary clay, possibly produced by massive wildfires ignited by the impact. Even more impressive are quartz grains, displaying multiple planes of distortion thought to result from a powerful shock, found last year in the K-T layer at sites around the world by Bruce F. Bohor of the U.S. Geological Survey. This form of quartz had previously been seen only near known impact craters; its global occurrence therefore suggests a global-scale cataclysm.

Where was ground zero? The lack of an obvious K-T impact crater embarrassed proponents of the impact theory for several years, but a 35-kilometer-wide impact structure of just the right age, buried under the fields of Manson, Iowa, is now thought to be a good candidate, even though it is smaller than the 200-kilometer-wide crater Alvarez had predicted. A North American site would explain why shocked quartz grains are orders of magnitude more common, and also larger, at the K-T boundary in North America than they are in Europe, according to Glen A. Izett of the Geological Survey.

Ronald G. Prinn of the Massachusetts Institute of Technology has supplemented the initial asteroid hypothesis with a proposal that the extinctions resulted from acid rain produced by shock heating of the atmosphere. Calculations suggest that a meteorite a few kilometers in diameter would produce enough nitrogen oxides to turn rain over a vast area into a strong solution of nitric acid. J. Douglas Macdougall of the Scripps Institution of Oceanography has found evidence supporting the acid-rain scenario. He detected a sudden change in the isotopic composition of strontium in marine sediments at exactly the K-T boundary, which could have resulted as acid

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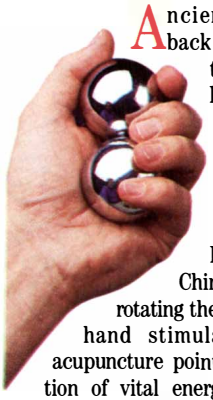

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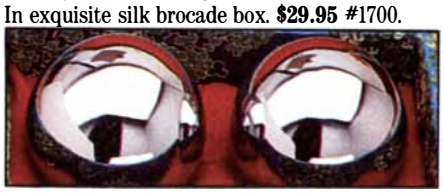

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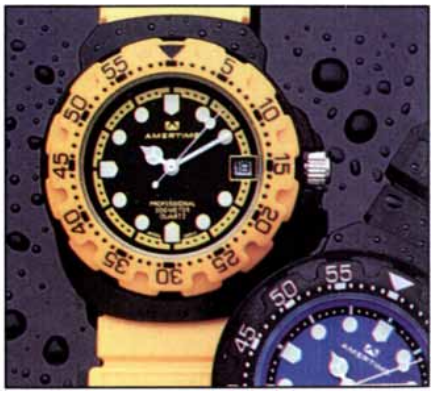

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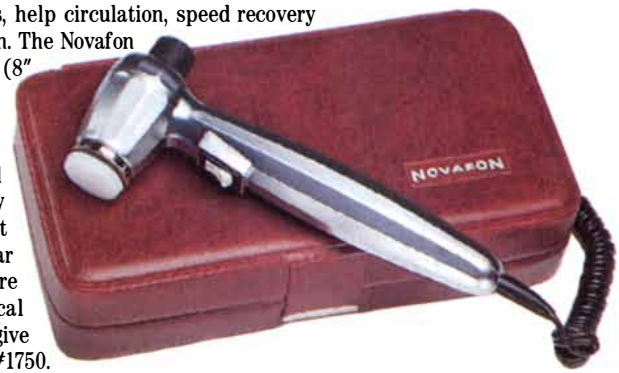

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rain increased the rate of dissolution of strontium from the continents.

Nevertheless, the asteroid theory of K-T extinctions has not been universally accepted. A few dissenters contend that both the extinction and the geologic hallmarks of the K-T boundary resulted from something other than an impact, whereas others (including many paleontologists) do not dispute the geologic evidence for an impact but deny that it caused the global mass extinction.

Charles B. Officer of Dartmouth College and Neville L. Carter of Texas A.&M. University fall into the first camp. They think the prolonged, intense volcanic activity that took place at the end of the Cretaceous, combined with the global lowering of sea level that also occurred then, could have produced both the distinctive geologic features of the K-T boundary and the mass extinction. Officer asserts that the K-T iridium anomaly is not globally uniform and that iridium can be found up to two meters above and below the K-T boundary itself. This pattern indicates that the iridium was not deposited all at once by an impact, Officer argues, but erupted from the earth's mantle over thousands of years; acid rain from the eruptions might have contributed to the extinctions.

Officer and Carter have found what they think is shocked quartz associated with the iridium that occurs far from the boundary. They believe the quartz was shocked by volcanic activity and is evidence that the iridium also originated in volcanoes. Bohor disagrees, saying that Officer and Carter's quartz was deformed by ordinary tectonic activity. He argues that if shock features could be produced by volcanism, they should be common in volcanic rock.

Other dissenters point out that the iridium and the shocked quartz are concentrated at the top of the anomalous boundary clay. Some other global change, they argue, must have been under way before the iridium and quartz were deposited. Some impact theorists deal with the objection by proposing multiple impacts in a very short time—"in the same weekend," Eugene M. Shoemaker of the Geological Survey suggests. The first meteorites might have contained little iridium and landed in the ocean, which lacks quartz, throwing up the debris preserved in the clay layer; a later impact would have laid down the iridium and shocked quartz.

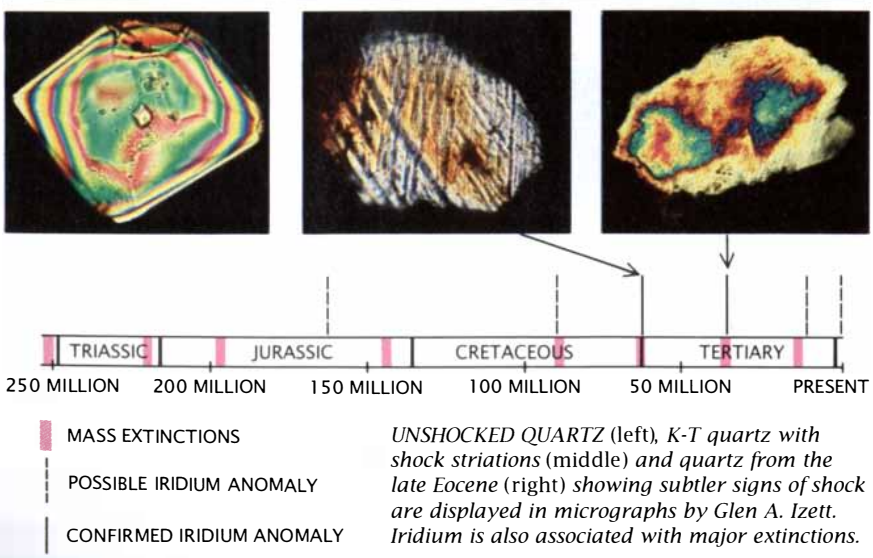
Still other objectors hold that the fossil record does not favor a catastrophic extinction. J. David Archibald of Yale University, who has worked in Montana studying some of the best fossil lineages straddling the K-T boundary, typifies the views of many paleontologists. He argues that many groups died out long before the boundary itself was laid down, and that even if a large impact occurred, it could not explain this prolonged decline. Furthermore, although many marine animals and plankton became extinct at or close to the K-T boundary, along with the dinosaurs and flying reptiles, many land plants, freshwater animals and deep-sea animals survived. He, like Officer and Carter, favors the idea that the K-T extinction resulted from a variety of terrestrial causes.

Indeed, most "mass extinctions" appear to have been complex, multistep events that typically took place over hundreds of thousands of years rather than a few months. Even so, some geologists have attempted to extend the impact explanation to other mass extinctions. Only one other iridium layer in the geologic record is considered definite; it falls in the late Eocene epoch, about 35 million years ago. Recently, shocked quartz has been found at one site off the New Jersey coast at about the same level as this iridium layer. The relation between the presumed impacts and the substantial extinctions that occurred about then is not clear, however. Iridium layers have been found at several other stratigraphic boundaries, some of which apparently coincide with mass extinctions, says David M. Raup of the University of Chicago, but the layers may be only regional in extent.

To reconcile the apparently stepwise nature of mass extinctions with the extraterrestrial-impact theories, workers have proposed that multiple impacts might have taken place over a substantial but geologically brief period of a few hundred thousand years. According to Piet Hut of the Institute for Advanced Study, disturbances of the Oort Cloud, the billions of comets thought to orbit the sun well beyond Pluto, might cause multiple impacts. Calculations indicate that a star passing close to the sun would dislodge millions of comets from the Oort Cloud; some tens of the errant comets would probably strike the earth over a period of one or two million years.

Perhaps the grandest extension of the original Alvarez hypothesis envisions periodic comet showers. In this view a periodic disturbance of the Oort Cloud could explain the 26-million-year periodicity of mass extinctions over the past 250 million years that has been reported by Raup and his colleague J. John Sepkoski, Jr. The statistical analysis that indicated the periodicity is contentious, but the periodic-extinction theory is still "alive and well, if somewhat nervous," according to Raup. A variety of astronomical triggers for the periodic showers, including the solar system's regular passages through the arms of our galaxy and the galactic plane, have been proposed—and disputed. *—Tim Beardsley*

Do microscopic features in quartz grains record the massive shock from meteorite impacts?



UNSHOCKED QUARTZ (left), *K-T quartz with shock striations* (middle) *and quartz from the late Eocene* (right) *showing subtler signs of shock are displayed in micrographs by Glen A. Izett. Iridium is also associated with major extinctions.*

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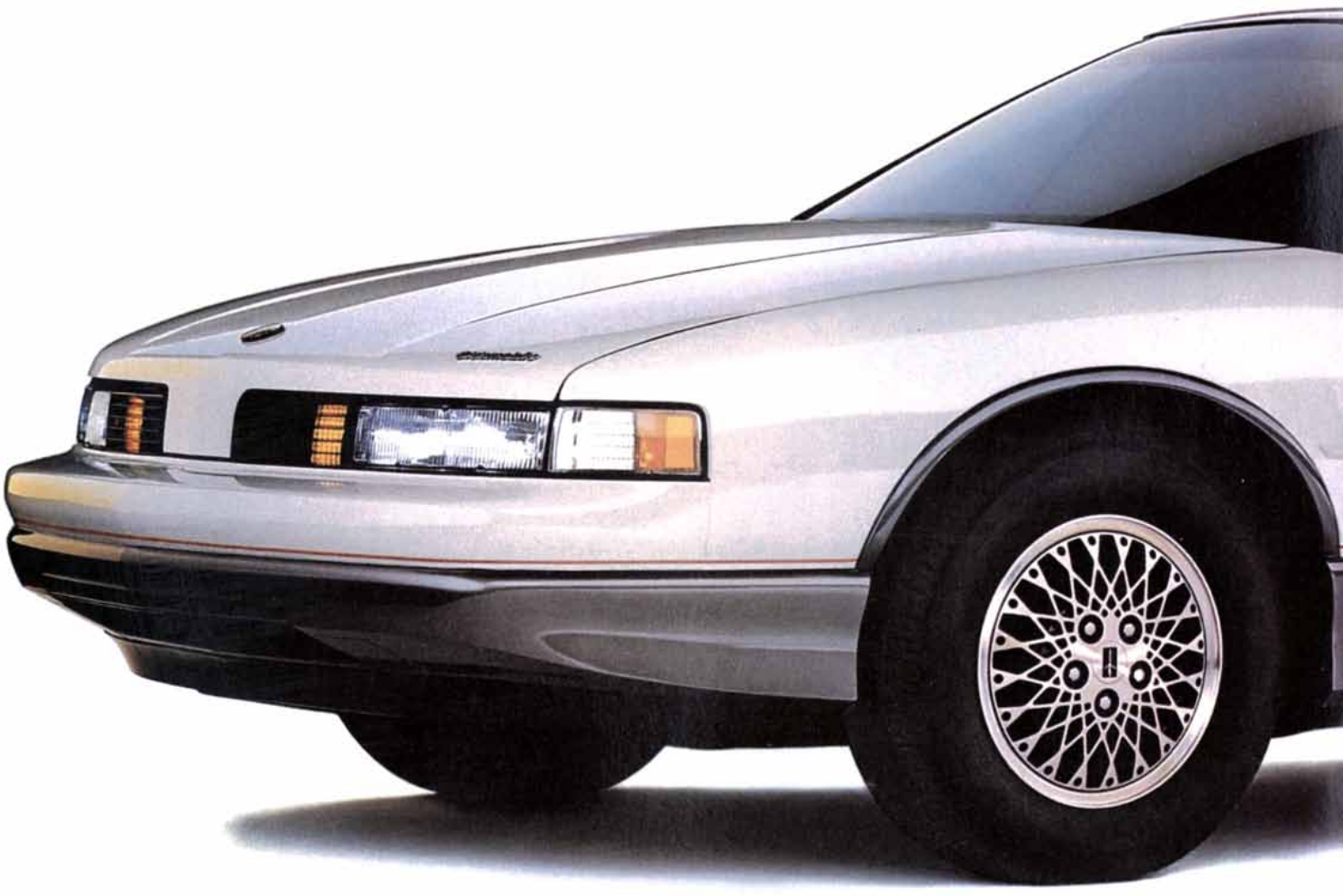

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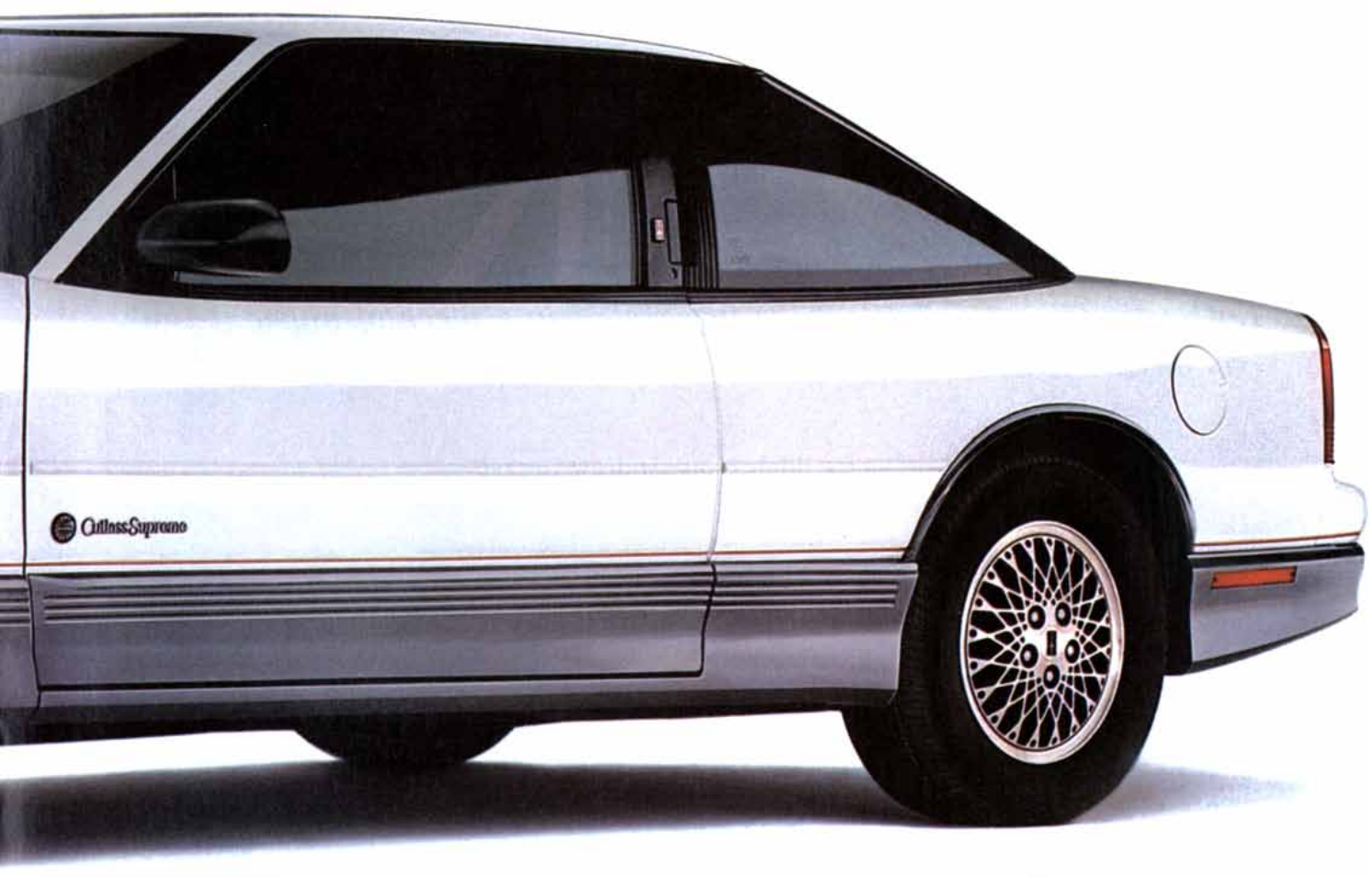

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SCIENTIFIC AMERICAN April 1988 Volume 258 Number 4

Computers in Music

Computers can make sounds that no usual instrument can duplicate. Both varieties of sound can be integrated in a piece of music if the composer works with technicians in articulating the underlying ideas

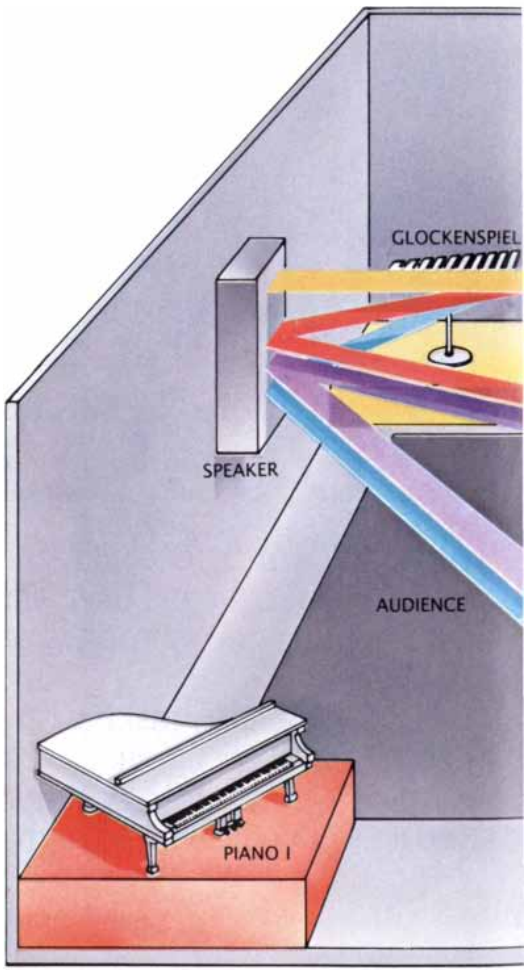
by Pierre Boulez and Andrew Gerzso

Composers have had essentially one medium through which to express their musical ideas in a form an audience can appreciate: the sounds that musicians can elicit from traditional instruments. With the advent of computers and other equipment for processing digital signals an entirely new means of musical expression has become available. A composer who applies these electronic devices is bounded only by imagination in creating an "orchestra" of sounds.

Music that seeks to integrate computer-generated sounds with traditional instruments presents a great challenge to a composer. Not only must the composer express musical ideas convincingly but also he or she must do so in a manner that is readily translatable into both mediums. Moreover, the ideas must be resilient enough to be passed back and forth between the two mediums during the course of a performance. Otherwise the listener might wonder what role the computer was meant to have in relation to the other instruments and be puzzled (and perhaps even repelled) by the lack of coherence.

Exploring possible musical relations between computers and traditional instruments requires much communication between composers and those who design computer hardware and software. Through such collaboration electronic devices can be constructed that serve the composer's immediate purpose while preserving enough generality and flexibility for future musical exploration—a task complicated by the fact that the composition's musical complexity is usually not commensurate with the technical complexity needed for its realization. What appears to be a simple musical problem often defies an easy technological solution. Perhaps for the first time in history a composer has to explain and formalize the way he or she develops and manipulates concepts, themes and relations in a musical context in order for technicians (who may have little musical training) to bring them into existence. These are the kinds of problems we confront at the Institut de Recherche et Coordination Acoustique/Musique (IRCAM). The institute, part of the Centre Georges-Pompidou in Paris, is dedicated to musical and scientific research for the integration of the traditional instrumental medium with the new medium afforded by computers.

The relation between the two mediums can be explored along several different lines. One line of study seeks to model how common instruments produce their characteristic sounds, so that the models can then



"SPATIALIZATION" OF THE SOUNDS produced by six instrumental soloists at their simultaneous entrance in *Répons,* a composition by one of the authors (Boulez), involves circulating each sound among four speakers in a pattern shown by an arrow of a color corresponding to that of the soloist's instrument. The speed with which a sound moves around the performance hall depends directly on the loudness of the sound. Because the sounds of the instruments die out at different rates, the sounds slow down at different rates. Several technicians seated at a panel just behind the orchestral ensemble control the various electronic and audio devices that make such an effect possible.

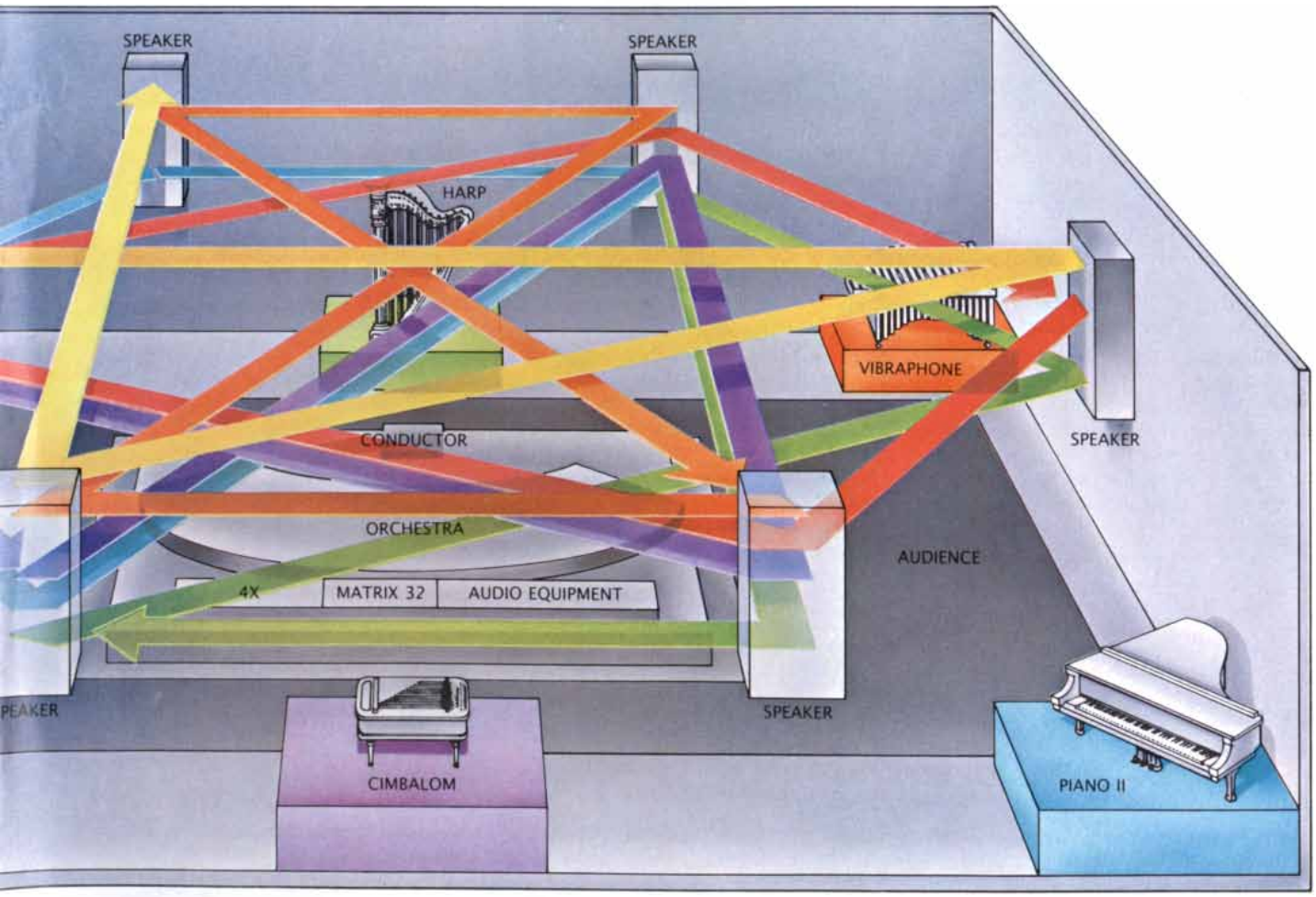
be applied to synthesize a palette of sounds closely or distantly related to the instrumental sounds [see "The Computer as a Musical Instrument," by Max V. Mathews and John R. Pierce; SCIENTIFIC AMERICAN, February, 1987]. The aim is to make it possible for a composer to score music for a computer as though it were a traditional instrument, specifying the kinds of sounds a computer operator is to elicit and when and how they are to be produced. Another line of study searches for ways in which the sound of traditional instruments can be modified. Applying this approach, the music-making capabilities of an entire ensemble can be extended beyond human or instrumental limits in one stroke.

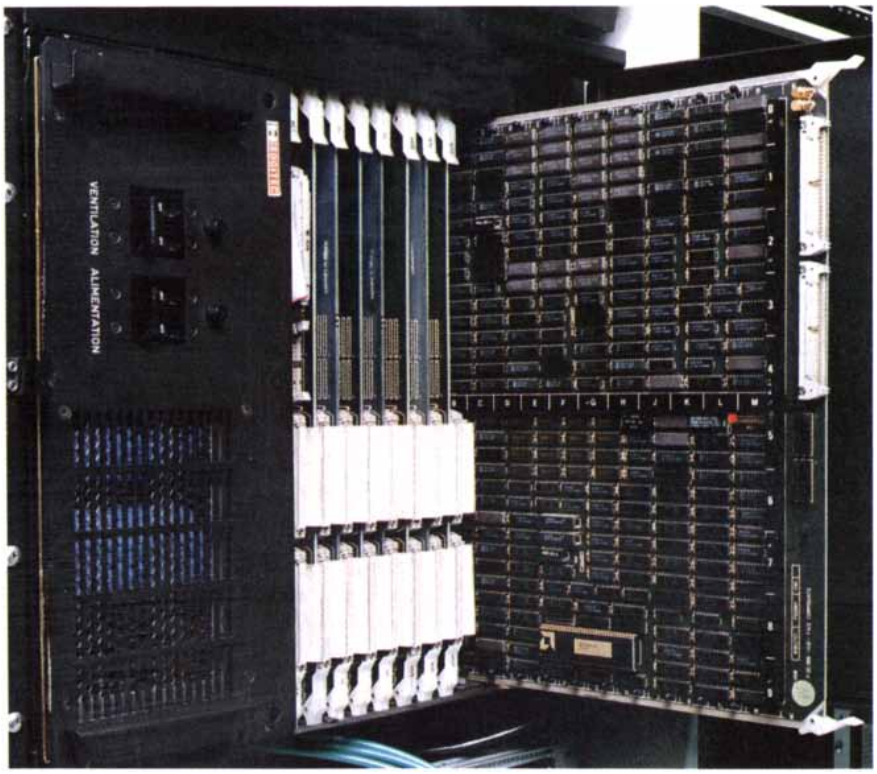
Making a sound with a computer requires generating a sequence of binary numbers, called samples, that describes the sound's waveform: the air-pressure fluctuations of the sound as a function of time. The samples can then be made audible by converting them into a sequence of proportional voltages, "smoothing" and amplifying the stream of discrete voltages and sending the electrical signal to a loudspeaker. The number of samples the computer must generate for each second of sound, called the sampling rate, depends on the highest component frequency of the sound's air-pressure fluctuations. In particular, the sampling rate must be twice the highest component frequency. This, for most purposes, means that if a computer is to synthesize or transform a sound, it must be capable of generating or manipulating in one second between 16,000 and 40,000 samples, each of which can require a number of calculations.

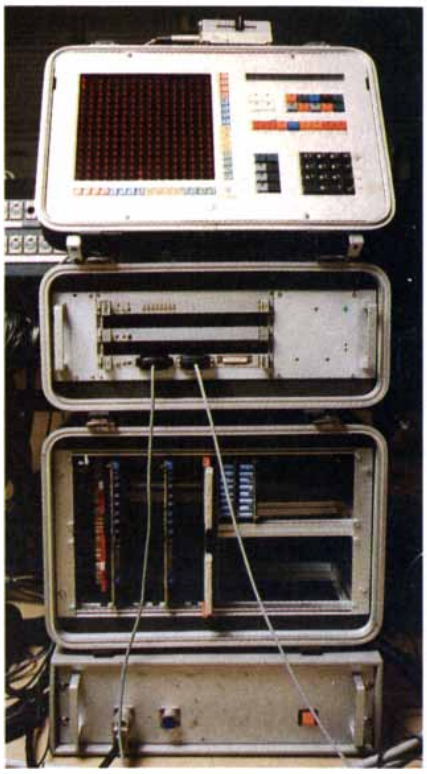
In the past such processing of sounds could be done only rather slowly and painstakingly on a computer. Hence a composer wanting to make use of computer-processed sounds in conjunction with sounds produced by "live" instrumentalists had to first record the processed sounds on tape so that they could later be played back during a performance with the instrumentalists. But a tape recorder lacks the suppleness in timing that is so crucial in live concerts. Give and take with the tempo of a piece is one of the basic features of music. Moreover, prerecorded material may also disappoint people who enjoy seeing musicians playing their instruments on stage.

Today computers are fast and powerful enough to synthesize original sounds or transform instrumental sounds in "real time": in step with the instrumentalists. Composers can now blend the role of the computer with that of the other instruments much more easily and thereby demolish the rather artificial barrier that had often existed between the two types of instruments.

The real-time transformation of instrumental sounds is particularly interesting for several reasons. Altering the sound of traditional instruments after they have been produced by musicians enables a composer to explore unfamiliar musical territory even while scoring for the instruments with which both he and the audience are familiar. The contrast between the familiar and the unfamiliar can thus be readily studied by creating close and distant relations between the scored instrumental passages and their computer-mediated transformation. In addition, since the







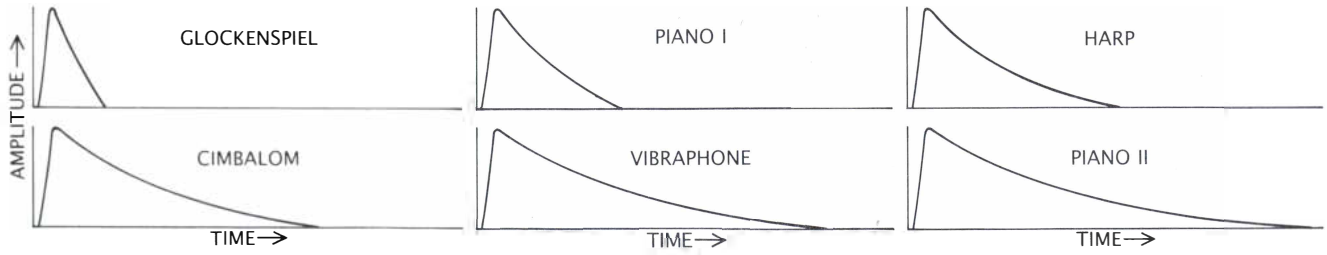
ELECTRONIC DEVICES that have integral roles in performances of *Répons* include the 4X (*left*) and the Matrix 32 (*right*). The 4X consists of eight processor boards each of which can be independently programmed to store, manipulate and recall digitized sound waveforms: sequences of numbers that correspond to the air-pressure fluctuations of a sound. The Matrix 32 is basically a programmable audio-signal traffic controller, routing audio signals from the soloists to the 4X and from the 4X to the speakers.

transformations are done instantaneously, they capture all the spontaneity of public performance (along with its human imperfections).

The equipment for electronically modifying sound in real time has only recently been developed in transportable form, allowing it to be brought into the concert hall. One such device, the 4X, is the fourth generation in a series of real-time digital-signal processors used at IRCAM not only for transforming sounds but also for analyzing and synthesizing them. The prototype was designed and built at IRCAM in 1980 by Giuseppe Di Giugno with assistance from Michel Antin, and the final version was manufactured in 1984 by the French company SOGITEC.

Capable of up to 200 million operations per second, the 4X is made up of eight processor boards, each of which can be independently programmed with any combination of methods for processing digital signals. In a technique known as additive synthesis, for example, musical sounds are generated by adding large numbers of sinusoidal waveforms. Each board in the 4X is capable of generating 129 such waveforms. Each board can also be programmed to have as many as 128 different filters, which can be applied to transform sounds in real time. A processor board also has its own so-called wave-table memory, which allows it to store as much as four seconds of sound and then to play back the sound in any rhythmic pattern.

The basic operations needed to manipulate the digital waveforms are coded in so-called modules, or self-contained subprograms, that can be interconnected so that the output from one module is the input for another. The modules themselves as well as the connections between them are programmed by means of "patches": higher-level programs written in a computer language designed by one of us (Gerzso) and



WAVEFORM ENVELOPES of sounds reflect the way the amplitude, or loudness, of the sounds varies with time. The envelopes produced by each of six solo instruments in *Répons* are similar in shape, displaying a steep attack, or beginning, followed by a gentler decay, or end. The duration of a decay depends on both the pitch of the sound and the instrument on which it is played.

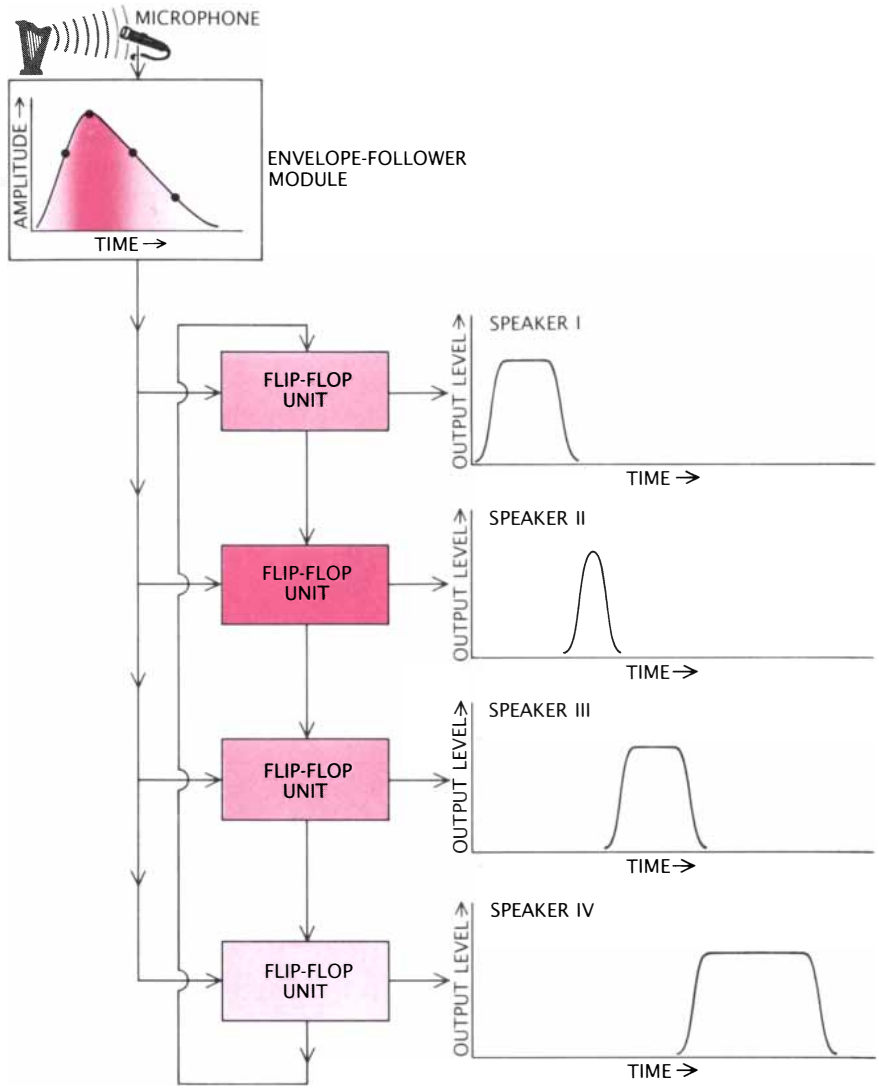
implemented by Patrick Potacsek and Emmanuel Favreau. (The terms "patch" and "module" are holdovers from the days of analog sound synthesizers, which had actual patch cords to interconnect tangible oscillator, amplifier and filter modules.)

Individual patches are stored on a magnetic disk of the 4X's "host" machine and can be loaded into the 4X in half a second or less. The host machine also runs a real-time operating system and event scheduler (developed by Miller Puckette, Michel Fingerhut and Robert Rowe), which tells the 4X what program to run and when. Hence during a musical performance a number of different patches, each of which essentially "rebuilds" the 4X in a fraction of a second, can be loaded on cue. Music demands this kind of flexibility.

Musical performances in a large auditorium also demand flexibility in switching and mixing sounds among speakers. This is the function of another piece of electronic equipment developed at IRCAM: the Matrix 32. The device, designed and built by Michel Starkier and Didier Roncin, serves as a kind of audio-signal traffic controller: it establishes connections between a set of inputs (the signals coming from microphones or the 4X) and a set of ouputs (signals going to the 4X or the speakers) and also specifies the level of the output signals. By means of software written by one of us (Gerzso), it can at any given moment be programmed to route a soloist's sound to a particular speaker for amplification. At another moment it might route the sound of each of several soloists to different module inputs in the 4X and sends the transformed sounds to different speakers. The Matrix 32 can be reconfigured in about a tenth of a second.

Both the 4X and the Matrix 32 have integral roles in *Répons,* a composition by one of us (Boulez) for six instrumental soloists, chamber orchestra and real-time digital-signal processors. The work was commissioned by the Southwest German Radio and premiered in Donaueschingen, West Germany, in 1981. It was most recently performed in 1986 as part of the program in a five-city U.S. tour by the Ensemble InterContemporain, a French avant-garde chamber-music group.

"Répons" is a medieval French term for a specific type of antiphonal choral music: a compositional form in which a soloist's singing is always answered by that of a choir. The term is an apposite name for the contemporary composition, since it explores calls and responses on many different musical levels. In *Répons* one can find all kinds of dialogues: between the soloists and the ensemble, between a single soloist and the other soloists, and between transformed and untransformed passages. Almost all other aspects of music are also involved in such back-and-forth interplay: pitch (the perceived frequency of a tone), rhythm (the pattern and timing of beats), dynamics (the loudness of a tone) and timbre (the characteristic tonal quality of an instrument's sound). Real-time transformations of the solo instruments' sounds are necessary to bring about many of these oppositions. (In order to make the transformations possible all the solo instruments are equipped with microphones. In this way electrical-signal analogues of their sounds are



4X SPATIALIZATION PROGRAM takes the sound that is picked up by a microphone and directs an envelope-follower module, or subprogram, to generate a timing signal (*color*) whose frequency (indicated by the intensity of color) changes in step with changes in the amplitude of the sound's waveform envelope. The timing signal in turn serves as input for four other modules called flip-flop units (FFU's), which control the level of the sound broadcast from each of four speakers. The signal passes from one FFU to the next as one is switched off and the next is switched on. (Only one FFU can be on at any given time.) The signal's frequency determines how long a particular FFU remains on; the higher the frequency is, the sooner the FFU is switched off. In this illustration the timing-signal frequency corresponding to the first point on the envelope controls how long the first FFU is on, the frequency corresponding to the second point on the envelope controls how long the second FFU is on, and so on. By arranging the FFU's in a loop the sound can be made to circulate repeatedly from speaker to speaker at a speed determined by its amplitude. Because the sound level takes some time to rise to its maximum level and to fall back to zero, there is a bit of overlap among the speakers.

instantly available to be processed and sent on to speakers.)

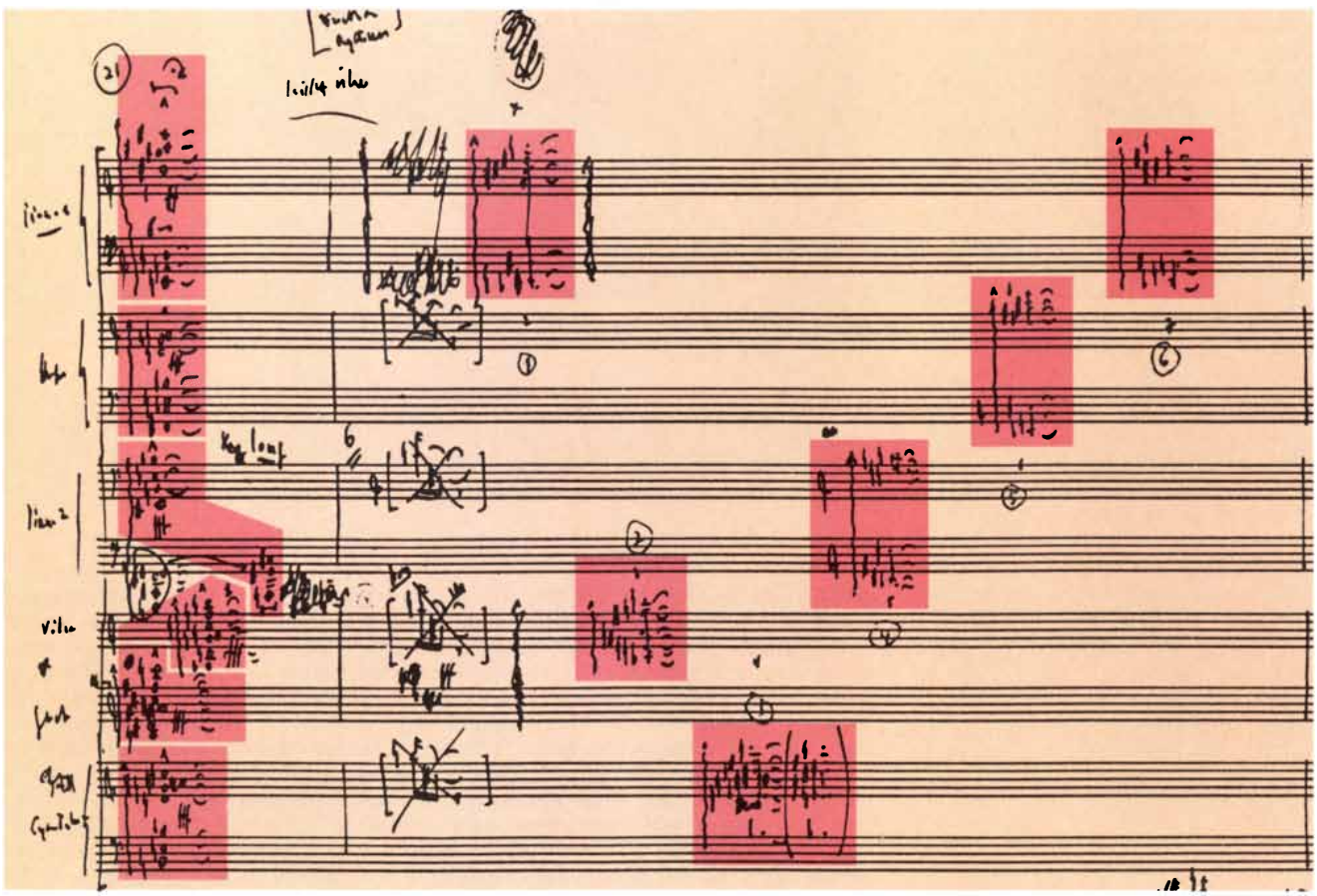
The traditional antiphonal form of composition also suggests two further ideas that were incorporated into *Répons*. The first is the notion of displacing the music in space, since the soloist and the choir are in different physical locations. Building on that notion, the six soloists in a typical performance of *Répons* are positioned at the periphery of the concert hall (as are six loudspeakers), whereas the instrumental ensemble is placed in the center. (The audience surrounds the ensemble.)

Displacement can also be understood in more general terms as a shift along any dimension. If one considers frequency as a dimension by which to characterize musical sounds, then a displacement would amount to shifting frequencies—similar to the common musical device of transposing a melody into different keys. By the same token a displacement in time amounts to a delay, since it involves shifting notes into the future.

Another idea that one can draw from antiphonal music is related to the fact that in such music one voice (the soloist) is answered by many voices (the choir). This suggests the notion of multiplication and proliferation of sounds, which can be realized by means of computer processing techniques that take a single note or chord and create a multitude of notes or chords all of which are related to the original one.

Répons opens with a seven-minute movement played only by the instrumental ensemble in which the musical tension slowly builds up for the entrance of the soloists, whose instruments are a cimbalom (a wire-strung instrument whose strings are struck with hand-held, padded hammers), a xylophone, a glockenspiel, a vibraphone (a xylophonelike instrument), a harp, a Yamaha DX 7 keyboard synthesizer and a pair of pianos. (Although there are six soloists, there are eight instruments: one soloist plays both the xylophone and the glockenspiel parts and another doubles on piano and synthesizer.) At the end of the introduction the soloists make a dramatic entry. Each soloist plays in unison with the others a different short arpeggio: a chord whose component notes are sounded in sequence from the lowest pitch to the highest. The resonance of the arpeggios then rings throughout the hall for about eight seconds, until the sound has virtually died out. During this flourish the 4X and the Matrix 32 are brought into action for the first time: they take the sounds of the chords the soloists have built note by note on their instruments and shift them from speaker to speaker.

The attention of the audience is thereby suddenly turned away from the center of the hall to the perimeter, where the soloists and the speakers are. The audience hears the soloists' sounds traveling around the hall without being able to distinguish the paths followed by the individual sounds. The overall effect highlights the antiphonal relation between the central group and the soloists by making the audience aware of the spatial dimensions that separate the ensemble from the soloists and that separate the individual soloists as well. Indeed, we say the maneuver has "spatialized" the sound.



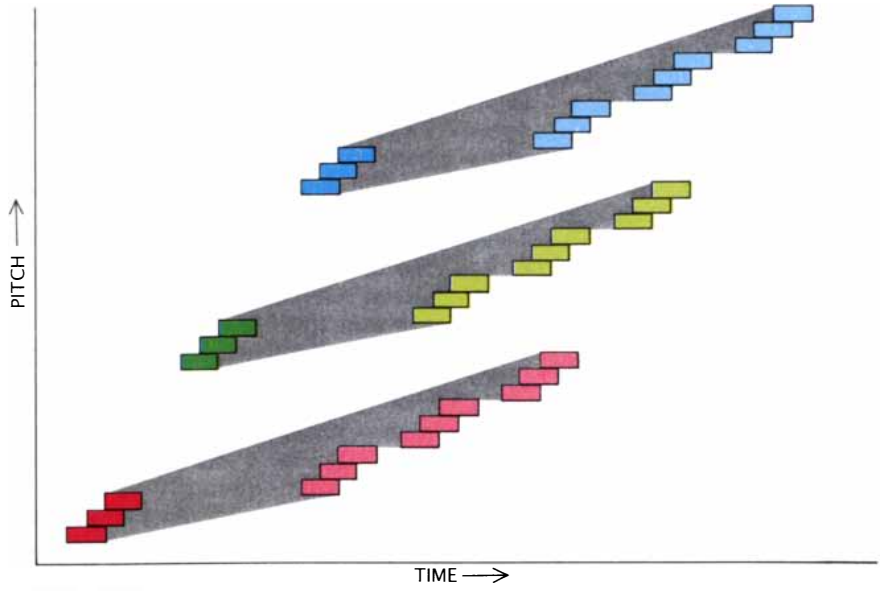
EXCERPT FROM ORIGINAL SCORE of *Répons* shows chords (*highlighted in red*) that six soloists play as arpeggios, sounding each note sequentially from bottom to top. The soloists play the first set of arpeggios together and the second set separately.

A soloist's sound does not move at a fixed speed from speaker to speaker; the speed depends directly on the sound's loudness, which at any given time is proportional to the amplitude of the envelope, or contour, of the sound's waveform. The larger the amplitude is, the faster the sound will appear to move. Although the soloists' instruments produce envelopes that are similar in shape (displaying a very sharp attack followed by an exponentially decreasing decay), the duration of an envelope's decay depends on the pitch of the notes as well as the instrument on which they are played. For example, high notes on a piano have steeper attacks and shorter decays than its low notes, and a note sounded on a glockenspiel has a steeper attack and a shorter decay than the same note played on a piano.

Because the sounds of the soloists' instruments die out at different rates, the sounds also slow down at different rates. The overall impression for the listener is that of a single spectacular gesture slowly breaking up into several parts. Furthermore, as the overall amplitude decreases, the original impression of sounds moving rapidly around the hall is replaced by a sense of immobility.

The amplitude-dependent spatialization is achieved by increasing the sound level of a particular solo instrument to a maximum at one speaker while reducing the instrument's sound level to zero at another. So-called flip-flop modules in the 4X control the simultaneous turning up and turning down of the sound levels and also determine the length of time the maximum level is maintained at a given speaker [*see illustration on page 47*]. Since the sound of each soloist circulates in a pattern among four speakers, the flip-flop units are arranged in loops containing four units. A flip-flop module operates on a timing signal whose frequency changes in proportion to changes in the amplitude of the sound's waveform envelope, which is continuously traced out by an "envelope follower" module. Hence drops in the envelope's amplitude (as during a sound's decay) lower the timing frequency and thereby cause a flip-flop module to hold the maximum sound level longer at a speaker before the next flip-flop module shifts the sound to the next speaker.

As soon as the sounds of the spatialized arpeggios have died out sufficiently, the conductor at roughly



ARPEGGIO OF AN ARPEGGIO OF AN ARPEGGIO similar to the one found in *Répons* is depicted schematically on a graph that has time and pitch as axes. Because an arpeggio can be broadly considered as the displacement in time and pitch of any set of musical entities (not just the notes of a chord), three arpeggiated three-note chords (*dark-color boxes*) played at different times and in different pitch ranges by instrumentalists can in themselves be thought of as constituting an "arpeggio." By the same token, the spreading out in time and frequency of three computer-generated copies (*light-color boxes*) of each of the arpeggiated chords is also an "arpeggio." In *Répons* five soloists play seven-note arpeggiated chords that are copied, frequency-shifted and played back 14 times.

equal intervals cues each soloist to play another arpeggiated chord, answering the simultaneous arpeggios with separate ones. Five of the arpeggiated chords are routed to the 4X, which continuously writes, or stores, the sounds in its wave-table memory. Immediately after the 4X writes the sound data it continuously recalls them with 14 "read" modules, so that 14 exact copies of the original sound are produced, each of which has a different time delay. Each copy is then shifted in frequency by another module in the 4X and played back.

The example just described is essentially an arpeggio (the spreading out of 14 copies in time and frequency) of an arpeggio (the sequentially played notes of a chord) of an arpeggio (the individually cued soloists). By means of the delays and frequency shifting, the idea of an arpeggio—displacement of musical entities in time and pitch—has been effectively translated from instrumental to electronic composition.

There is also a method behind the shifting of pitches in *Répons,* regardless of whether it is specified in the instrumental composition or the electronic composition. Much of the writing in the piece can be seen as a series of chord derivations based on shifting notes up or down in pitch by various intervals. Without going into too much detail, we can simply say that much of the harmonic material in *Répons* can be traced to five chords, which are heard in the first bar of the piece.

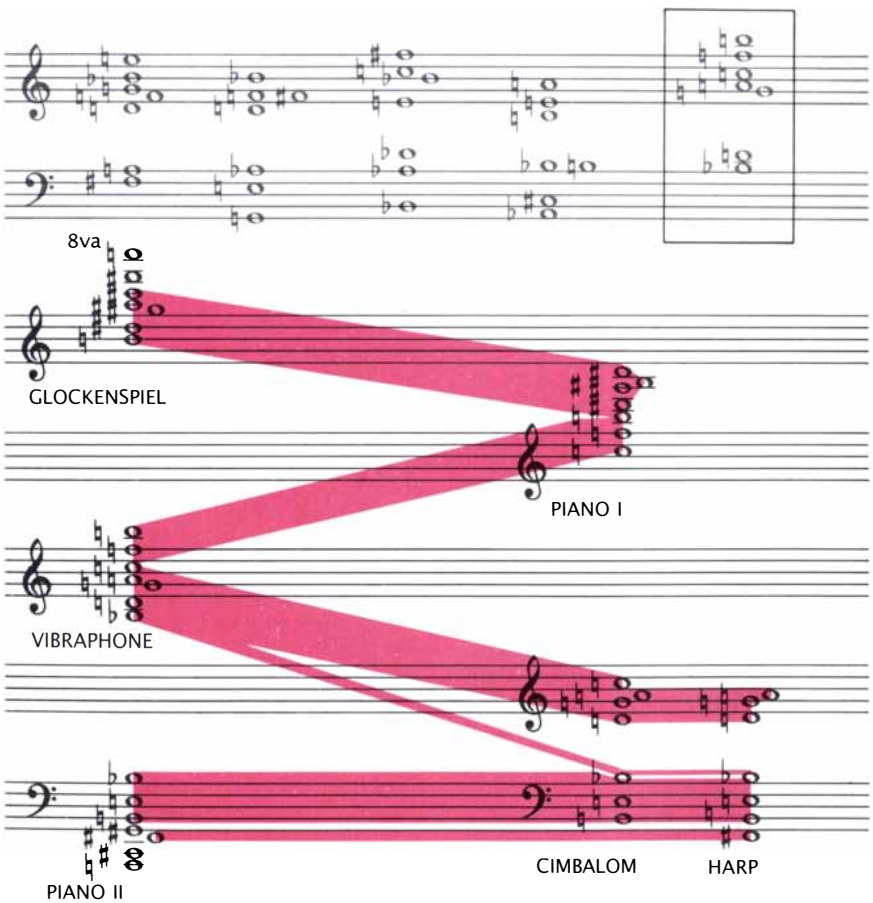
In fact, the six arpeggiated chords played simultaneously by the soloists at their entrance, as well as the ones later played separately, are all derived from the same basic chord. The chords of the soloists' entrance are constructed by transposing the basic chord a half step up and a half step down and then putting pieces of the resulting two chords together in different ways. (A half step is the smallest unit of transposition possible in traditional Western music. Transposing a chord 12 half steps results in the same chord but an octave higher or lower.) The derived chords are also shifted up or down an octave or two so that they are played in different octave ranges on the different solo instruments.

The separately played arpeggios, on the other hand, are obtained by successively transposing the basic chord up an amount equal to the number of half steps between the topmost note of the chord and each of the other notes constituting the chord. In addition the notes of the resulting chords are adjusted up or down an octave to fall between the lowest and the highest note of the ba-

sic chord. The procedure in essence "rotates" the chord by folding those notes that exceed the pitch limits back into the chord.

The frequency shifts of the 14 copies of the separately played arpeggios also conform to the same general pitch-shifting pattern. Each input chord is transformed in such a way that the pitches of its notes remain the same, although in a different octave. The frequency shifting thereby reinforces the original chord while at the same time giving it a new harmonic quality. Because one basic chord is shifted to create a new set of chords, which in turn are shifted in frequency by the 4X, the net result can be thought of as a transposition of a transposition. The underlying idea linking the instrumental writing and the computer writing in this case is displacement along the frequency dimension.

Transposition by a frequency-shifter module of the 4X is not entirely equivalent to the ordinary transposition of chords, however. The module does not preserve the tonal relations between a tone's partials, or frequency components. Normally a tone has a pitch-determining partial called the fundamental frequency and a number of other partials that are generally whole-number multiples of the fundamental frequency. The whole-number frequency ratios of a tone's partials as well as the partials' relative amplitudes, which vary while a tone is played, determine the tone's timbre. Hence in shifting each partial of a tone by the same fixed amount, the ratios between the partials are not preserved and the timbre of the original tone is altered as well. This problem could be overcome if one could shift the frequency of each partial independently by an arbitrary amount. Of course, in order to do this more powerful real-time analysis and control techniques need to be linked together. This is an area in which we are currently working at IRCAM.



TRANSPOSITIONS, or shifts in pitch, of five basic chords (*on gray staff*) constitute much of the harmonic material of *Répons*. The chords that are played by the soloists at their entrance are all derived from one basic chord (*in box*). The boxed chord is the same as the one played by the vibraphonist. Shifting the chord up two octaves and a half step and down two octaves and a half step yields the chords played respectively on the glockenspiel and the second piano. The chords for the other soloists are constructed by combining the top and bottom parts of the three chords and shifting the pitches up or down an octave so that each chord's notes fall within two octaves and a half step.

The computer, although a relative newcomer to music, has already opened intriguing perspectives from which composers and sound designers can explore new ideas or novel juxtapositions of old ideas. To do so they need powerful devices that can be programmed in a number of ways. No composer or sound designer can be satisfied with a device that allows the study of only one method for analyzing, synthesizing or transforming sound.

For example, the electronic manipulations involved in the two short passages from *Répons* we have described were implemented by means of a single 4X patch that programs six modules for spatialization, five for multiple delays, 30 for frequency shifting and assorted noise-reduction modules for each soloist. Yet both passages combined account for only about 30 seconds of a work that lasts for almost 45 minutes, during which some 50 other patches have to be loaded on cue. Clearly machines of extraordinary flexibility are necessary for performing mixed-medium pieces such as *Répons* in concert.

Unfortunately the recent trend has been toward the manufacture of specialized devices, each of which has its own method for processing digital signals. This is partially the result of marketing constraints, which demand that the devices be relatively cheap. Yet trying to link several electronic devices inevitably results in problems of control and coordination. Moreover, only a fraction of the total computing power can be applied at any given time. In addition to being wasteful, this arrangement makes it impossible to muster the total combined computational power into one method for processing digital signals. It is IRCAM's goal to help composers, sound designers and electrical engineers solve these problems without losing sight of the music.

Interested readers can obtain a cassette tape containing short excerpts of several computer-music compositions, including *Répons,* by sending $8.50 to Département Diffusion, IRCAM, 31, rue Saint-Merri, 75004 Paris, France.

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The Self, the World and Autoimmunity

Autoimmunity—in which the immune system recognizes and attacks the self's own tissues—is not as simple as it seemed. Self-recognition appears to be at the heart of health as well as of certain diseases

by Irun R. Cohen

It is generally assumed that the main job of the immune system is to distinguish between what is "self" and what is "not self." Once the distinction has been made, "self" is preserved and "not self" is destroyed. At the most general level, of course, this is true, and human beings remain alive and healthy only because it is so. Recently it has become clear, however, that at a finer level of detail the distinction between self and other is not absolute. One of the paths to this insight has been provided by the autoimmune disorders, in which the immune system attacks normal, healthy tissue. Autoimmune disease, which may be crippling or fatal, can strike any tissue or organ. Its victims are often in the prime of life, and for unknown reasons they are more frequently women than men.

Work in my laboratory on a form of autoimmune arthritis shows that the basis of autoimmunity may be a resemblance between a specific foreign molecule and a molecule of the self. What is more, our work is consistent with a model of the immune system in which the immune-system receptors that perform the work of recognition can themselves be recognized by other receptors. Such "self-recognition," which was strictly outlawed by older models of the immune system, may form the basis of a network whose equilibrium keeps the body healthy. When it is disrupted, as it is in autoimmunity, disease results. This new picture, in which self and world are no longer absolutely distinct, has already begun to yield practical benefit in the form of vaccines that may ultimately ease the substantial suffering caused by autoimmune diseases.

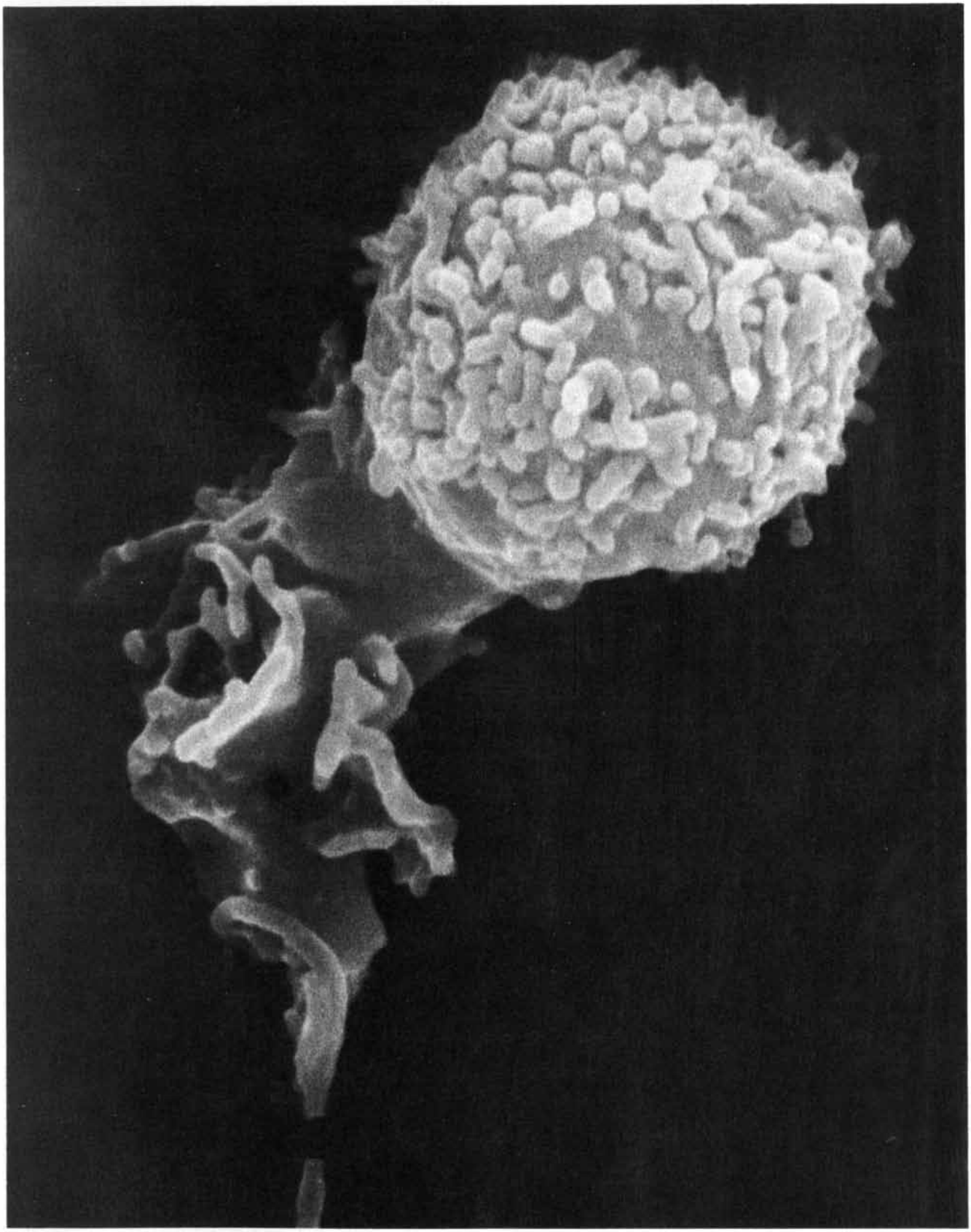
The list of autoimmune diseases is both long and disturbing. It includes multiple sclerosis, in which the tissue attacked is myelin (a substance that sheathes nerves in the central nervous system); myasthenia gravis, in which the target is a receptor molecule for the important neurotransmitter acetylcholine; rheumatoid arthritis, whose target is the peripheral joints; type I (juvenile) diabetes mellitus, in which the cells producing insulin are destroyed, and systemic lupus erythematosis, in which DNA, blood vessels, skin and kidneys are attacked. In contrast to AIDS, which is marked by an inactivation of key cells in the immune system, in all these diseases the immunological response is strong and well focused; it is, however, directed at some essential component of the body. The immune system is itself the culprit. How can that be?

Clearly the answer lies in the problem of recognition. That problem in turn touches on the cells that mediate recognition in the immune system: the lymphocytes. The immune system includes two such classes of cells, which are called *T* lymphocytes and *B* lymphocytes. Both types arise from stem cells in the bone marrow. The stem cells, however, lack the receptors that enable *B* and *T* cells to recognize specific molecules as targets for immune attack. Such immune receptors appear as the multipotential stem cells mature. As a result of the process of maturation, each *B* or *T* cell ultimately comes to have many copies of one immune receptor on its surface and therefore is able to recognize only one other molecule. Any molecule so recognized is called an antigen.

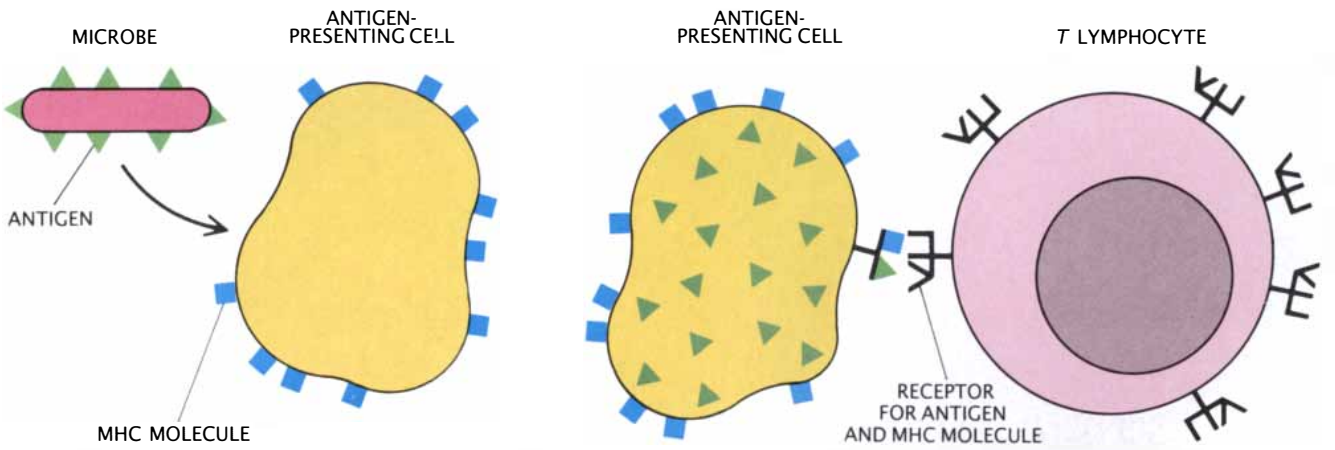
One of the remarkable features of the process of recognition is that it requires not the whole antigen but only a small piece known as an epitope. If (as is often the case) the molecule to be recognized is a polymer such as a protein or a sugar chain, the epitope frequently consists of as a few as from four to six of its thousands of monomeric subunits (amino acids in proteins, sugar units in sugar chains). The shape and the electric charge of each epitope are such that it will best fit a particular receptor. When an epitope finds its complementary receptor, they form a reversible association that generates a signal in the *T* or *B* cell.

At the heart of this process is the fact that each lymphocyte bears receptors with but a single specificity. For the immune system to be able to recognize a wide range of pathogens, however, there must be a great diversity of receptors, and indeed new receptors are constantly being produced at random by a process of genetic recombination in the progenitor stem cells. Not all the receptors created in this way are equally useful, and the immune system weeds out the unnecessary ones by a process called clonal selection. The lymphocyte whose receptor happens to have the closest fit to an epitope on a microbial antigen enjoys an advantage over its competitors: it replicates faster, and soon it may come to predominate over the other *T* and *B* cells in its vicinity.

The descendants of the progenitor make up a clone that not only increases in size but also differentiates into specialized forms. *B* cells may become plasma cells, which secrete antibodies (molecules with the same shape as the clone's antigen receptor), or memory cells, which persist



T LYMPHOCYTE, a white blood cell that forms an essential part of the immune system, is shown magnified 30,000 diameters. The villi (surface protuberances) are caused by the ruffling of the cell's outer membrane; they increase the surface area available for transactions with the environment. The stalklike structure extending from the cell body (known as a uropod) appears to have a role in cell mobility. The cell shown here is a *T*4 "helper" lymphocyte; it facilitates the action of other immune-system cells. By recognizing and attacking joint cartilage, helper *T*4 cells cause an experimental autoimmune disease called adjuvant arthritis. The micrograph was made by Yaakov Naparstek and Dorit Gurfel of Hadassah University Hospital in Jerusalem.



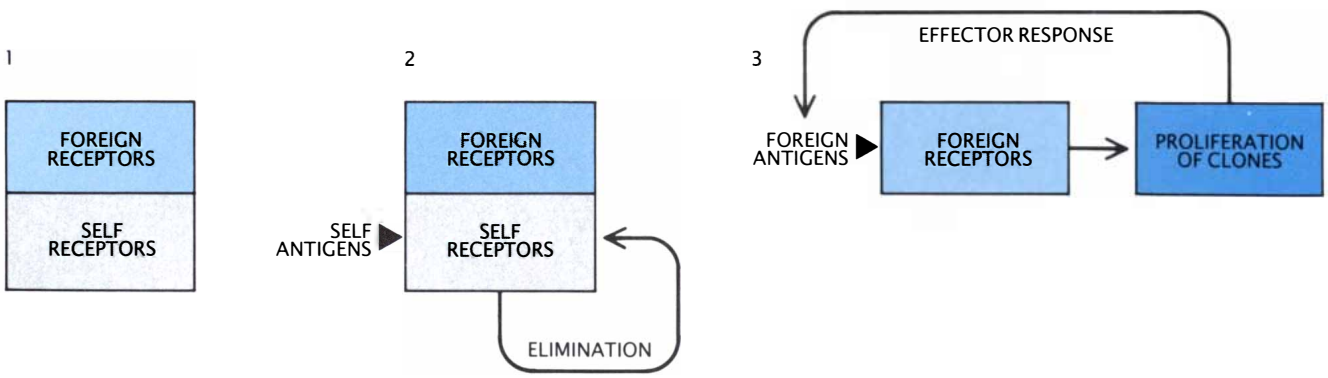
T CELL RECOGNIZES ANTIGEN presented by a specialized cell. An antigen is any molecule that is recognized by a receptor on a lymphocyte or by an antibody. When the antigen-presenting cell encounters a microbe, it digests the invader and presents its components to the *T* cell, along with molecules of the major histocompatibility complex, or MHC, which belong to the antigen-presenting cell itself. The fit of the antigen and MHC molecules with the *T* cell's receptor triggers a response in the lymphocyte.

to identify the epitope with increased efficiency if the pathogen returns. *T* cells mature into one group bearing a surface marker known as *T*4 and another bearing a marker known as *T*8. Within each group are cells that act directly ("effectors") and others that act by influencing other immune-system cells ("regulators"). *T*8 effectors are cytotoxic: they kill cells bearing a specific antigen. *T*8 regulators are suppressive: they inhibit the activities of other *T* or *B* cells. *T*4 effectors damage tissue by activating other white cells; *T*4 regulatory cells are "helpers" that facilitate the action of both *B* and *T* cells.

Now, the random generation of new receptors and their winnowing by clonal selection endows the immune system with great flexibility. The number of possible receptor structures is enormous: perhaps millions of different *T*-lymphocyte clones and hundreds of millions of *B*-lymphocyte clones. From the randomly generated receptors that are continually being produced, clonal selection narrows the field to a few dominant types for each antigen. From a theoretical point of view clonal selection can be seen as a form of digital processing, in which the system is able to direct its attention to the most relevant information (the receptor that best fits an epitope) and disregard the rest (all, or almost all, competing receptor-epitope pairs).

Yet that very flexibility is the source of a problem: self-recognition. If the immune system can recognize almost anything, why not the molecules that belong to the self? F. Macfarlane Burnet of the University of Melbourne, author of the theory of clonal selection, proposed a solution to the problem of self-recognition. During prenatal development, Burnet argued, all the antigens that were present would be self antigens. If recognition of an epitope during gestation triggered clonal suicide, the immune system would be purged of all self-recognizing clones. Recognition of epitopes after birth would induce active immunity, but by then the immune system would be blind to self structures. Burnet explained the appearance of autoimmune disease by exposure after birth to self-antigens that had been accidentally sequestered during gestation.

To be reliable, however, clonal elimination requires distinguishing absolutely between self and not-self: receptors that recognize self must be eliminated and those that do not must be spared. Yet it seems clear

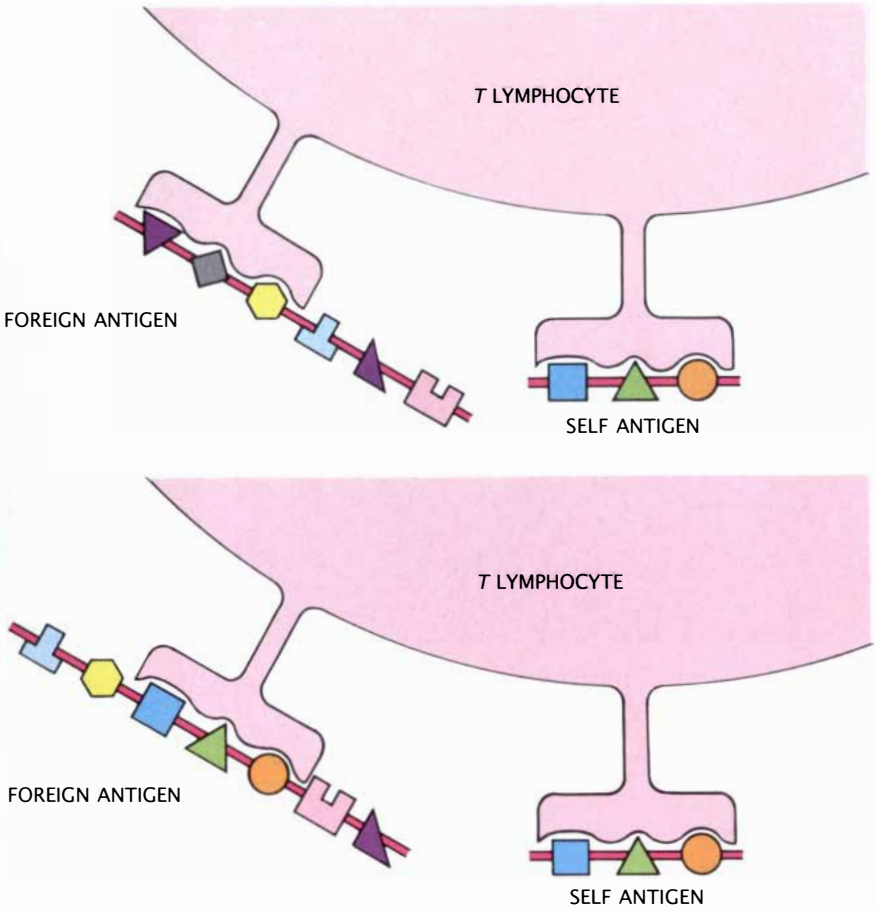


CLONAL SUICIDE was a theory developed to account for the absence of autoimmune disease in most people. A clone is a group of cells descended from the same progenitor and hence genetically identical. The immune system can create clones capable of recognizing both self and foreign antigens (*1*). In clonal suicide all clones having receptors for self antigens are eliminated before birth (*2*). Clones that recognize foreign antigens persist. On encountering the corresponding antigen, they proliferate and differentiate to combat the invader (*3*). This theory was formulated in the 1950's by F. Macfarlane Burnet of the University of Melbourne. Recently it has become clear that self and foreign antigens cannot be distinguished by such a simple mechanism.

that such an absolute distinction cannot easily be made. One reason is that although the receptor-antigen relation is generally thought of as a lock-and-key affair, in reality the fit is not exact or exclusive. Within certain limits a single receptor can combine with many different epitopes, each of which it fits with greater or lesser precision. The capacity of millions of different receptors to bind many epitopes enlarges the functional repertoire so greatly that it is difficult to imagine that any biological molecule could pass unrecognized by at least one receptor—including the molecules of the self.

The challenge is compounded by the fact that the self and the invader are made up of the same building blocks: proteins, carbohydrates, nucleic acids and lipids. What is more, molecules such as enzymes or hormones that perform key biological functions tend to be conserved in evolution so that self and invader may have identical—or at least very similar—molecules. Finally, it seems that some pathogens actually make hostlike antigens as a means of disguise. For example, leishmania parasites (some types of which cause trypanosomiasis) synthesize antigens similar to those of the red blood cells of their mammalian hosts. It appears that antigenic "mimicry" is a persistent feature of the struggle between self and pathogen.

To understand the role of antigenic mimicry in autoimmunity my colleagues and I studied an experimental disease of rats called adjuvant arthritis, which was first observed by Carl M. Pearson of the University of California at Los Angeles in the 1950's. Pearson noted that rats inoculated with a mixture of mineral oil and killed organisms of *Mycobacterium tuberculosis* (the tuberculosis agent) developed arthritis. Adjuvant arthritis caused degeneration of the cartilage in the joints, and its symptoms, Pearson and others noted, were much like those of rheumatoid arthritis. Rheumatoid arthritis is typically manifested as a progressive inflammation of hands and feet. Unlike osteoarthritis (which often accompanies aging), rheumatoid arthritis typically strikes young women, and it can lead to tragic deformity.

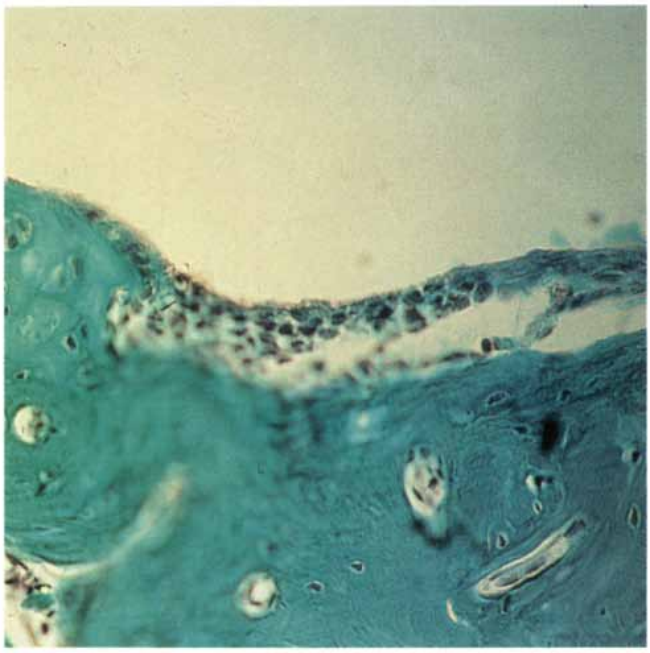


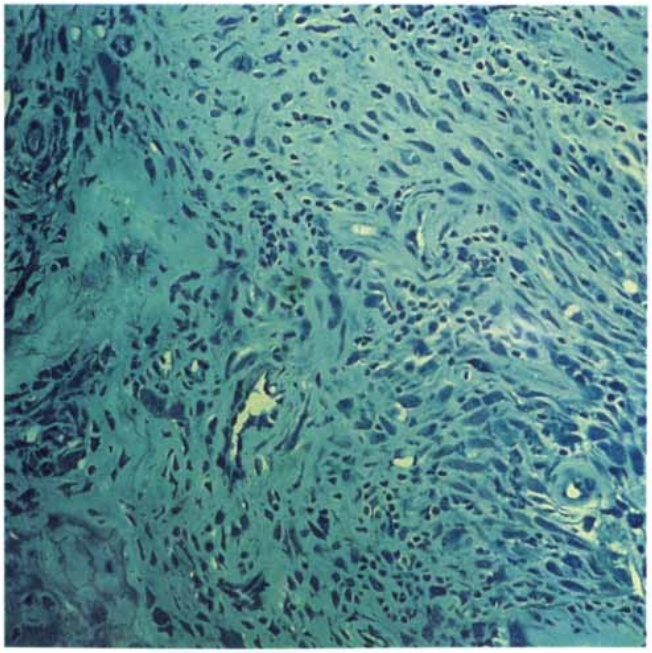
ANTIGENIC MIMICRY is based on a resemblance between a self antigen and a foreign one. Antigens are often polymers such as proteins or sugar chains; the sequence of monomeric subunits underlies the lock-and-key fit with the receptor of a lymphocyte or an antibody. If a self antigen and a foreign one resemble each other, both may fit the same receptor. The resemblance may arise because different monomers have similar shapes (*top*) or because different polymers share a sequence of subunits (*bottom*).

Since both rheumatoid and adjuvant arthritis were assumed to be due to autoimmunity, my co-workers and I hoped that explication of the disorder in rats would help us to understand the human disease. The tissue damage seen in adjuvant arthritis was characteristic of *T* lymphocytes rather than *B* lymphocytes or other immune components, and so our strategy was to isolate the clones of *T* cells that were attacking the cartilage in the rats' joints. Although the strategy sounds simple, in actuality it required some substantial technical advances, most of which were due to the pioneering work of Avraham Ben-Nun, who was then one of my graduate students.

Ben-Nun's work was based on another induced autoimmune disorder, known as experimental autoimmune encephalomyelitis (EAE). Considerably more was known about EAE than about adjuvant arthritis. It could be induced in laboratory animals by inoculation with basic protein, a component of myelin in the central nervous system. The immunity to basic protein is manifested by paralysis (often fatal) and inflammation in the region of the brain and spinal cord where the nerve fibers are sheathed in myelin. Some workers consider EAE to be the best laboratory model of multiple sclerosis, and much work had gone toward characterizing the epitopes of basic protein that are responsible for EAE in rats, guinea pigs and mice as well as in other experimental animals.

Like adjuvant arthritis, EAE was thought to be caused by *T* cells rather than *B* cells or antibodies, and our strategy was to isolate clones of *T* cells that responded specifically to basic protein. Ben-Nun worked out a method for growing such clones. *T* cells from rats immunized against basic protein were grown in a culture medium containing the basic-protein antigen. Although the cells that recognized basic protein were a small minority, the presence of their antigen stimulated them to proliferate at the expense of the other lymphocytes: it was clonal selection in tissue





CARTILAGE DAMAGE, hallmark of adjuvant arthritis, results when *T* lymphocytes attack joint cartilage. The micrograph at the left shows rat joint tissue eight days after inoculation with an "adjuvant" containing ground-up *Mycobacterium tuberculosis* (the tuberculosis pathogen) in mineral oil. Lymphocytes have begun to invade the cartilage (*upper layer of tissue*). The micrograph at the right, made 27 days later, shows the normal cartilage architecture extensively disrupted by white blood cells.

culture. That procedure enabled us (in this work Ben-Nun and I collaborated with Hartmut Wekerle, then at the Max Planck Institute for Immunobiology in West Germany) to obtain pure clones of *T* cells that respond to basic protein; all the clones isolated so far have been of the *T*4 type.

Further work showed unequivocally that these *T*4 cells cause EAE. Yaakov Naparstek showed that they accumulate in the brain and spinal cord just before the onset of paralysis. Moreover, we were able to retrieve anti-basic-protein *T* cells from immunized rats and, by injecting them, cause EAE in other rats. This was the first time a specific clone of *T* cells had been shown without question to be responsible for a known autoimmune disorder. Paradoxically, although the *T* cells from the immunized rats were able to cause disease, in some instances the rats they were taken from had already recovered from their severe paralysis and seemed to be clinically well. That perplexing finding implied the existence of mechanisms for holding autoimmunity in check—a subject to which I shall return.

Soon after these experiments were done, Joseph Holoshitz, who was spending a leave in my laboratory, suggested that we apply our experience with EAE to adjuvant arthritis. It seemed a sound idea. The catch was that in the case of EAE the antigen that caused the disorder—basic protein—was well known to begin with. In the case of adjuvant arthritis, however, the relevant antigen was not known. It was assumed that the antigen must be one belonging to *Mycobacterium tuberculosis,* but *M. tuberculosis* includes many thousands of antigens. How could we find the antigenic needle in this immunologic stack?

We reasoned that only the human investigators on the case were ignorant of the right antigen. Surely the *T* lymphocytes that cause the disorder recognize the relevant antigen. Accordingly, Holoshitz cultured cells from arthritic rats with pulverized *M. tuberculosis* organisms. If antigenic mimicry was indeed at work and there existed bacterial antigens resembling the self antigens that were under attack in the arthritic rats, the disease-causing *T* cells might pick them out from among all the other bacterial antigens. When that happened, the relevant clone would predominate by clonal selection. That is just what happened. The second *T*-lymphocyte line that was obtained was found to induce arthritis when injected into rats. Holoshitz went on to isolate a clone called A2b that caused even severer disease.

Having induced the bacterial antigen to pick out the relevant *T*-cell clone, we could now employ the *T* cells to find the antigen itself. That work was undertaken by Willem van Eden, who came to my laboratory as a postdoctoral fellow from the Netherlands. Van Eden cultured clone A2b with fractions of ground-up *M. tuberculosis* organisms and with various components of joint tissue. As expected, A2b recognized a mycobacterial fraction (one prepared by my colleague Ayalla Frenkel). In addition the clone recognized proteoglycan, a joint-cartilage molecule that includes sugar and protein components; as it happens, the epitope recognized by A2b was on the part of the proteoglycan molecule called the core protein.

This double recognition was exciting, because it amounted to antigenic mimicry in the test tube: a clone of *T* cells with a single specificity had recognized both a foreign antigen and a self antigen. Adjuvant arthritis could now be explained as the result of a resemblance between those antigens.

But what were the precise epitopes involved? Van Eden's initial work had identified only a fraction of ground-up bacterium, not a specific epitope. To identify a specific epitope we needed to separate *M. tuberculosis* organisms into their component molecules and determine which molecule was recognized by A2b. Once the molecule had been identified we could break it down into progressive-

ly smaller pieces until we found the smallest defined piece A2b would recognize, which would constitute the relevant epitope.

Although the process is simple to describe, it might not have been possible without a useful trick of genetic engineering. Mycobacteria are notoriously difficult to study biochemically. Hence biochemists have resorted to inserting their genes into *Escherichia coli,* a well-behaved and much studied laboratory pet. When the genes are expressed by *E. coli,* large amounts of mycobacterial antigens are made available for study. The availability of such "expression libraries" of *M. tuberculosis* proteins offered us a relatively simple way of identifying the antigens that had been recognized by clone A2b.

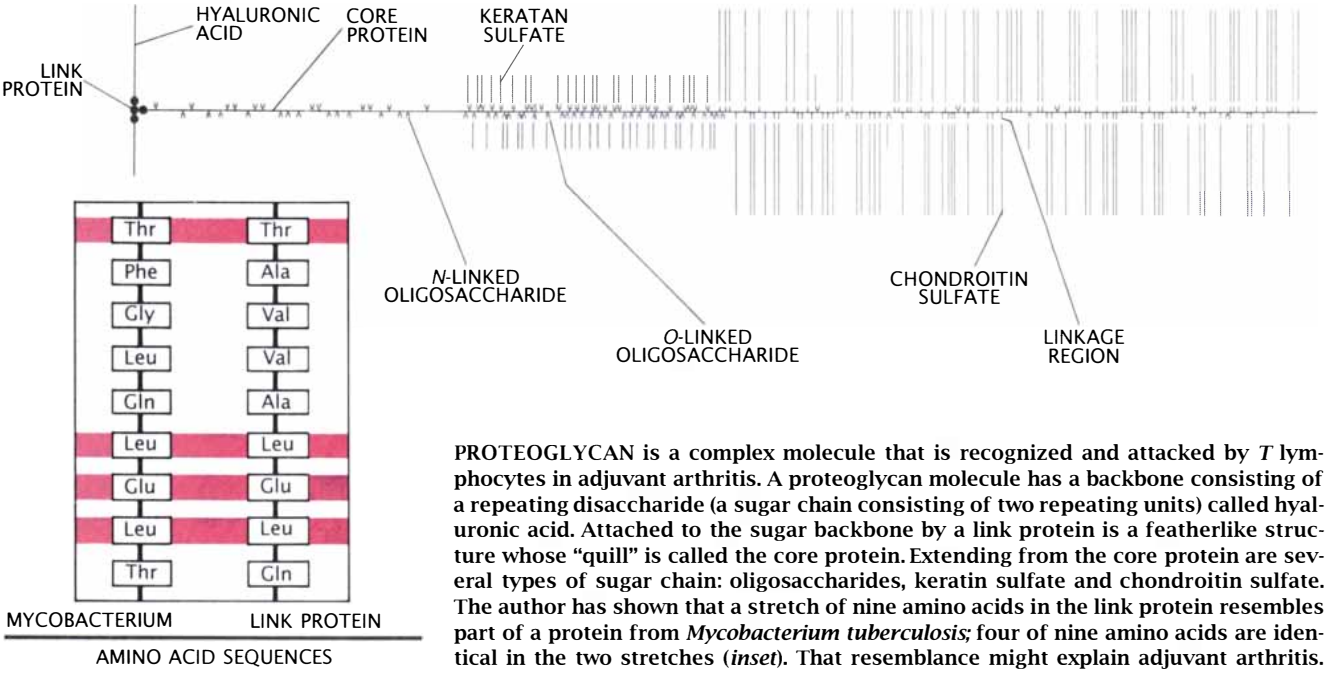
Van Eden tested the responses of A2b to an expression library prepared by Jan D. A. van Embden and Jelle E. R. Thole of the National Institute of Public Health and Environmental Hygiene in the Netherlands. To our delight A2b responded to one of the mycobacterial gene products, a protein with a molecular weight of about 65,000 (a hydrogen atom has a molecular weight of 1), the amino acid sequence of which had already been worked out. Thole and Embden obtained fragments of the protein and tested them against A2b. Ruurd van der Zee of the State University of Groningen then synthesized amino acid chains spanning the area of the protein likely to contain the relevant epitope. The chains were tested and the epitope, consisting of nine amino acids, was identified.

The precise resemblance between the bacterial epitope and the protein part of the proteoglycan remains to be specified. Fortunately the amino acid sequences of proteoglycans have been worked out quite thoroughly. The nine amino acids of the bacterial epitope were compared with published core-protein sequences, and a resemblance was found to a stretch of the link protein that joins the core protein to the proteoglycan's sugar backbone. Four of the nine amino acids in the two stretches are identical. We are currently testing whether that resemblance could account for the double recognition of the two epitopes by clone A2b and therefore for the autoimmunity that underlies adjuvant arthritis.

Does such molecular mimicry also have a role in causing rheumatoid arthritis in human beings? Although there is no definitive answer, early findings are suggestive. We investigated immune responses of some 50 patients suffering from rheumatoid arthritis or from a nonautoimmune degenerative disease of the joints. *T* lymphocytes from both groups were exposed to a mycobacterial fraction containing the cartilage-mimicking epitope. The cells from the rheumatoid arthritis patients underwent a markedly augmented proliferation; those from the others showed a much lower rate of proliferation that was comparable to the rate in healthy people.

Rheumatoid arthritis does appear to be associated with a specific reactivity of *T* cells to a mycobacterial antigen. Such findings, however, by no means establish a causal relationship. The reactivity of the *T* lymphocytes might be the result of arthritis rather than its cause. For example, rheumatoid arthritis might trigger a response of *T* cells to cartilage proteoglycans. The *T* cells might then cross-react to mycobacterial epitopes that happen to resemble the cartilage antigens. There is certainly no obvious connection between *M. tuberculosis* infection and the subsequent development of rheumatoid arthritis. Yet nonvirulent mycobacteria are ubiquitous, and perhaps a clinically invisible exposure might later lead to autoimmunity.

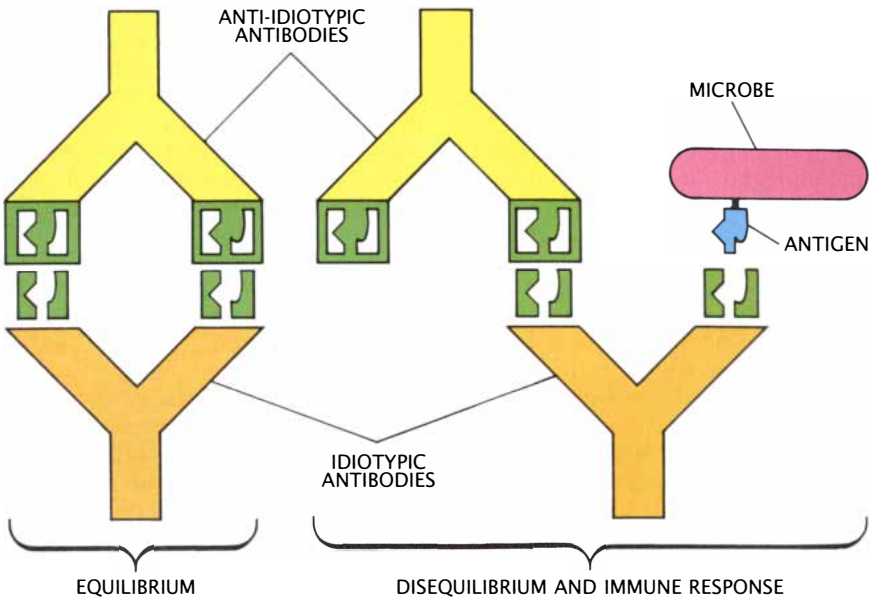
Such connections are known for other pathogens. Acute rheumatic fever, for example, a condition characterized by inflammation of the heart, joints and nervous system, is almost always preceded by an acute infection (usually of the throat and tonsils) with a type of streptococcal bacterium. In the 1960's Melvin H. Kaplan of Case Western Reserve University showed that antibodies made by rabbits against streptococcal antigens also bind to human heart tissue. It should be noted, however, that although all the streptococci of a particular strain may carry human-mimicking epitopes, only a small minority of infected people ever come



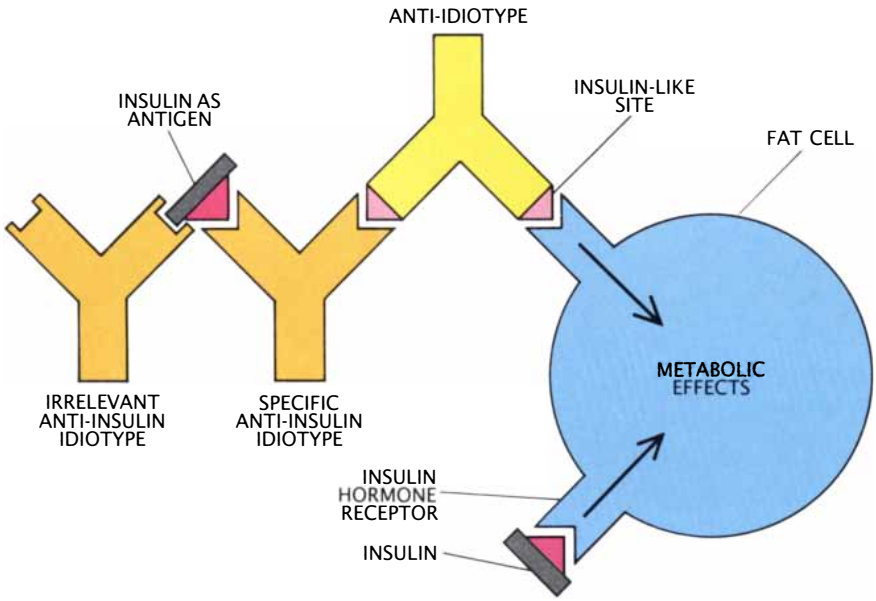
PROTEOGLYCAN is a complex molecule that is recognized and attacked by *T* lymphocytes in adjuvant arthritis. A proteoglycan molecule has a backbone consisting of a repeating disaccharide (a sugar chain consisting of two repeating units) called hyaluronic acid. Attached to the sugar backbone by a link protein is a featherlike structure whose "quill" is called the core protein. Extending from the core protein are several types of sugar chain: oligosaccharides, keratin sulfate and chondroitin sulfate. The author has shown that a stretch of nine amino acids in the link protein resembles part of a protein from *Mycobacterium tuberculosis;* four of nine amino acids are identical in the two stretches (*inset*). That resemblance might explain adjuvant arthritis.

down with acute rheumatic fever. Moreover, the autoimmune attack is generally brief. It would seem that the immune system has the capacity to regulate autoimmunity. How?

Surprisingly, the great scope of the receptor repertoire, which causes the problem by encompassing both the self and the world, may also provide a solution. In the early 1970's Niels Kaj Jerne of the Basel Institute for Immunology formulated a theory of immunity based on observations by several investigators that antigen receptors could themselves be recognized by other receptors on lymphocytes or antibodies. A receptor could also be an antigen! Therefore in addition to receptors for each epitope (as postulated by Burnet), Jerne's conception included receptors for each receptor [see "The Immune System," by Niels Kaj Jerne; SCIENTIFIC AMERICAN, July, 1973]. The original Burnetian specificity of the receptor is referred to as its idiotype, and the specificity of the receptor's receptor is called the anti-idiotype.



ANTI-IDIOTYPE NETWORK may underlie the immune system's response to disease. The idiotype is a receptor's specificity for an antigen. The anti-idiotype is a second receptor's lock-and-key fit with the first. Under ordinary, equilibrium conditions, idiotypic and anti-idiotypic receptors may bind, holding each other in check (*left*). If a microbial antigen is present, it binds to an idiotypic receptor, creating a disequilibrium that leads to the immune response (*right*). It is also possible that the equilibrium between idiotypes and anti-idiotypes somehow restrains the harmful effects of autoimmunity.

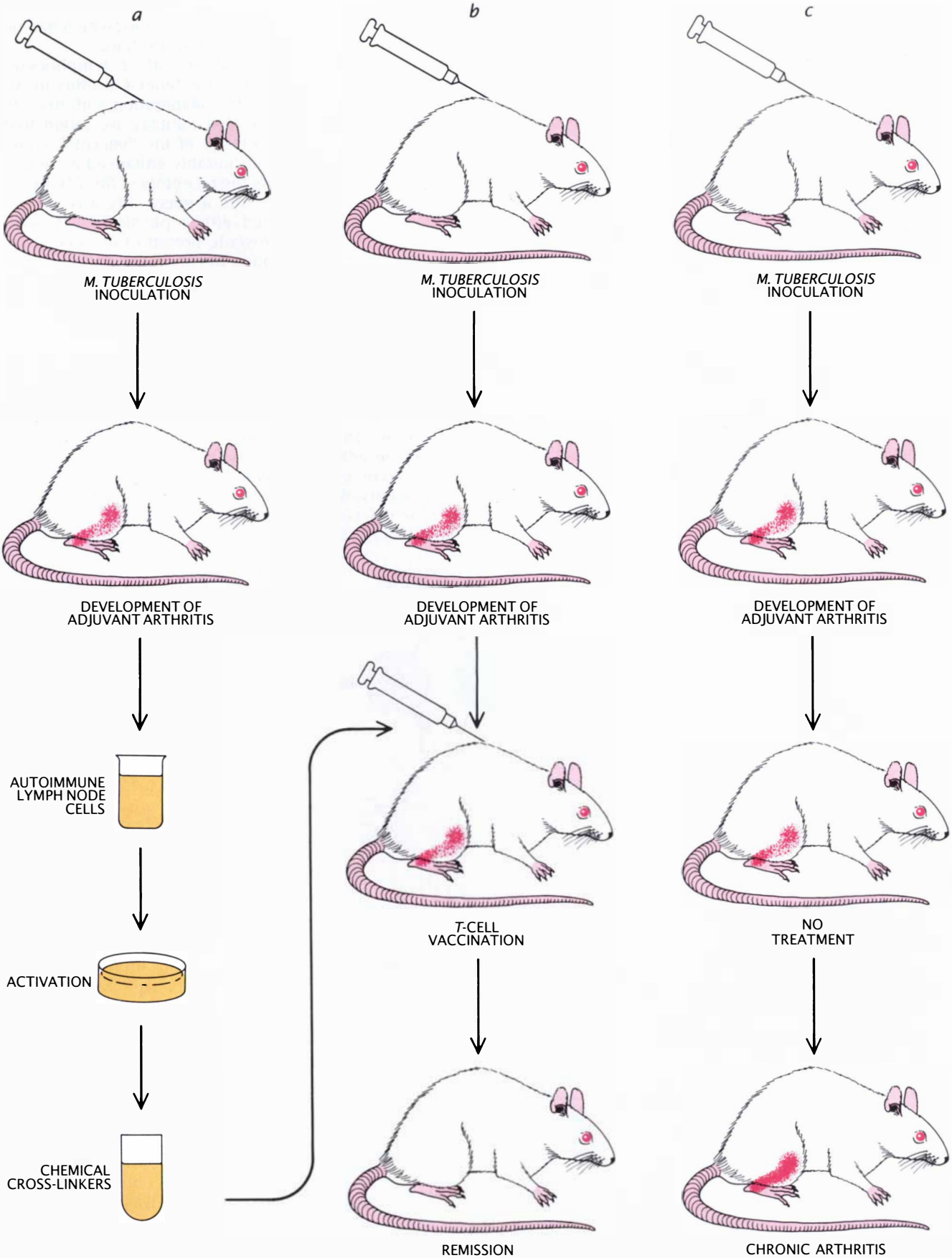


HORMONES CAN BE SHORT-CIRCUITED by the effects of the idiotype-anti-idiotype network, as is shown in a schematic representation of work done in the author's laboratory. Mice immunized to the hormone insulin develop antibodies to several structures on the insulin molecule, including the part (*red*) that binds to the insulin receptor of fat cells. The mice then spontaneously develop anti-idiotypic antibodies that bind to the idiotypic receptor. The receptors of the anti-idiotypic antibodies resemble the configuration of the part of insulin that binds to the insulin receptor. Hence the anti-idiotypic receptors also bind to the insulin receptor, causing a condition similar to diabetes.

That concept has some remarkable implications. If the epitope is thought of as a key and the idiotypic receptor as a lock, what of the anti-idiotypic receptor? Because it is complementary to the idiotype (the lock), the anti-idiotypic receptor must have the form of the key. The key, however, is also the form of the epitope. Hence the epitope and the anti-idiotypic receptor may have the same shape. Jerne argued that in addition to a set of receptors complementary to the antigenic world, the immune system contains a set of receptors (the anti-idiotypic ones) that are homologous to the antigenic world: the system contains not only itself but also the world. This self-recognizing network establishes an equilibrium that regulates the behavior of the immune system, according to Jerne.

Jerne's ideas have generated many experiments, and results are accumulating that support the network concept. Several workers have found that immunization with an epitope leads to the production of antibodies complementary to the epitope, followed thereafter by the production of anti-idiotypic antibodies that mimic the shape of the epitope. Yoram Shechter, Ruth Maron, Dana Elias and I carried out such experiments in mice. We employed an insulin epitope and obtained an anti-idiotypic antibody that resembles the relevant part of the insulin molecule. (In fact, we are now finding anti-idiotypic, insulin-mimicking antibodies in the blood of some people suffering from the autoimmune form of diabetes. What these antibodies are doing there is still a mystery.) On a more practical level, it is hoped that anti-idiotypic antibodies can be exploited for vaccines: the anti-idiotype mimics the shape of a microbial epitope (and so induces immunity) but is harmless.

If recognition of self through the formation of anti-idiotypic receptors is central to the immune system,



VACCINE AGAINST AUTOIMMUNITY was developed by the author and his colleagues. Three groups of rats were inoculated with an adjuvant containing *M. tuberculosis;* all three developed adjuvant arthritis. Autoimmune cells from the lymph nodes of one group (*a*) were removed, processed to increase their immunogenic effects and then injected into the second group (*b*). After inoculation the vaccinated group experienced remission of the disease. The untreated group (*c*) developed chronic arthritis.

what distinguishes between healthy self-recogition and autoimmune disease? Immunologists who accept Jerne's ideas would propose that an equilibrium between idiotypic and anti-idiotypic receptors somehow yields a tolerance to self-epitopes and prevents autoimmune disease. Harmful self-recognition, they would argue, is checked by the mesh of the network and not merely by the presence or absence of a specific antigen. Indeed, it does seem that the immune system can live with and control autoimmunity. As I mentioned above, *T* lymphocytes capable of causing EAE can persist in rats that have recovered from the disease, and people do recover from rheumatic fever and other autoimmune disorders.

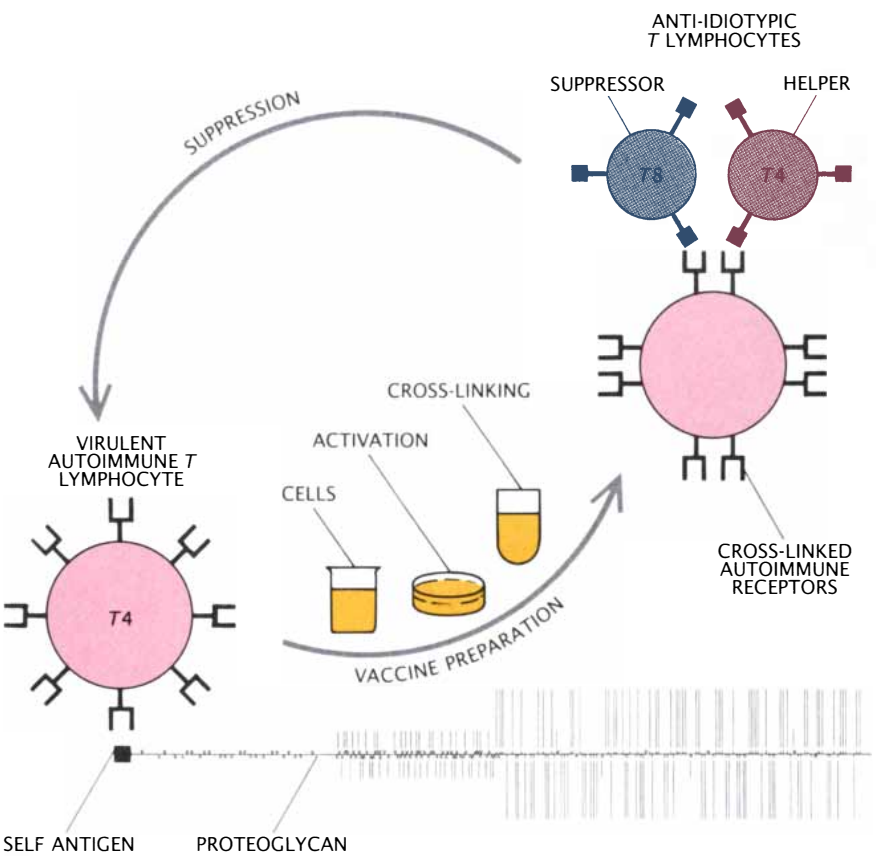
Although the network model offers a convincing interpretation of autoimmunity, it has not been conclusively established. Even without full theoretical understanding, however, the first practical steps have been taken toward preventing and treating autoimmune diseases. Having in hand the specific *T* lymphocyte clones responsible for EAE, adjuvant arthritis and some other experimental diseases, we decided to find out whether they could be used as "vaccines" against autoimmunity.

The first step was to take the line of anti-basic-protein *T* cells responsible for EAE and subject them to gamma radiation. The treated cells lost their virulence and were no longer able to induce EAE when they were injected into rats. The animals into which the *T* cells were injected, however, acquired permanent resistance to EAE: immunization of the rats with basic protein no longer triggered an attack on tissues of the central nervous system. The rats were perfectly capable of responding to other antigens and could even develop adjuvant arthritis when they were exposed to *M. tuberculosis* antigens. We had achieved an experimental vaccine. Its basis was immunizing the rats against the *T* cells, which had receptors for basic protein.

Vaccination with *T* lymphocytes was quickly extended to adjuvant arthritis. In collaboration with my colleague Meir Sinitzky we found that the potency of the "vaccine" could be considerably enhanced by aggregating the receptors of the *T* lymphocytes into a mass; this was accomplished either physically (through hydrostatic pressure) or chemically (through agents that cross-link cell-surface receptors). Apparently, aggregating the receptors makes them much more potent in generating anti-idiotypic lymphocytes. Even more striking, the vaccine also serves as a form of therapy: rats receiving cross-linked *T* lymphocytes taken from other sick rats quickly underwent permanent remission of their autoimmune disease.

It is not yet known exactly how *T*-cell vaccination induces resistance to the autoimmune process, but some suggestive data are being accumulated. Our most recent work confirms that in response to vaccination anti-idiotypic *T* lymphocytes emerge that specifically recognize the receptors of the disease-causing *T* cells. The anti-idiotypic lymphocytes include both cells with the *T*4 marker and those with *T*8. The *T*4 cells are helpers and the *T*8 cells are suppressors, which inhibit the growth of clones of other lymphocytes. We do not know which type is responsible for resisting the autoimmune disease. It is conceivable that the two groups work in concert to regulate the lymphocytes that cause the autoimmune disease.

The effectiveness of *T*-lymphocyte vaccination in activating lymphocytes capable of modulating autoimmunity is certainly compatible with the general idea of a Jernian network. Our observations, however, by no means establish the physiological role of the network proposed by Jerne; much more work will be required for that. Yet the work done so far has established that the border between the self and the external world is not nearly as clear as was once thought. Self-recognition is not merely a sin punished by autoimmune disease, as Burnet and others believed. On the contrary, it is central to health as well as to illness. The immune system is much more complex than it seemed when immunologists thought it perceived only the external world. That knowledge may ultimately be of very real help in easing the pain of autoimmune disease.



POSSIBLE MECHANISM of the vaccine against adjuvant arthritis is illustrated schematically. The critical cells are the virulent autoimmune *T*4 cells—with receptors for proteoglycan—that are removed from arthritic rats. Preparation of the vaccine entails aggregating the receptors, a process that increases their potency. When they are injected into other rats suffering from adjuvant arthritis, the aggregated receptors evoke anti-idiotypic *T*4 and *T*8 cells. The *T*8 cells are "suppressors" that may inhibit the proliferation of the autoimmune lymphocytes. The *T*4 cells are "helpers." Helpers facilitate the growth of *B* and *T* cells; their function in the vaccinated rat is not as yet understood.

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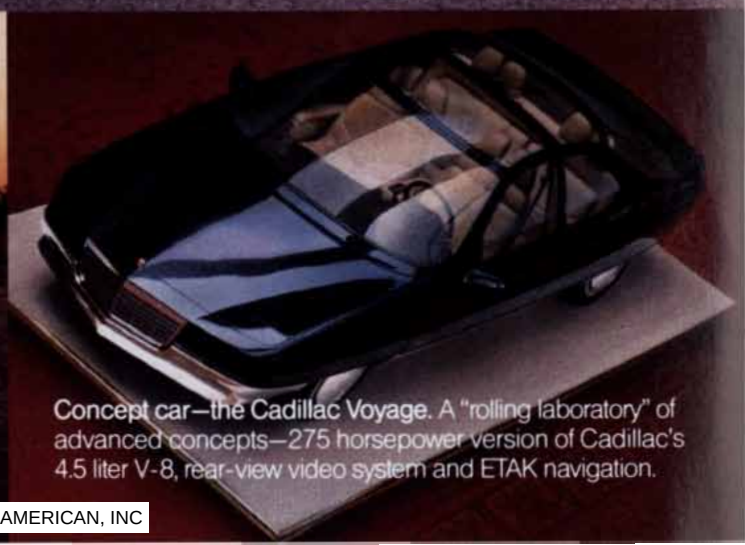

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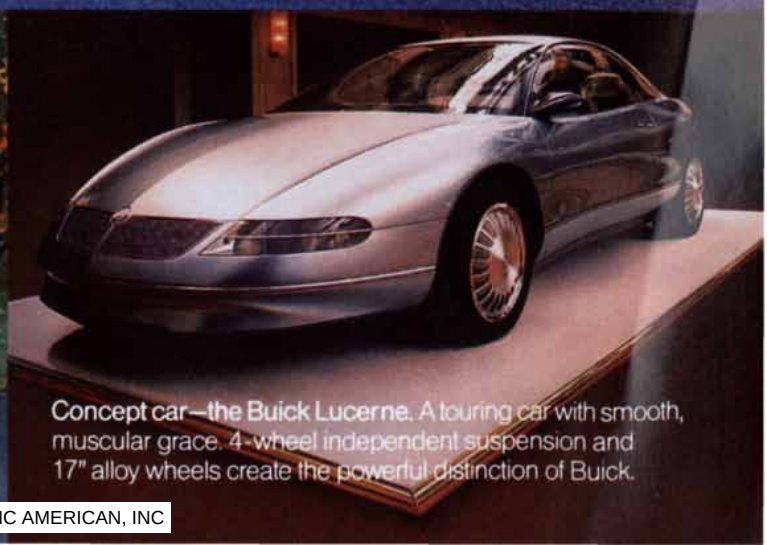

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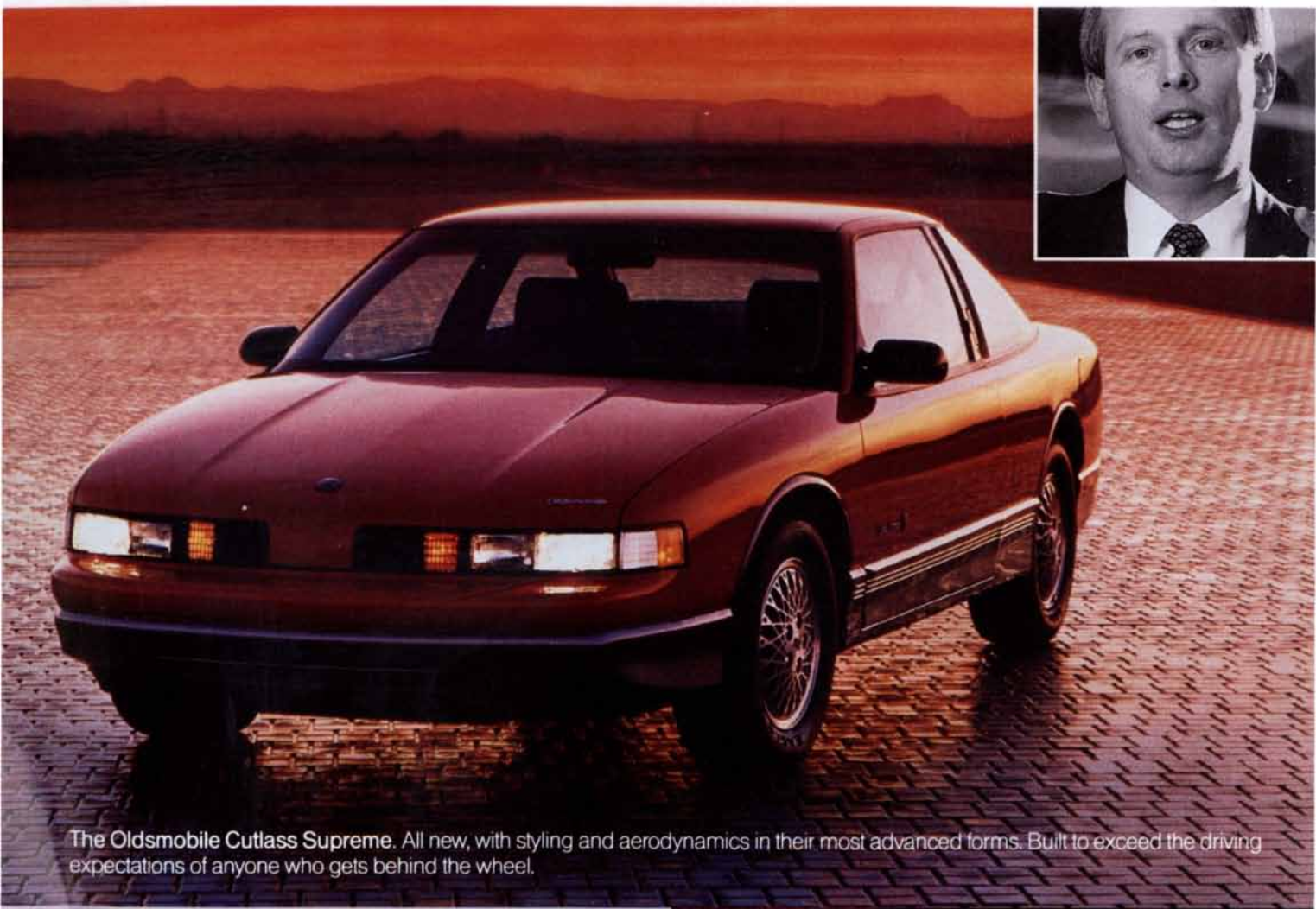

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The Membrane Paradigm for Black Holes

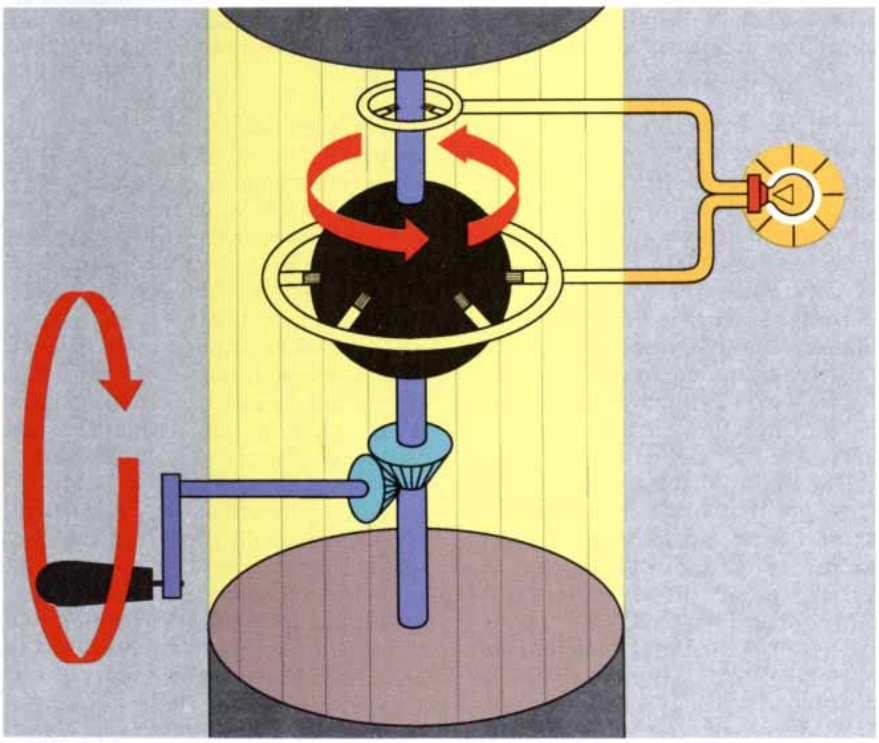
How can one picture the interaction of a hole in spacetime with the matter and fields of its environment? It is fruitful to conceive of the black hole as an electrically conducting, spheroidal membrane

by Richard H. Price and Kip S. Thorne

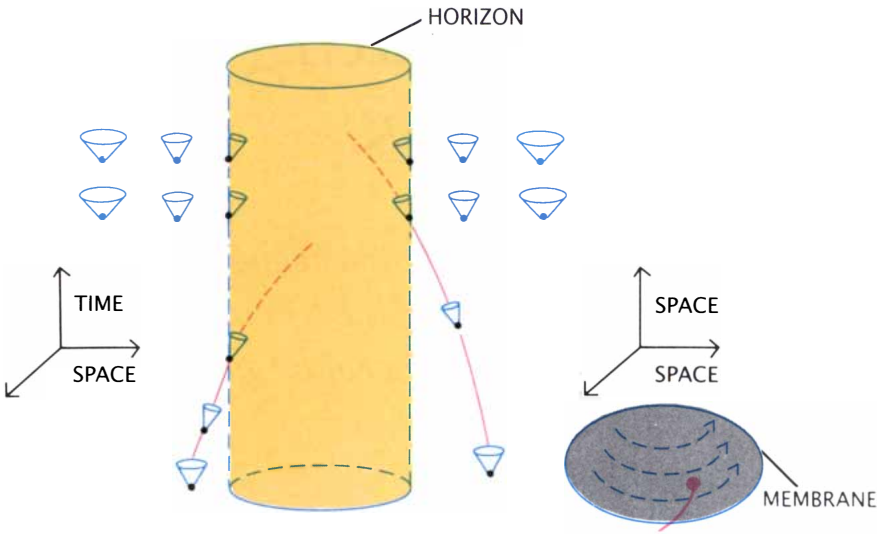
Can one understand black holes in simple, physical terms? Can these offspring of general relativity, which trap light, curve space and slow time, be added to the astrophysical catalogue of objects with intuitively clear behaviors? It is now widely accepted that black holes exist and have an astrophysical role, in particular as the likely power source of quasars: distant, pointlike beacons of light that shine as brightly as an entire galaxy. To understand this role with ease, we and our colleagues have developed a new paradigm for black holes—a new way to picture, think about and describe them. As far as possible it treats black holes as ordinary astrophysical objects, made of real material. A black hole, in our description, is a spherical or oblate surface made of a thin, electrically conducting membrane.

As theoretical entities black holes have a long history. Two hundred years ago the English physicist John Michell, and independently the French mathematician Pierre-Simon Laplace, predicted the existence of "dark bodies": astronomical objects with a gravitational pull so strong that light could not escape them. The prediction, based on Newton's corpuscular theory of light and his action-at-a-distance theory of gravity, did not survive for long. In the early 19th century, experiments revealed that light consists of waves rather than Newtonian corpuscles and set the stage for James Clerk Maxwell's wave theory of light. Laplace, seeing the foundation of his prediction crumble, retracted it.

In 1917, however, with the introduction of general relativity, Newton's description of gravity was displaced by Einstein's. Physicists then realized that even though Maxwell's light waves were immune to Newtonian gravity, they could be trapped by Einsteinian gravity. The first observational hints of this trapping came in 1919 during an eclipse, when astronomers saw that light rays from distant stars are deflected ever so slightly by the sun. From the equations of general relativity it was straightforward to deduce that if the sun were compressed while its mass stayed fixed, starlight grazing its surface would be deflected ever more sharply. Ultimately, when the sun's circumference reached 18.5 kilometers, the starlight would be trapped, as would any light emitted by the



LABORATORY ELECTRIC GENERATOR and the black holes powering quasars—distant, brilliant astronomical objects—may have some features in common. This simple generator extracts energy from a metal sphere spinning between the poles of a magnet. The motion of the conducting metal through the magnetic field lines produces a voltage difference between the poles of the sphere and its equator. Brushes make electric contact at the axis and the equator, and wires complete a circuit that powers a light bulb. The authors, building on the work of Roger D. Blandford and Roman Znajek of the University of Cambridge, argue that a black hole in a quasar can be viewed similarly, as a spinning membrane of conducting material interacting with a magnetic field.



IMAGES OF A BLACK HOLE differ in the curved-spacetime paradigm (*left*) and the membrane paradigm (*right*). Curved spacetime combines space and time in unified, four-dimensional spacetime. (The illustration omits one dimension of space.) "Light cones" represent the propagation through spacetime of light emitted at specific points; "world lines" (*red*) trace particle trajectories. Any particle that has mass must move more slowly than light; as a result light cones from points along its world line enclose the line completely. Far from the black hole all light cones open directly upward; nearer the hole they all tilt inward as the gravity of the hole affects light's propagation. A vertical surface called the horizon is tangent to the outer edges of light cones. Hence a photon of light can hover there, moving along the line of tangency, but a massive particle must fall through the horizon into the hole. In the membrane paradigm the black hole is pictured in ordinary, three-dimensional space as a spheroidal membrane that has the same circumference as the horizon of curved spacetime. The spheroid is flattened because the hole is rotating. Photons (*blue*) can hover on the membrane, where they are swept around by rotation; massive particles fall through the membrane into the hole.

sun. The sun would become a dark body, superficially similar to the dark bodies of Michell and Laplace.

The physical structure of general relativity's dark bodies is radically different from that of the 18th-century dark bodies, however, and wonderfully richer. They are not made of matter, although they have mass and might be created from stellar matter by a process of gravitational collapse. Once formed they consist of curved spacetime, wrapped up on itself so tightly that it holds in light—a structure that was impossible to imagine before Einstein. In 1968 John Archibald Wheeler of Princeton University coined the name black holes for these objects.

It had taken more than four decades for theoretical physicists to accept black holes as a serious prediction of general relativity, a prediction worth searching for in the real universe. Astronomers were even more resistant to the idea. Until the mid-1960's many astronomers regarded the universe as a tidy place in which most phenomena were known and understood—an environment in which there was no place for something as bizarre as a black hole.

This view was shaken, however, by the discovery of quasars in 1963. Their enormous outputs of energy meant that a titanic mass would be needed to power them, but their rapid fluctuations in luminosity suggested that their central power source had to be very compact. Large mass and small size implied the existence of an intense gravitational field, and suspicions began to focus on black holes. Then, in 1967, came the discovery of pulsars, objects that emitted pulses of radio waves with apparently inexplicable regularity. Within a year they were understood as rotating neutron stars, fantastically dense objects with about the mass of the sun but with a circumference of only about 60 kilometers. That is just three times the size of a black hole with the same mass: squeeze a neutron star by a factor of three, general relativity insisted, and it would become a black hole.

Since then further surprises and puzzles have beamed their strange signals into telescopes, radio dishes and other detectors at a rate that keeps astronomers from feeling secure in their preconceptions. Black holes, created by the gravitational collapse of one or many stars, have become a possibility astronomers routinely consider in trying to explain their observations. In particular, it is now just short of establishment doctrine that a black hole with the mass of at least 100 million suns is the prime mover in a quasar.

An astrophysical role for black holes creates some awkwardness, the nature of which is brought out by Thomas S. Kuhn's concept of a paradigm. Kuhn, a physicist turned philosopher and historian of science, introduced the term in the mid-1960's to describe the full set of tools a community of scientists uses to study a specific topic. The paradigms of theoretical physics, for example, encompass equations embodying the relevant laws of physics, many specific problems that have been solved with those equations and—most important for our purposes—a set of pictures or diagrams with a matching vocabulary, expressing some of the mathematics in a powerful and heuristic way. The pictures, diagrams and vocabulary are the key to physical intuition, and the intuition makes possible the sudden leaps of insight that quickly advance the frontiers of knowledge. The mathematics, of course, is the ultimate arbiter; only it can say whether the leaps of insight are correct.

In the 1960's and 1970's physicists developed an elegant and powerful paradigm for black holes: the curved-spacetime paradigm. Its mathematics is that of general relativity, which describes space and time as a single four-dimensional entity. Its characteristic pictures are spacetime diagrams, which span time and two of the three dimensions of space. Curves known as world lines trace the trajectories of particles such as photons (packets of light) through spacetime.

A black hole, in such a spacetime diagram, is represented by a cylindrical surface called the horizon, where spacetime is curved so sharply by intense gravity that photons are trapped on or inside the surface. The horizon marks a point of no return: photons and every other kind of particle can fall through the horizon into the interior of the hole but none can emerge. The horizon cuts off all communication between the hole and the rest of the universe.

These diagrams and the other tools of the curved-spacetime paradigm have yielded deep insight into the physical nature of black holes that

live in isolation, away from the influence of the external universe. Such insight was not enough for astrophysicists, however. Understanding a black hole as an astrophysical object—as the power source in a quasar, for example—requires understanding how the hole interacts with the gas and magnetic fields in its surroundings. Unfortunately those interactions cannot be studied with any ease in the curved-spacetime paradigm. Curved spacetime is fundamentally incompatible with the mental images on which astrophysicists base their insights about magnetized plasmas (hot, ionized gases). It is couched in the language of unified, four-dimensional spacetime, whereas descriptions of magnetized plasmas are in the more familiar language of three-dimensional space, with time completely separate.

How, then, have black holes been treated by astrophysical theorists seeking to explain quasars? Until the late 1970's workers generally dodged the incompatibility of language and images by avoiding the curved-spacetime paradigm. Instead of viewing gravity as a curvature of spacetime they went back to the Newtonian paradigm of gravity as an attractive force. Where gravity is weak, as it is far from the horizon, the predictions of Newtonian and Einsteinian gravity agree to high precision; where the agreement breaks down, as it does close to the horizon, the theorists artificially cut off their calculations.

Early models of quasars applied this approach to describe how the accretion of matter could provide a power source. A black hole in a region of dense interstellar gas will draw in material by its gravity; the inflow will be spherical if the gas has little angular momentum but will become concentrated in a disk in the more typical case of rotating material. As the gas flows inward it will be compressed and heated, and like any hot gas it will emit radiation in such forms as radio waves, light and X rays. In calculating the emission of energy, theorists included radiation from a region extending almost to the point at which Einsteinian gravity would produce a horizon; there the calculations were cut off by fiat.

This approach might seem rather crude, but the errors it introduced were modest compared with the uncertainties about physical processes in the turbulent, hot accreting gas. Attempts (by the authors and others) to model the same process in the more accurate curved-spacetime paradigm were hardly worth the effort. In dealing with the gravitational pull of a black hole, then, the astrophysical failings of the curved-spacetime paradigm could be avoided.

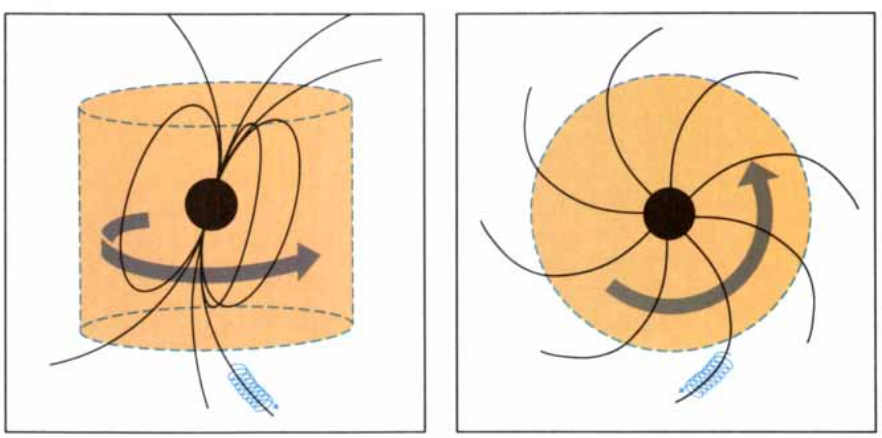
Yet gravitational pull is not a black hole's only source of energy. As Roger Penrose of the University of Cambridge showed in 1969, a black hole can store enormous amounts of energy in the form of rotation. James M. Bardeen of the University of Washington pointed out soon afterward that black holes are likely to spin rapidly in the real universe: as matter rotating at typical rates collapses to form a black hole or accretes onto an existing hole, it will whirl faster and faster as it moves inward, driving the hole into rapid rotation. A hole's rotational energy offered an intriguing alternative possibility for powering a quasar.

Numerical estimates made rotation seem particularly attractive as a power source. A black hole of a given mass has a maximum rotation rate: if the imploding or accreting matter rotates too fast, centrifugal forces counteract the inward pull of gravity and prevent the matter from falling into the hole and further amplifying its spin. Most black holes probably spin at just about their maximum rate, which makes it possible to estimate the amount of energy stored in their rotation. The rotational energy in a black hole as massive as 100 million suns (about 3×10^{48} kilowatt-hours) would be about right to keep a typical quasar shining at its observed luminosity for its longest plausible lifetime, several billion years.

Until 1977, however, no one could find an astrophysically believable mechanism for extracting that rotational energy. The Newtonian picture of black holes offered no clues to a mechanism: in Newtonian physics a gravitational field behaves exactly the same way when its source is rotating as it does when the source is stationary. There is a rotationally induced component of a gravitational field that is a purely Einsteinian, relativistic phenomenon, one that cannot be simulated in any way with Newtonian gravity.

The search for an energy-extraction scheme continued, however, and in 1977 Roger D. Blandford of Cambridge and his graduate student Roman Znajek managed to use the mathematics of general relativity to show that magnetic fields threading the horizon of a black hole can tap its rotational energy. When we studied the mathematical analysis, we had to agree. The mathematics was clear. But for us the physical, intuitive picture was fuzzy: we had no simple images or language to describe the interaction of the rotating hole and the magnetic field.

It was our quest to understand the Blandford-Znajek process intuitively that led us to create the membrane paradigm. Our strategy was to translate the general-relativistic mathematics of black holes into the same language of three-dimensional space that is used for magnetized plasmas and to create a new set of black-hole



PULSAR'S POWER OUTPUT can be understood by imagining magnetic field lines "frozen" into the conducting interior of a spinning neutron star (*left*)—the compact, fantastically dense object at a pulsar's center. Beyond a certain radius (*cylinder*) the field lines whirl through space faster than light. Charged particles spiraling around the lines cannot keep pace; the result, shown from above (*right*), is that they bend the lines backward and slide outward along the lines at slightly less than the speed of light. Thus rotation of the star drives an outflow of plasma that is ultimately transformed into radiation.

diagrams and pictures to go along with the language. The translation was undertaken in the early 1980's by a group of investigators who were then at the California Institute of Technology but are now scattered over the U.S. and Europe. The Caltech Paradigm Society, as it came to call itself, included Douglas A. MacDonald, Wai Mo Suen, Ian H. Redmount, Xiao-He Zhang, Ronald J. Crowley, Wojciech H. Zurek and us.

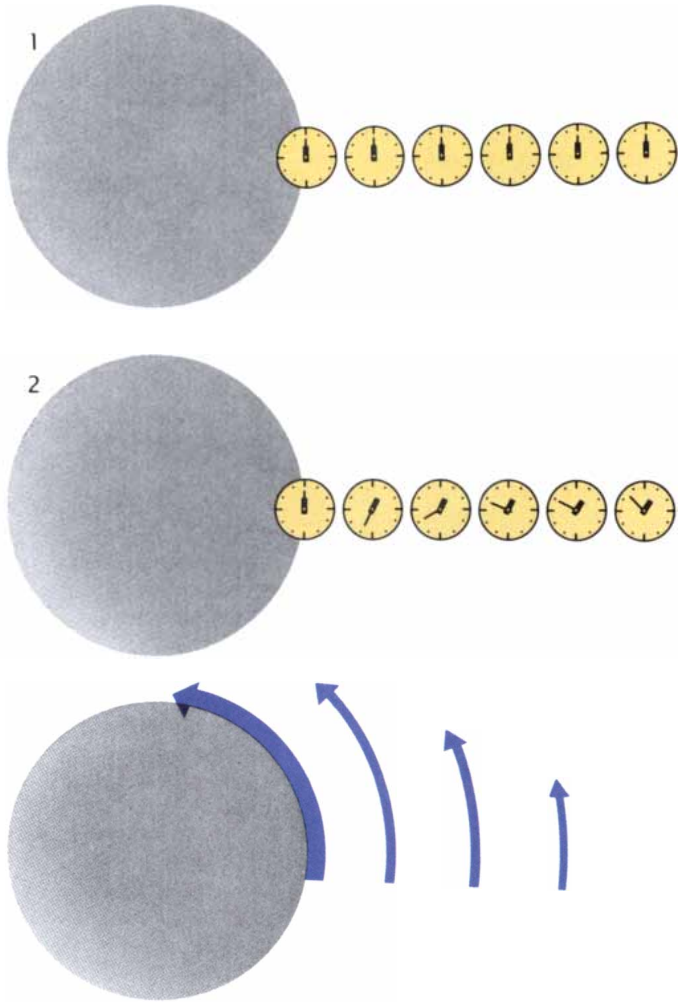
The membrane paradigm seeks to treat a black hole as a simple, three-dimensional object that is not greatly different from its closest cousin, a neutron star. A rotating neutron star energizes a pulsar by way of magnetic fields. The standard description of the pulsar mechanism was a model for the kind of picture we hoped to develop for understanding energy extraction in quasars, and so it is worth reviewing here.

In spite of its name a neutron star, formed by the collapse of a massive star's core, contains not only neutrons but also protons and electrons, which make it highly conducting, even superconducting. Electric currents persist almost indefinitely in a neutron star, as do the magnetic fields they create. In appropriately pictorial, paradigmatic language, these magnetic fields are described as being "frozen" into the highly conducting material.

The neutron star, then, resembles a permanent magnet; it can be imagined as having magnetic field lines emerging from a north-polar region, looping out through space and swinging back into the star at a south-polar region. This astrophysical magnet spins. The normal stars from which neutron stars are created always rotate, at least a little, and the collapse that forms the neutron star amplifies the rotation. Hence most neutron stars are expected to be born spinning quite rapidly, with a period of between a thousandth of a second and one second. Since a neutron star's magnetic field is frozen into its electrically conducting interior, the magnetic field lines must also rotate.

The mental image of magnetic field lines suggests an important consequence of the rotation: even if the neutron star is turning slowly, at a sufficiently large remove these imaginary lines will be whirling through space at a speed greater than that of light. Charged particles (plasma) in the neighborhood of the neutron star are frozen to the field lines just as the field lines are frozen in the neutron star's interior. But since the particles cannot move faster than light, they resist the lines' rotation by bending them backward and sliding outward along them at velocities just under the speed of light. The field lines thereby act as levers for transferring the energy of the star's rotation to outflowing plasma.

The details of how this energy is transformed into pulsed radio emission and other phenomena typical of pulsars are complicated and are not at all the point here. The point is that one can get a good general grasp of the nature of pulsars and their influence on their surroundings with simple intuitive aids (magnetic field lines) and rules of thumb (the freezing together of field lines and conductors). These are the kinds of thought tools we should like to have for understanding how a magnetic field might extract the rotational energy of a black hole.



TIME AND SPACE are affected by the horizon of a black hole. At the top, clocks belonging to observers at various distances from the horizon are followed for an hour of "universal" time—time as it is measured far from the hole. Initially synchronized (*1*), the clocks show different times after the hour has passed (*2*). Because of gravitational time dilation the clocks tick more slowly compared with universal time the closer they are to the horizon; the reading of a clock just outside the horizon has not changed at all. At the bottom, the motion of observers (*arrows*) at various distances from a spinning black hole is viewed from a distance. An observer just outside the horizon circles the hole in step with its rotation; more distant observers orbit more slowly. Each observer is at rest in "absolute space," but space itself is dragged along by the rotation of the hole.

Our first order of business was to take black holes out of four-dimensional spacetime and describe them in three-dimensional space. We did so not only to make black holes easier to picture but also because in spacetime magnetic fields do not

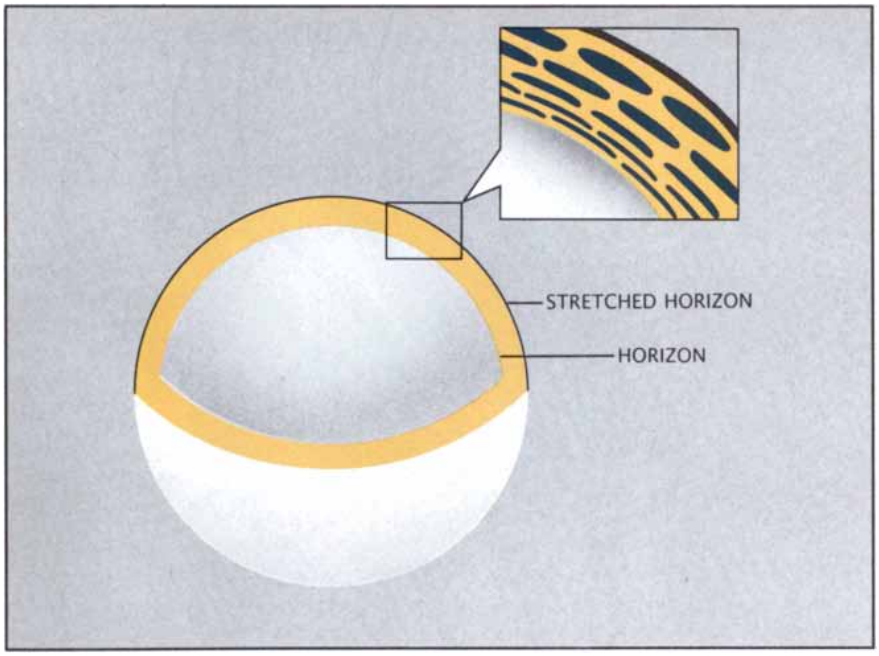
exist as distinct entities. Rather, they lose their separate identity and merge with electric fields in a single, unified electromagnetic field, which wreaks havoc with ordinary physical intuition. In order to divide the unified field into separate magnetic and electric fields, we had to reestablish a three-dimensional space consistent with the mathematics of unified spacetime.

To do so we needed a set of observers. An observer, in Einstein's theories, can be thought of as a being who carries a small framework of aligned measuring rods and a set of synchronized clocks for marking the location of events and measuring velocities, accelerations and so on. Relativity theory insists that two observers at the same point who are moving with respect to each other will measure different values for many physical quantities. Perhaps more shocking is the insistence that the observers will differ in their definition of three-dimensional space. They will disagree about which points in spacetime occur at the same time—which points make up three-dimensional space at that moment.

Three-dimensional space and with it an independent magnetic field, then, can be defined only in terms of a specific observer. In the membrane paradigm we recover an independent magnetic field, and the ability to imagine magnetic field lines around a black hole, by choosing a specific observer in each region of spacetime. The result is a family of observers who make a three-dimensional "slice" through spacetime and thereby define which part of the electromagnetic field is electric and which part is magnetic. We call these observers FIDO's, for fiducial observers. It is from their point of view that we examine the physics near the hole. Having chosen our FIDO's, we can begin talking about black holes in familiar, three-dimensional language.

To give the membrane paradigm simplicity and power, the FIDO's must be chosen according to strict mathematical rules. As it happens, these rules appear quite natural when they are translated into words and pictures. Each FIDO must remain at the same distance from the black hole and at the same latitude with respect to the hole's axis of rotation. The FIDO's also have a specific state of orbital motion: they are all, in a very special sense, at rest in three-dimensional space.

Does "at rest" mean that each FIDO, at any distance from the hole, is at rest with respect to distant stars? No: a rotating gravitational field tugs "absolute space" along with it. Near the earth the effect is expected to be minute, but it is dramatic near a rotating black hole: the hole drags space, and with it the FIDO's, into motion just as a golf ball spinning in maple syrup would drag along nearby syrup. The FIDO's, in this analogy, are at rest in the syrup (absolute space), but the syrup rotates with respect to the walls of the kitchen (the distant stars). Close to the horizon the FIDO's and the space they inhabit rotate nearly as fast as the hole itself (once every 90 minutes for a rapidly rotating black hole of 100 million solar masses); far from the horizon they are almost stationary with respect to distant stars.

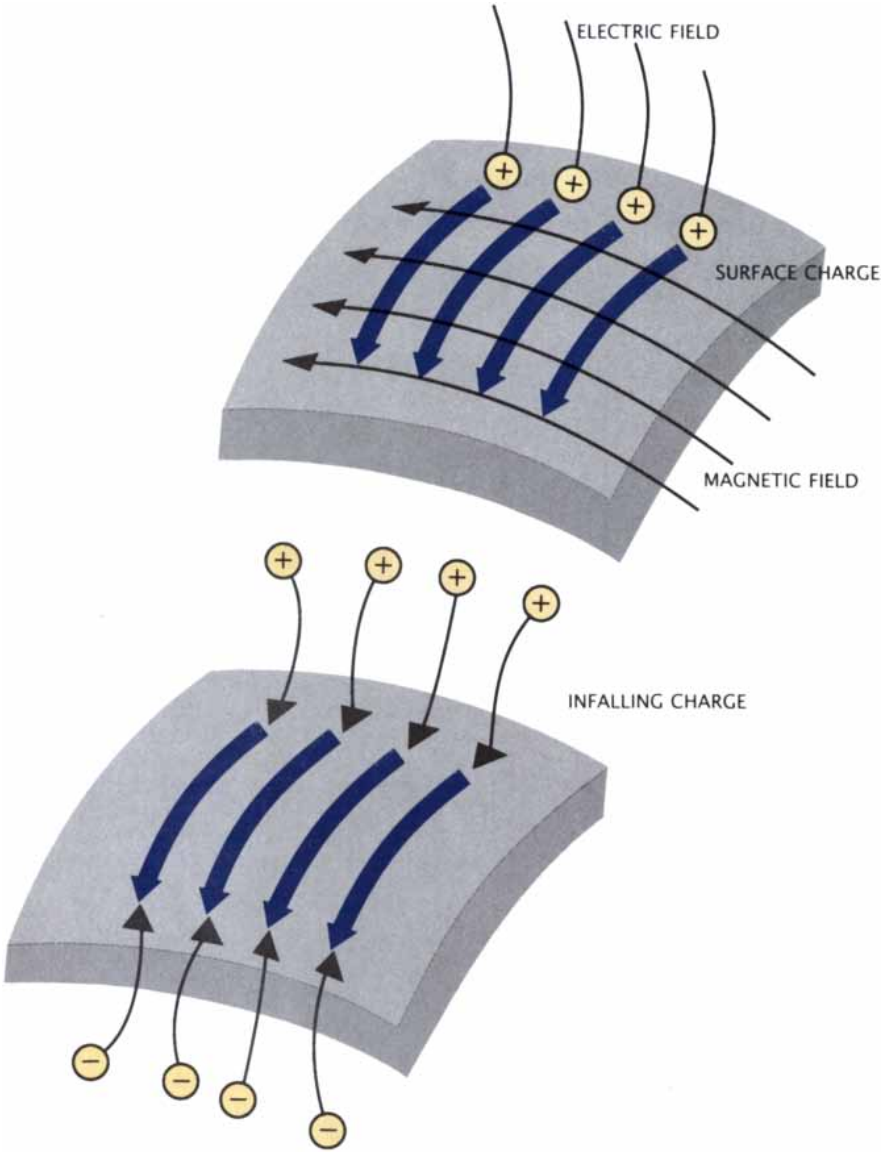


STRETCHED HORIZON, an imaginary surface just outside the black hole's true horizon, is taken to be the hole's boundary in the membrane paradigm. The horizon itself cannot be studied in the paradigm because no physical observer can be placed there. Between the stretched horizon and the actual horizon is a clutter of matter and fields that have accreted onto the hole since its formation; because of gravitational time dilation, material approaching the horizon falls ever more slowly (from a distant observer's point of view) and never quite penetrates the hole's interior. These "sediments," which are irrelevant to astrophysical processes, are hidden by the stretched horizon.

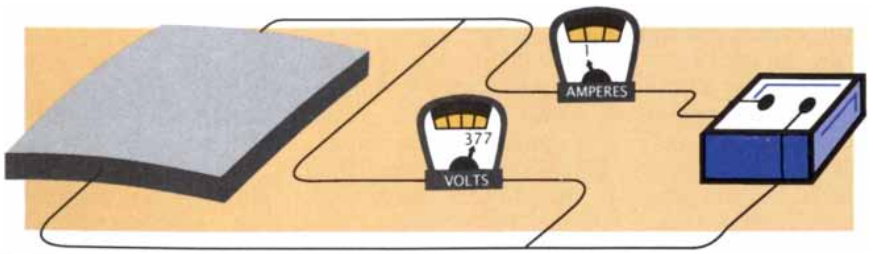
Speaking of rotation rates in this way suggests a universal standard of time. But to an observer watching from afar, the FIDO clocks appear to tick at different rates. The closer a FIDO is to the horizon, the slower his clock will appear to run. Clocks belonging to FIDO's arbitrarily close to the horizon tick arbitrarily slowly. This phenomenon, called gravitational time dilation, also occurs in the earth's gravitational field, but there it is tiny: a difference of one part in a billion between the ticking rate of a clock on the earth and one on a geosynchronous satellite.

The clock time of a specific FIDO can serve for describing physics at a point. But in order to enable the membrane paradigm to cope with large-scale physical processes that involve an extended region of space we define a second kind of time. We imagine at each point a clock adjusted in rate and starting time so that clocks close to the horizon keep time with clocks farther away in spite of the strong gravitational field. These adjusted clocks, then, define a "universal" time that ticks at the same rate everywhere, like the time of classical physics and our (nonrelativistic) intuition.

Our family of FIDO's suffers one major embarrassment: no FIDO can possibly reside at or inside the horizon. At the horizon the gravitational field is so strong that only photons, which move at the speed of light, can hover there. FIDO's, being physical observers, must move more slowly than light. If any FIDO were to find himself at or inside the horizon, he would fall toward the center of the hole. His distance to the horizon would necessarily change, and so he



SURFACE CHARGES AND CURRENTS develop on the stretched horizon in the membrane paradigm, as they would on a membrane of conducting material. Like a true conductor, the membrane develops surface charge in response to a perpendicular electric field; similarly, it develops a surface current (*blue*) in response to a parallel magnetic field (*top*). The density of charge and the amount of current are just enough to shield the interior of the membrane from the external fields. When charged particles fall toward the black hole (*bottom*), they are imagined as accumulating on the membrane. The charge is conserved, and it gets redistributed over the membrane by surface currents.



MEMBRANE HAS ELECTRICAL RESISTIVITY, like most conducting materials; the precise value, 377 ohms, means that 377 volts would be needed to drive one ampere of current across a square patch of membrane. This relatively high value is also the resistivity of a material capable of completely absorbing all electromagnetic signals striking it. The membrane material thus mimics the true horizon's ability to absorb all radiation.

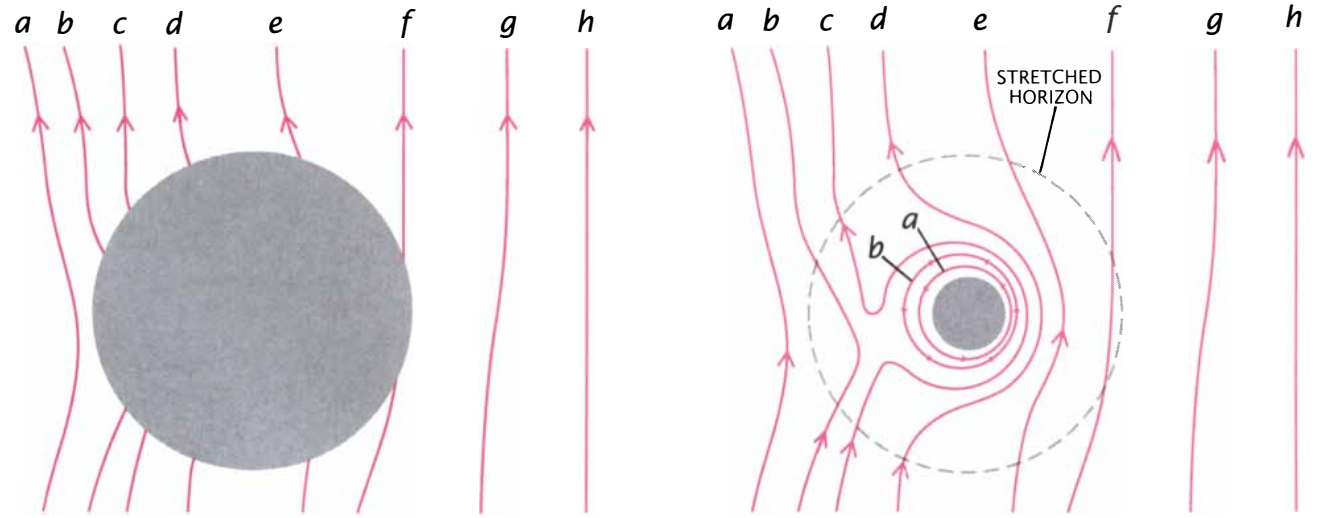
would violate our rules for the choice of FIDO's. Because we cannot place a FIDO at the horizon, the membrane paradigm's absolute space must stop just short of it.

This omission seems less distressing when one examines physics arbitrarily close to the horizon. As seen from afar, physical clocks tick progressively slower as they approach the horizon. Correspondingly, every physical process slows to an infinitesimal pace there. For example, if a marble is dropped into the hole and its fall is timed by a distant FIDO, the marble falls rapidly at first but then slows as it nears the horizon. It gets plastered onto the horizon, moving inward at an exponentially dying rate but orbiting the hole in lockstep with the hole's rotation.

As seen by a FIDO hovering near the horizon, in contrast, the falling marble is accelerating to nearly the speed of light, and it undergoes the "Lorentz-FitzGerald contraction" that affects objects moving at relativistic speeds. The FIDO sees the marble become compressed to arbitrary thinness as it falls past him. (From the point of view of a third observer, who falls into the hole together with the marble, it plunges through the horizon without slowing or contracting. Such is the peculiarity of time and space in general relativity!)

In this way, according to the FIDO-based membrane paradigm, the horizon becomes cluttered with remnants of the past, accumulating in infinitesimally thin layers like sediments on the ocean floor. This layered structure, doomed to sink exponentially closer to the horizon, has no bearing on the rest of the universe. Since the membrane paradigm is designed for astrophysical intuition, its inability to offer insight into processes at or inside the horizon is not a handicap. Indeed, we sweep them under the rug in the membrane paradigm by constructing a new, "stretched horizon" just outside the true horizon and ignoring everything inside it.

If we are to abandon the study of all matter and fields inside the stretched horizon, the influence of the hole on its environment must be expressed in terms of this new surface. Specifically, the interplay of FIDO-observed magnetic and electric fields on the stretched horizon must mimic the effect of the actual horizon on the electromagnetic field, an effect we have deduced from the old, curved-spacetime paradigm. Hence



THOUGHT EXPERIMENT in which a black hole travels across an intense magnetic field is a test of the membrane paradigm. The paradigm holds that the stretched horizon acts as a conducting sphere with a surface resistivity of 377 ohms (*left*). Magnetic field lines sliding across such a sphere would excite surface eddy currents and become slightly distorted; at the same time the sphere would experience a modest drag. A view inside the stretched horizon (*right*) reveals that the field lines in fact do not cross the horizon; they wrap around it and eventually pinch off as loops. These complexities, shrouded by the stretched horizon (shown much farther from the true horizon than it actually is), have no effect on the black hole's astrophysical interactions.

we define the properties of the new paradigm's stretched horizon so that it influences the FIDO-measured fields in a way that is consistent with the predictions of curved spacetime.

Znajek and, independently, Thibaut Damour of the University of Paris showed in 1978 that there is a resemblance between the equations describing the electromagnetic field at the horizon and those relating electric and magnetic fields in conducting material. In the membrane paradigm we exploit this resemblance. We treat the stretched horizon as a spherical or (if the hole is rotating) oblate membrane of electrically conducting material.

Like every other conductor, this stretched-horizon membrane develops surface charge in response to an external, perpendicular electric field, and specifically just the right distribution and concentration of charge to terminate the perpendicular electric field lines and prevent them from penetrating its interior. This shielding accords with Gauss's law, which states that electric field lines can only start and end on electric charges. The membrane also develops a surface current in response to a parallel magnetic field, in keeping with Ampere's law, which relates magnetic fields to electric currents. In the membrane the surface current has just the right value to shield the interior from the parallel magnetic field.

It turns out that general relativity's description of the electromagnetic field at the horizon is beautifully and simply expressed in terms of membrane charges and currents. One aspect of the description is fulfilled by regarding the membrane as obeying the law of conservation of charge. Whenever real electric charge, carried for example by electrons or positrons, falls into the hole, the charge can be regarded as changing into membrane surface charge as it hits the stretched horizon. The charge then moves from place to place on the membrane in the form of membrane surface currents. Charge is neither created nor destroyed, from this point of view. The sum of the real charge in the black hole's environment and the fictitious (but intuitively powerful) charge accumulated on the membrane remains constant.

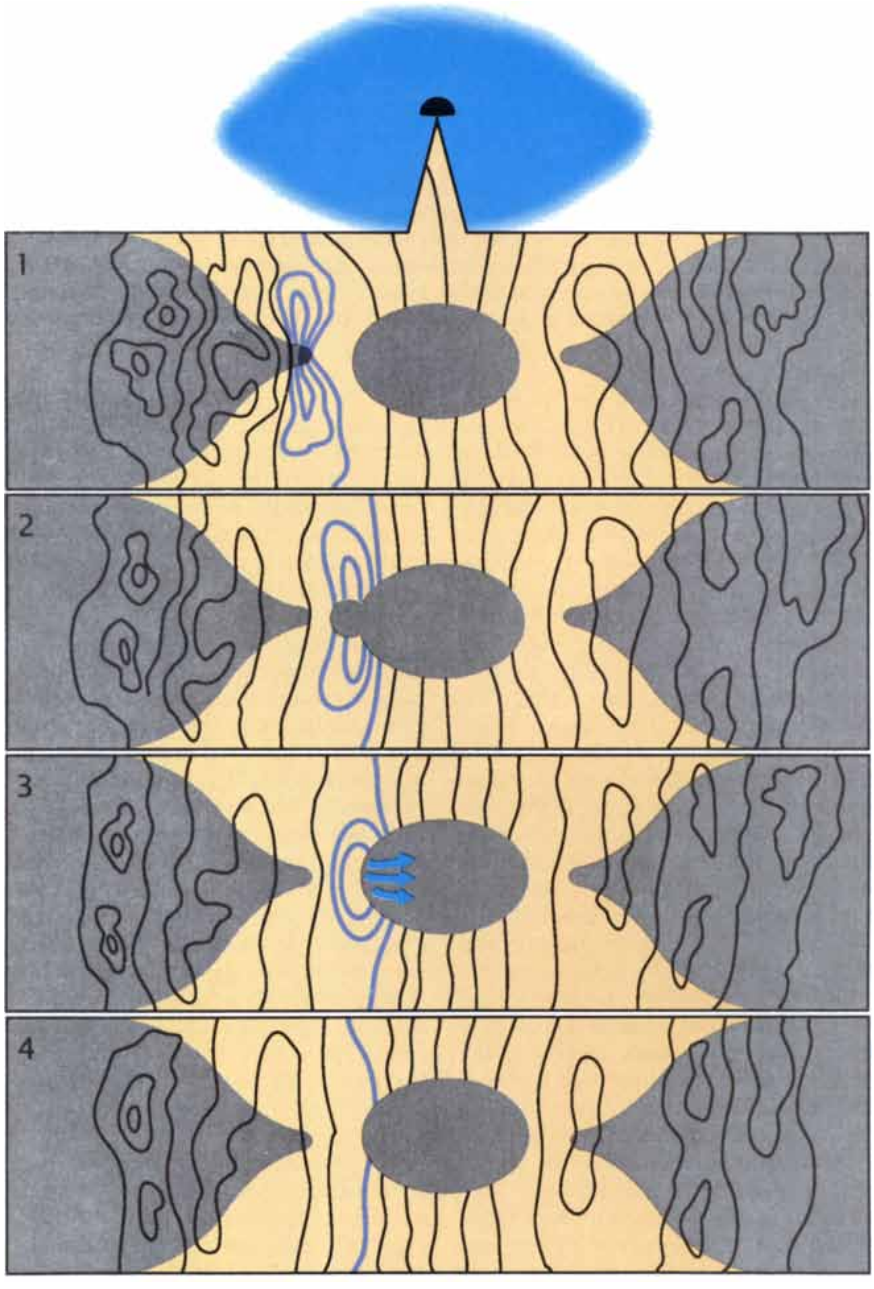
A second aspect of the description takes the form of an equally simple stipulation, a variant of Ohm's law, which relates currents to the electric fields that drive them. Nearly every conductor offers some resistance to the flow of current; for a thin sheet of conductor the resistance is quantified as surface resistivity. The mathematics of general relativity, translated into the membrane paradigm, specifies a precise value for the surface resistivity of the membrane. It is 377 ohms, which is to say that an electric field of 377 volts would be needed to drive one ampere of current across a square patch of membrane material. This resistivity is quite high compared with that of, say, a copper sheet (a copper sheet one millimeter thick has a surface resistivity of .000018 ohm), and it has a special significance: it is the surface resistivity of a perfect absorber of electromagnetic radiation. The 377-ohm resistivity is the manifestation in the membrane paradigm of the fact that radiation can flow only into and not out of the hole.

In the context of astrophysics our main concern is not how a black hole interacts with radiation (rapidly oscillating electromagnetic fields) but how it interacts with large-scale magnetic fields that change relatively slowly. To see how viewing the hole as a conducting membrane is an aid in picturing such interactions, consider a simple thought problem. An intense magnetic field, like that in the gap of a laboratory magnet, exists somewhere in a galaxy far, far away. A black hole enters the intense field on a path perpendicular to the field lines. How does the hole influence the field, and how does the field affect the hole's motion?

The membrane paradigm suggests that the hole will interact with the field in roughly the same way as would a spheroidal membrane of conducting material with the same circumference as the horizon and a surface resistivity of 377 ohms. When a conducting surface enters a magnetic field, according to electromagnetic theory, the surface currents ("eddy currents") that are induced contribute a new component to the magnetic field, thereby distorting the original field lines. At the same time

the external field exerts a force on the induced currents, retarding the conductor's passage.

The membrane paradigm thus provides a picture in which the field lines are distorted slightly as they brush over the stretched horizon. At the same time the hole experiences a modest drag, whose precise value can be calculated by solving the equations of the membrane paradigm. It is worth emphasizing that the mathematics of the curved-spacetime paradigm yields exactly the same result. The advantage of the membrane paradigm is that the picture is obvious and intuitive; before any calculations are done it gives a feel for the nature and amount of distortion and drag.



ORDERLY MAGNETIC FIELD could build up on the stretched horizon of a black hole at the center of a quasar. The hole is surrounded by a doughnutlike accretion disk of hot, ionized gas (*top*). When a blob of plasma from the inner edge of the disk plunges into the stretched horizon (*1, 2*), it drags along a tangle of chaotic magnetic field lines (*color*). As the chaotic field sinks in, it drives eddy currents (*arrows*) that dissipate the energy of the tangles by flowing through the highly resistive membrane (*3*). Only the orderly line extending beyond the hole persists, joining other lines deposited earlier (*4*).

It does so in part by hiding irrelevancies. If we put aside the membrane viewpoint for a moment and take a peek inside the stretched horizon, we find that, because of gravitational time dilation, the field lines never cross the horizon. Instead lengths of field line become wrapped around the black hole and eventually pinch off, forming loops that shrink inward toward the horizon. These tightly wrapped lines are an example of the layered remnants of the past that are shrouded by the stretched horizon. Only the modest distortion of the lines is astrophysically important, and only it is visible outside the stretched horizon.

How does the membrane paradigm help us to understand the more complex interaction of a rotating black hole and a magnetic field that may power a quasar? The paradigm emphasizes that black holes cannot maintain a magnetic field on their own, as the magnetized neutron stars that drive pulsars do. The resistance-free flow of current in the interior of a neutron star can sustain a magnetic field almost indefinitely, but the black-hole membrane's high resistivity means that similar currents there would be dissipated within a few minutes, and the magnetic field would die out. To have a role in powering a quasar, a magnetic field would have to thread the stretched horizon for the quasar's full lifetime.

There is an external source for such a field: the interstellar gas being drawn into the hole. All interstellar gas harbors magnetic fields, and the field lines become frozen into the gas as it is heated and ionized near the hole. Rotation and turbulence in this accreting plasma drive the field lines into a chaotic tangle, parts of which are deposited onto the stretched horizon by infalling clumps of plasma. Eddy currents flowing through the membrane continually dissipate the energy of the chaotic field, leaving orderly, "cleaned" field lines threading into the membrane at a south-polar region and out again at a north-polar region. Once an orderly line has been deposited on the hole, it cannot be dissipated; the accretion disk's plasma and magnetic field hold it in as long as the disk is not blown away or swallowed by the hole. In this way the hole acquires a magnetic field of perhaps 10,000 gauss (more than 10,000 times stronger than the earth's magnetic field).

How does this orderly field rotate?

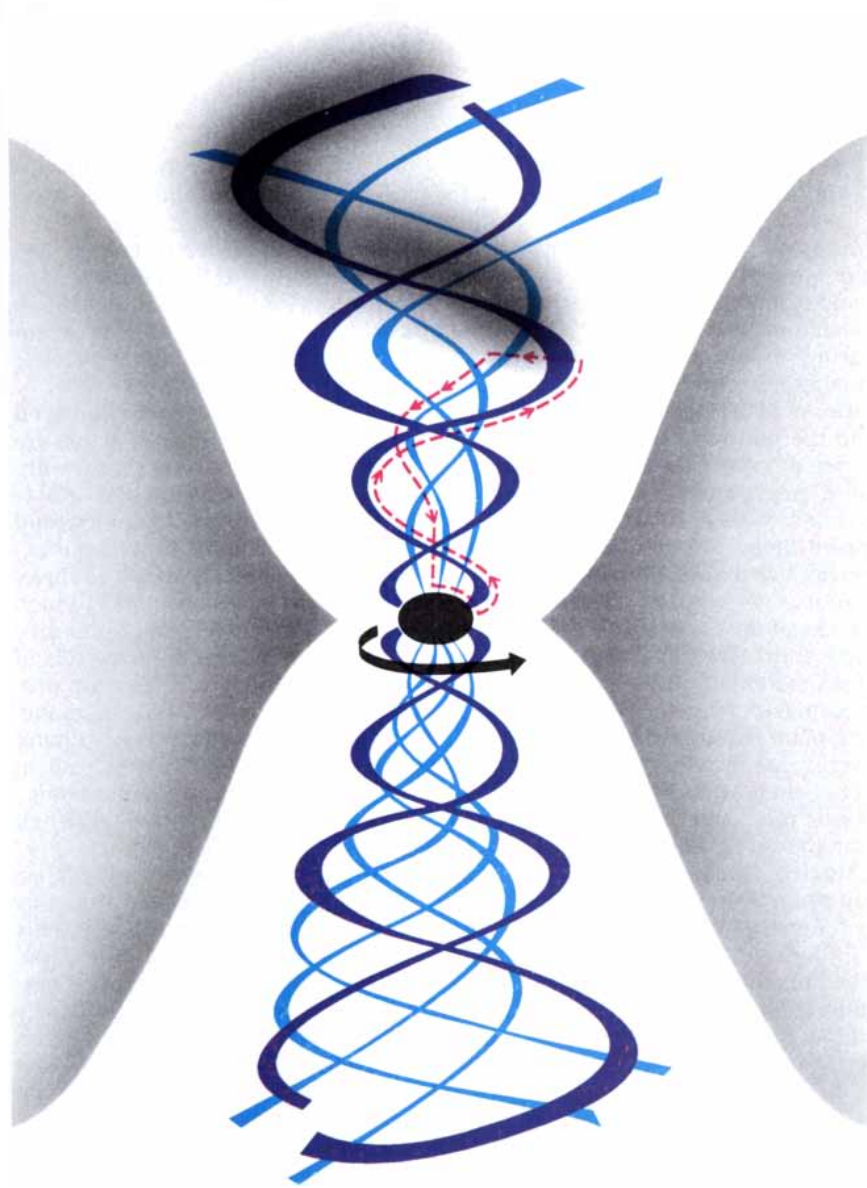
If, like a neutron star, the membrane had an electrical resistivity of zero, the field lines would be frozen into the membrane and would be forced to rotate at the same rate. If its resistivity were infinite, the lines could slip freely across the membrane and so avoid rotating. The actual resistivity of 377 ohms suggests that the lines will tend to rotate along with the membrane, but with some slippage. The image for energy transfer in pulsars, then, applies equally to quasars: the lines, whirling even though they slip, act as levers to fling plasma outward at great speeds, transforming the hole's rotation into a rapid outflow of gas.

The membrane paradigm suggests a second and equally valid way of thinking about this same process, a way that offers quantitative as well as qualitative insight into the energy transfer. The motion of any magnetic field generates an electric field. In the case of a rapidly rotating, magnetized black hole, the electric field generated near the stretched horizon can produce an enormous voltage difference between the poles of the membrane and its equatorial region: as much as 10^{20} volts. It is as though the stretched horizon were a huge battery.

The magnetic field lines carry current driven by the voltage difference to distant parts of the quasar, linking the membrane with its environment in a gigantic direct-current circuit. Positive charge flows up field lines from the equatorial region of the membrane, in the form of an excess of negatively charged particles falling into the hole; it flows back down other field lines to the polar regions, in the form of an excess of positively charged particles. Current flows from polar to equatorial regions on the stretched horizon, completing the circuit at one end. At the other end, far from the hole, current crosses from equatorial to polar field lines through the intervening plasma.

The resistivity of this distant load region is probably similar to that of the membrane. As in any earthbound circuit, such "impedance matching" of the generator and the load region leads to the greatest possible transfer of power. About half of the energy in the circuit is deposited in the distant plasma and half is dissipated in the form of "waste heating" of the stretched horizon.

The net result is that the plasma in the load region is accelerated outward, in keeping with Blandford and Znajek's original calculations. Through complex processes of plasma physics some of the plasma's kinetic energy may then be transformed into the intense radiation of a quasar. The accelerated plasma may also feed the focused jets of ionized gas that are seen emerging from the nuclei of many quasars, often stretching out into space for many light-years [see "Cosmic Jets," by Roger D. Blandford, Mitchell C. Begelman and Martin J. Rees; SCIENTIFIC AMERICAN, May, 1982]. It is likely—but far from certain—that many quasars are powered in this way. The membrane paradigm has thus enabled us to picture some of the processes that link a black hole with the rest of the universe.



ROTATING BLACK HOLE might power a quasar by whirling the magnetic field lines that thread the stretched horizon. Plasma frozen to the field lines far from the hole retards them and twists the field. The mechanism by which the lines transfer the hole's rotational energy to the distant plasma can be viewed as a giant direct-current circuit. The rotating magnetic field induces an enormous voltage drop between the poles of the stretched horizon and its equator. Current (*color*) is driven from the poles to the equator and then out along field lines to a great distance, where it crosses to polar field lines and returns. As it crosses, the current deposits its energy in the intervening plasma and accelerates it outward. This hypothetical but plausible mechanism could explain quasars' luminosity and the jets of gas often seen emerging from their center.

Energy-efficient Buildings

Energy conservation and economic development can go hand in hand. Efficiently designed homes and offices will slash energy bills, liberate investment capital and avoid the expense of building new power plants

by Arthur H. Rosenfeld and David Hafemeister

Jimmy Carter and Ronald Reagan are not known for holding similar opinions on questions of national policy, but on the subject of the energy crisis both presidents shared the view that conservation was a remedy that necessarily demands a decline in living standard. President Carter, in his politically disastrous "malaise" speech, called on Americans to make sacrifices in order to end the nation's "intolerable dependence on OPEC oil." Eighteen months later, president-elect Reagan derided conservation as an approach that meant being too cold in winter and too hot in summer. Both men, to put it plainly, were wrong. Since the oil shocks of the early 1970's Americans have enjoyed a 35 percent rise in the gross national product without increasing their energy consumption. The main reason is that the services energy can provide—comfort, mobility, a cold beer on a hot day—are generated much more efficiently today than they were back in 1973.

Much of the decline in energy consumption is due to the more efficient use of energy in homes and offices. In buildings, new technologies and better management of lighting, heating and ventilation systems have cut $45 billion from the nation's energy bills. More tangibly, in spite of the addition of 20 million households and 15 billion square feet of commercial and residential floor space, heating-fuel demand has dropped by 1.2 million barrels of oil per day, an amount equivalent to two-thirds of the output of the Alaska pipeline. (The output of the pipeline, 1.9 million barrels per day, is henceforth referred to as an "Alaska.") The 125 million household refrigerators and freezers in operation today require the electricity from 30 standard 1,000-megawatt power plants. If they were as inefficient as the average 1975 model, they would require 50 power plants.

The size of these savings is not surprising. After all, the buildings sector, rather than transportation, is the single largest consumer of energy—40 percent—in the U.S. economy. For electricity alone, the sector accounts for an even larger share: 75 percent of the nation's $150-billion electric bill is consumed in buildings.

All told, the savings from improved "end-use efficiency" in all sectors are enormous. If Americans today were to use as much energy per unit of G.N.P. as they did in 1973, they would need 35 percent more fuel than is actually being consumed. If one looks at the savings in oil and gas (which are interchangeable), this difference is equivalent to 13 million barrels of oil per day, or half of the entire production capacity of OPEC. In monetary terms, conservation is saving this country $150 billion per year in energy costs, a sum that approaches the size of the Federal budget deficit or the U.S. trade deficit.

With the recent plunge in oil prices, however, energy conservation has ceased to be a national concern. This is shortsighted in the extreme. First, the cost of oil amounts to only 3 percent of the cost of generating electricity, the most expensive form of energy. Second, the oil glut will not last forever. U.S. oil production has already crested in 1970 and world oil extraction is expected to begin declining early in the next century, led by the stabler and friendlier oil exporters: Canada will begin a steep decline in about 15 years and the U.K. in about 20 years. By then OPEC will be a smaller, more cohesive group with greater leverage than it has today.

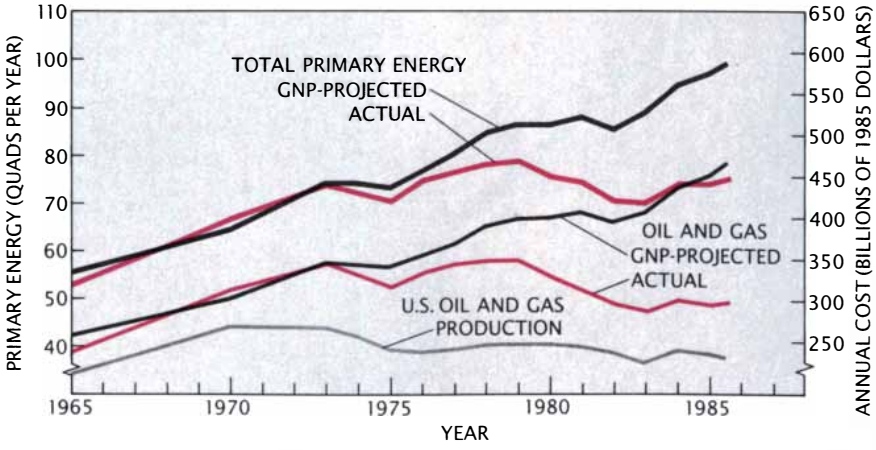
Whether the shift comes in the next 10 years or 30 years, no one doubts that the era of cheap oil will end. When that time comes, this country's economy and national security could be endangered. Fortunately there are many cost-effective steps the U.S. can take now to prevent such a catastrophe. In this article we shall describe technologies and policies for energy-efficient buildings that could cut energy consumption further by at least $50 billion per year. These changes are urgent: 50 to 100 years from now—as long as buildings from the 1980's still stand—this country will have to pay the price of construction decisions made today.

Profiting from Conservation

Energy conservation has already made more energy available to the U.S. economy than any other single source. Yet there is room for even larger gains. In 1985 this country spent $440 billion on energy, which amounts to $5,000 per household or 11 percent of the G.N.P. If all cost-effective conservation measures were taken and the U.S. became as energy-efficient as, say, Japan, this country would consume half as much energy as it does today and save $220 billion per year. The annual cost of achieving this goal would be only about $50 billion per year.

Moreover, by slowing the growth in demand for new energy capacity, conservation could liberate 10 percent of U.S. industrial investment capital for other uses. Already the rate of capital investment in new power plants has fallen sharply owing to energy conservation. In 1982 utilities spent $50 billion, 14 percent of the total U.S. investment in industrial plant and equipment. In 1985 the amount dropped to $30 billion. By 1991 it is forecast to fall to $17 billion. The electric industry predicts that investment will eventually rebound to $45 billion, but if the measures discussed in this article are adopted by 1990, the need for new capac-

SKYLIT SOLAR COURT provides 40 percent of the lighting and 20 percent of the heating in the new passenger terminal at the Albany County Airport in Colonie, N.Y. A microcomputer, programmed with the solar altitude and azimuth angles until the year 2000, continuously gauges the indoor and outdoor environment and selects the most energy-efficient position for the louvers. The dark masonry wall supporting the skylight stores solar heat. The stone floor provides additional thermal mass. When daylight is available, photoelectric controls dim the artificial lighting supplied by efficient fluorescent and mercury-vapor lights. Einhorn Yaffee Prescott designed the terminal, and the energy consultant was W. S. Fleming & Associates, Inc.



ENERGY CONSUMPTION was assumed to be tied to the gross national product (G.N.P.), as was in fact the case before the oil embargo. Since then, however, energy consumption has leveled off at 73 quads (quadrillion B.t.u.) per year even though the G.N.P. has risen by 35 percent. The difference between G.N.P.-projected consumption and actual consumption is 25 quads. The savings for oil and gas lead to a direct reduction in oil imports of 13 million barrels per day—half of the entire production capacity of OPEC.

ity can be delayed and attenuated.

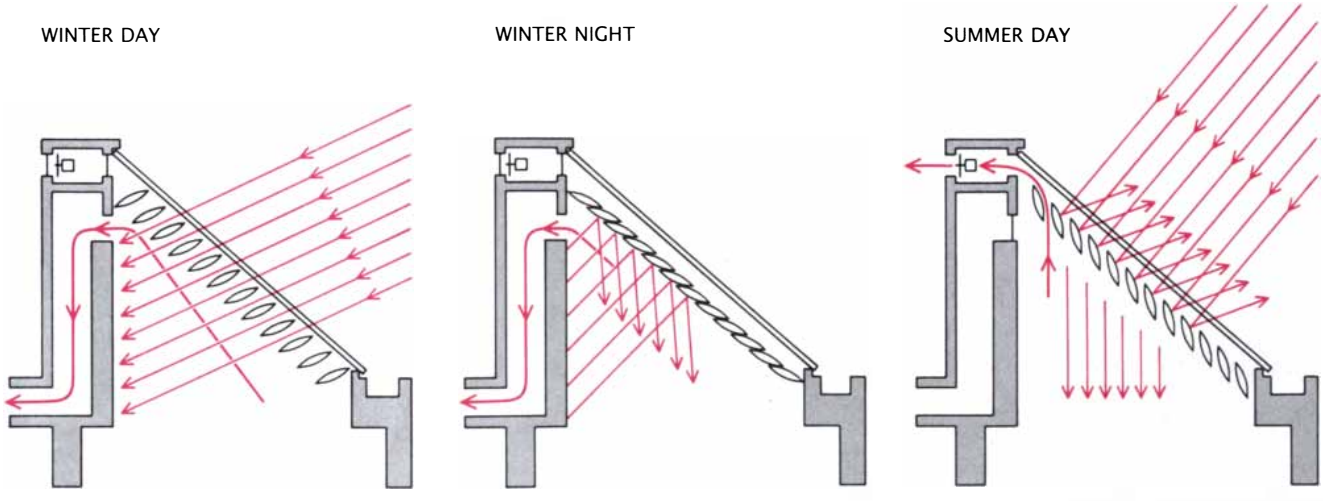
Many players in the energy market, from oil companies to regulators, now recognize the importance of investing in end-use efficiency. This has not always been the case. In 1975, for example, California's utilities predicted an annual growth rate for electrical demand of about 5 percent, even though one of us (Rosenfeld) warned that rising energy costs would cause consumers to improve their end-use efficiency so that the growth rate would be much lower, about 2 percent. By now the difference between these two projections is about 15,000 megawatts, the output of 15 large power plants.

As it turned out, demand grew at only 2 percent, and the 15 plants were never built—testimony to the market forces that led people to use energy more efficiently when the price rose, and to the foresight of regulators who imposed standards on appliances and buildings and also prevented the construction of the new plants. Chastened by cost overruns, lengthy delays, plummeting bond ratings and competition from "cogeneration" by major customers, California utilities have indefinitely scrapped plans to build any new central power stations.

Today many utilities recognize it is much cheaper to improve customers' energy efficiency, because the saved energy can then be sold to new customers. The Pacific Gas and Electric Co., for example, reports that "conservation will allow us to avoid $5 to $7 billion in outlays for new capacity that would otherwise be needed in the next decade. It costs up to seven times as much to produce a kilowatt-hour from a new energy source as it does to save a kilowatt-hour through PG&E conservation programs."

Given that it pays to save energy, how should consumers and society choose among conservation options? The individual consumer normally considers "simple payback time," or the time that must elapse for the annual saving from conserved energy to repay the initial investment. A good investment might have a payback time of a year or less, and a poor investment might not pay back for 10 years. Society, however, needs a different measure that allows an investment in efficiency (such as a better refrigerator) to be viewed as a new source of energy, which can then be compared with an investment in new supply. This measure is the "cost of conserved energy" and is usually expressed in cents per conserved kilowatt-hour of electricity (or dollars per conserved gallon of fuel).

Suppose, for example, an efficient refrigerator conserves 1,000 kilowatt-hours per year but costs $100 more than a less efficient model. To distribute the $100 over the 20-year life of the refrigerator, one should figure a cost of $10 per year (assuming an inflation-corrected cost of money of 7 percent per year). The cost of conserved energy for the refrigerator is then $10 divided by 1,000 kilowatt-hours, or one cent per kilowatt-hour. The average U.S. price of one kilo-



COMPUTER-CONTROLLED LOUVERS at the Albany County Airport regulate sunlight entering through the skylight (*see illustration on preceding page*). On a bright winter day sunlight heats the back wall. Warmed air is drawn into a space behind the wall and recirculated through the building. At night the louvers, which are filled with foam insulation, are shut to trap heat. In summer the louvers reflect direct sunlight but admit diffuse light. Warm air collects under the skylight and is vented by exhaust fans.

watt-hour is 7.5 cents, so that the net saving is 6.5 cents per kilowatt-hour. If the 125 million refrigerators in the U.S. are replaced with new models each of which saves 1,000 kilowatt-hours per year, there will be an annual energy saving of 125 billion kilowatt-hours. At 6.5 cents per kilowatt-hour the net saving for the nation is about $8 billion. This kind of analysis enables us to study the real benefits and costs of the specific conservation measures we shall now discuss.

Office Buildings

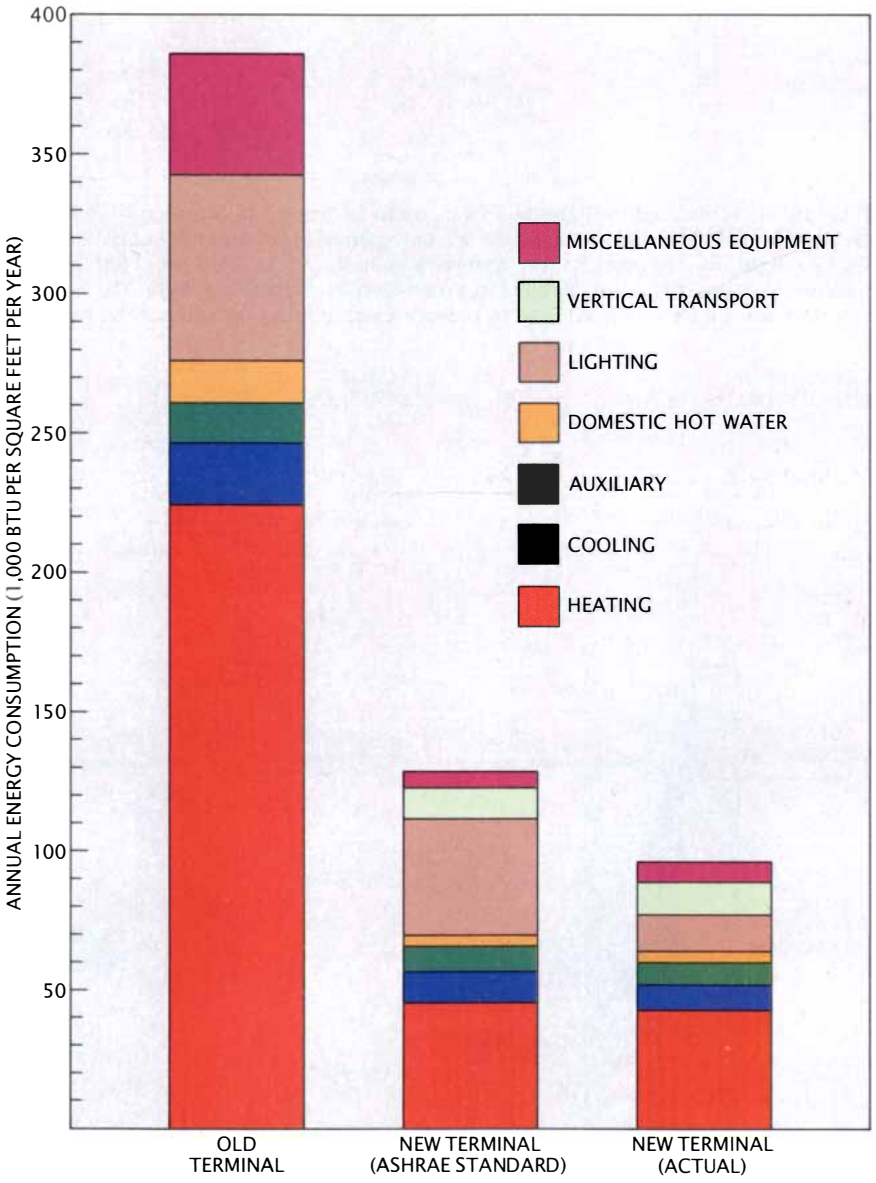
Before the 1973 oil embargo the supply of cheap energy encouraged flagrant inefficiency in office buildings. Acres of floor-to-ceiling single-glazed windows leaked warmth in the winter and admitted unwanted solar heat in the summer. To this was added more heat from excessive lighting by inefficient lamps and equipment. Inefficient building design meant that from 5 to 10 percent of total floor space had to be devoted to air-conditioning equipment.

In 1979 the average commercial building was 20 years old and annually consumed 270,000 B.t.u. of primary energy per square foot (the total amount of fuel needed for heat and electricity generation). At today's prices the energy bill for such a building would be an extravagant $1.60 per square foot. Some buildings were even worse, racking up annual energy bills of $3 per square foot. Such profligacy meant that over a building's 50-year life span the energy bill would be double or triple the construction cost. The embargo forced builders to recognize the absurdity of the situation and to start thinking in terms of a building's life-cycle cost. Since the embargo, energy use in commercial buildings has fallen by almost .5 Alaska, and it continues to fall, albeit less rapidly. With further improvements in lighting, automated controls and thermal storage, 100,000 B.t.u. per square foot should become standard.

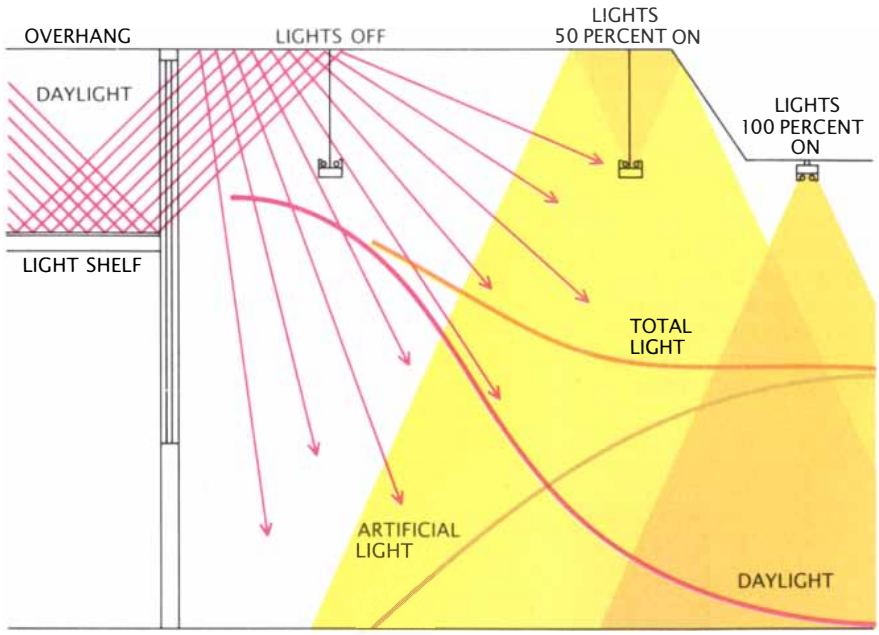
Efficient building design has had a particularly dramatic impact on heating needs. Because heat in large buildings comes mainly from internal sources—heat from people, appliances, lighting fixtures and so forth—it is possible to manage heating requirements by exploiting the thermal mass of the building, for example by storing excess daytime heat and using it to warm the building during the night. The worst of the early-1970's buildings required 170,000 B.t.u. per square foot for heating alone. The average 1979 buildings consumed 72,000 B.t.u. With yet more energy-efficient designs, heating needs will fall to less than 10,000 B.t.u., or six cents per square foot.

The decline for electricity is not as striking because new, improved equipment takes time to develop and install. For air conditioning, however, electric bills can be reduced through simple systems of thermal storage, which make it possible to move from 40 to 50 percent of electrical demand into off-peak hours. In 1979 annual electricity consumption was 27 kilowatt-hours per square foot in the worst office buildings and 18 kilowatt-hours in typical ones. New energy-efficient offices get by on between 10 and 15 kilowatt-hours.

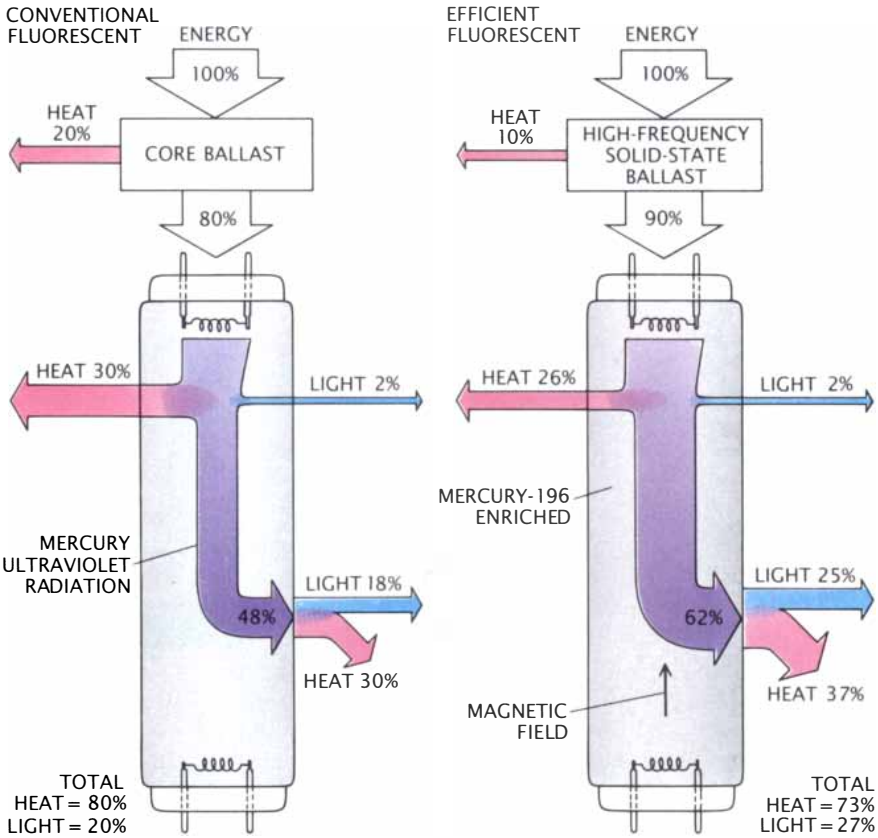
Remarkably, it costs no more to construct an energy-efficient office building than it does to construct an inefficient one. The reason is that by reducing the size of air-conditioning



DOE-2 COMPUTER PROGRAM is a powerful tool in the design of energy-efficient buildings. The program's analysis of annual energy requirements in the old and new terminals at the Albany County Airport is shown here. The simulation was based on the local climate and the building's thermal mass, internal heat gains, solar gains and air-conditioning and ventilation systems. The old terminal was a gas-guzzler. In 1975 the American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE) set standards for materials, lighting, ventilation and so on, which called for the new terminal to be markedly more efficient. Actually the final design performed even better than the standard. DOE-2 was developed for the Department of Energy by the Lawrence Berkeley Laboratory. It is now the national reference tool for building-energy analysis.



DAYLIGHTING can reduce lighting bills by up to 15 percent in commercial buildings. Overhangs and light shelves shade the windows from direct summer sunlight and reflect daylight into the work space. Systems actuated by photocells and controlled by microprocessors dim artificial lights in proportion to available daylight. The controls combine natural and artificial light to provide even lighting throughout the building.



FLUORESCENT lamp systems can be made at least 35 percent more efficient through various new technologies. In a conventional lamp a core ballast generates enough voltage to initiate the ionization of mercury vapor and then limits the current through the discharge. Ionized mercury atoms emit some visible light and a larger amount of ultraviolet photons, which diffuse through the vapor and strike phosphor molecules coating the inner wall of the tube, causing them to emit visible light. Energy losses can be reduced at each stage. Solid-state ballasts reduce heat loss in both the ballast and the filament. Enriching the vapor with the mercury-196 isotope or applying an axial magnetic field will further boost the intensity of ultraviolet radiation reaching the phosphor.

systems and getting rid of single-glazed windows and excess lighting, one can pay for insulation, smaller double-glazed windows and automated thermostat and lighting controls. Fifty years from now, when these improvements have been fully adopted for commercial buildings (assuming the same total floor-space area as today), this country will have liberated 85 power plants, costing two to three billion dollars each, and eliminated fuel needs equivalent to two Alaskas—not bad for an efficiency investment of zero.

Superinsulated Houses

Since the oil embargo fuel consumption in housing for the developed countries has fallen by about 30 percent. New "superinsulated" houses have done much better than this average, reducing fuel needs by more than 75 percent. These houses are built with heavily insulated walls and ceilings, tight-fitting components and, often, ventilation systems that recover heat from the exhaust air. The walls and ceilings have extremely high insulation values, or R values. (The R value is a measure of resistance to heat flow; a standard four-inch-thick insulated wall is R-11 and a standard attic ceiling is R-19.) A superinsulated house would have walls and ceilings rated up to R-30 and R-60 respectively. By investing from $2,000 to $7,000 to superinsulate a house it is possible to reduce annual heating costs to between $20 and $300, even in climates as cold as Minnesota and Saskatchewan.

The remarkably low heating bills result because superinsulated houses store the "free" heat from people, lighting, appliances and passive solar heating through windows. Even ordinary houses tend to "float" about five degrees Fahrenheit above the outdoor temperature because of the internal free heat. Therefore when the thermostat in a conventional house is set at 70 degrees, the furnace will not go on until the outdoor temperature falls below 65 degrees, the "balance point" of the house. The five-degree difference is called the free temperature rise of the building.

In a superinsulated house the free temperature rise can be as much as 30 degrees, so that if the thermostat is set for 70 degrees, the furnace will not go on until the outside temperature drops below 40 degrees; moreover, below 40 degrees it takes less fuel to heat the house. In a typical U.S. climate such as that of New York

City, if the thermal resistance of a house is doubled, annual energy consumption is cut by about two-thirds.

Lighting and Windows

Last year it took 500 billion kilowatt-hours—the output of 100 standard plants, or 20 percent of all electricity generated in this country—to provide lighting in the U.S. Incandescent lighting now accounts for 40 of the plants, fluorescent lighting for another 40 and high-intensity discharge lamps for the remainder. Technical advances in fluorescent lamps and their fixtures would eliminate 20 power plants, and compact fluorescents would replace enough incandescent bulbs to eliminate a further 20 plants, for a total saving of 40 plants. Moreover, because the new lights would give off less heat, there would be additional savings in air-conditioning bills.

Solid-state ballasts, which operate lamps at high frequency, can be major energy savers. The ballast in a fluorescent lamp provides a voltage high enough to initiate ionization of mercury vapor in the tube and then limits the current for stable operation. The new ballasts dissipate less power and also allow the brightness of the lamp to be adjusted over a wide range, making it economical to install lighting-control systems that reduce intensity when natural light is available or when work spaces are vacant. These advantages combine to reduce energy needs by from 25 to 70 percent, at a cost of about two cents per kilowatt-hour.

By 1995 solid-state-ballast lamps should gain 50 percent of the market. It is worth noting that the new ballasts were developed as a joint effort by the Lawrence Berkeley Laboratory's Lighting Research Program, under the direction of Sam M. Berman, and small entrepreneurial firms. It was only after the initial success of these developments that major companies such as Norelco and the General Electric Co. introduced similar products.

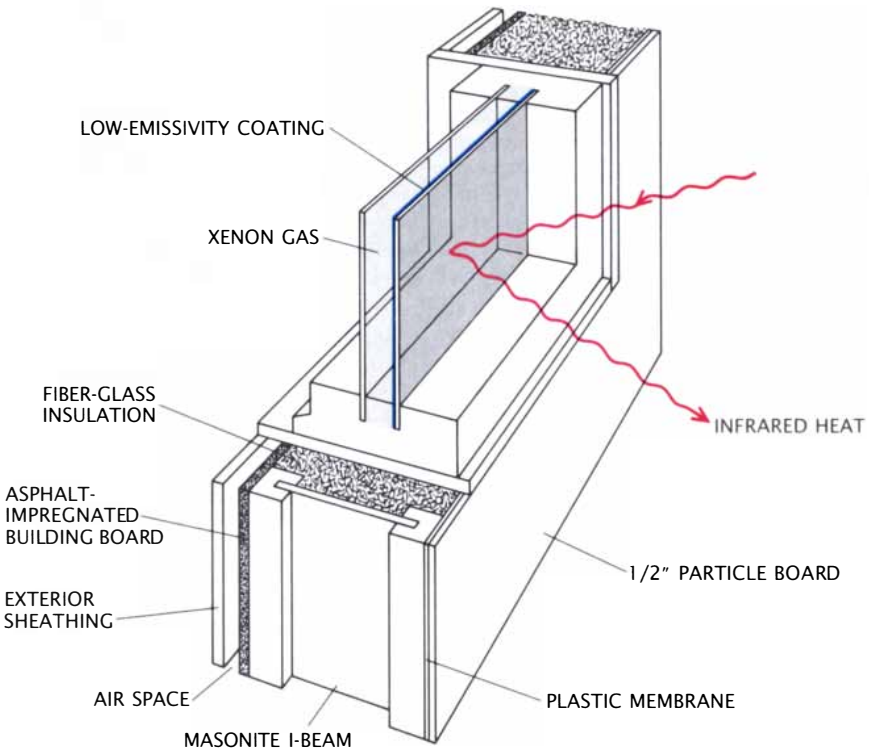
New, compact fluorescent bulbs are also beginning to replace many incandescent lamps. These fluorescents require only from a third to a fourth as much power as incandescents of equivalent brightness and last 10 times longer. The 18-watt Phillips SL-18, for example, costs $20 and consumes $10 worth of electricity during its 7,500-hour lifetime. In contrast, a 75-watt bulb with the same luminosity costs 50 cents but lasts for only 750 hours, during which time it consumes $4 worth of electricity. The life-cycle cost of the SL-18, then, is $30 compared with $45 for 10 incandescent bulbs. Moreover, the SL-18 eliminates nine bulb changes and the burning of 400 pounds of coal at the power plant.

Windows offer further ways to save energy. At present they leak about a third of the heat out of U.S. homes, corresponding to an astounding .5 Alaska. To reduce this waste it is necessary to increase the R value of windows. A normal single-glazed window is rated at about R-1, whereas a standard insulated wall is R-11 or better. The R value of windows can be raised from R-1 to R-11 by a series of steps. Half of the heat lost through single-glazed windows can be saved by double glazing, thanks largely to an insulating air space between the two panes. Such windows are rated at R-2. Double-glazed windows can be improved to an R-3 rating by coating one of the inner surfaces with a thin film of a transparent low-emissivity material, such as tin oxide, which reflects infrared heat radiation back into the house.

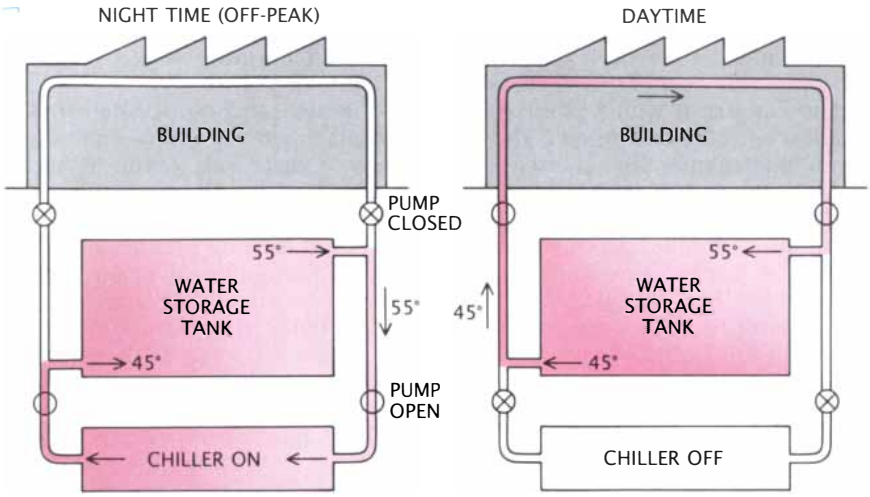
Windows can be upgraded to R-6 by replacing the air between the two panes of glass with xenon or argon gas, both of which are better insulators. One can obtain the same R value by inserting half an inch of a high-tech insulator called aerogel between the panes. (The substance is used by particle physicists as a radiation detector.) Aerogel consists of a very sparse skeleton of tiny glass particles that are transparent to visible light but scatter infrared radiation. If the air in the aerogel is then replaced with xenon gas or with a weak vacuum, one can achieve a window as resistive as a wall.

Home Appliances

Close to one-third of the energy consumed in buildings goes to power major home electrical appliances: refrigerators, freezers, water heaters and air conditioners. They account



SUPERINSULATED walls and windows can reduce home heating needs by more than 75 percent compared with homes built before 1973. In ordinary insulated walls, heat seeps through wood studs between the inner wall and the outer wall. This Swedish-designed wall overcomes the problem by using I-beam studs consisting of a sheet of insulating masonite held between two pine flanges. Heavily insulated walls must be sealed on the inside with a plastic membrane to prevent indoor moisture from condensing on the cold insulation in the wall. Heat loss through double-glazed windows can be cut in half by coating one of the inner surfaces with a low-emissivity material such as tin oxide and filling the air space with argon or xenon gas. Even on their own, low-emissivity windows conserve energy at a cost of $4 per million B.t.u. of natural gas; the cost is expected to fall to $2 per million B.t.u. When low-emissivity windows saturate the market early in the next century, they will save energy equivalent to one-sixth of an "Alaska."



STORAGE TANK for cold water, installed in a building's air-conditioning system, can reduce peak power demand. At night the chiller cools the water in the tank. During the day the chiller is turned off and the precooled water circulates through the building.

for 12 percent of the nation's energy budget, or 2.3 Alaskas, at a cost of more than $50 billion per year. Refrigerators, which are in virtually every home and operate 24 hours a day on electricity, presented an obvious target for an efficiency study. In 1977 Arthur D. Little, Inc., analyzed improvements such as better insulation, compressors and gaskets and concluded that at an extra retail cost of $100 it would be possible to have more efficient refrigerators consuming only one-third as much electricity as the average 1977 model.

A decade later these predictions are being realized in mandatory national standards, first set in California. In 1977 an automatic-defrost model with a capacity of from 16 to 18 cubic feet consumed 1,900 kilowatt-hours per year. Under the California standard the figure dropped to 1,500 in 1979 and to 1,000 in 1987; by 1993 it should reach 700 kilowatt-hours per year. These improvements add less than $150 to retail cost, and the payback time for the 1993-standard model (compared with 1977 models) is only one year. For the 125 million refrigerators and freezers in the U.S. the energy saving will be equivalent to the output of 30 power plants. In other words, an investment of $12.5 billion in improved efficiency will avoid the need to spend $60 billion on 30 new plants, eliminate their operating costs and spare the environment of their pollutants.

Efficiency improvements in other home appliances can also produce large economic benefits. In 1975 Congress directed the Energy Research and Development Administration to devise mandatory standards to minimize the life-cycle cost of 13 major appliances, but the Reagan Administration opposed the concept and delayed its implementation.

Impatient with the delay, several states set their own standards. The lack of uniformity troubled manufacturers, who in 1986 met with public-interest groups and developed new standards, which Congress then adopted as mandatory. President Reagan pocket-vetoed the bill, but it was reintroduced and signed into law last year. Its sponsors estimate that, under the standards, appliances sold by the year 2000 will decrease the nation's peak load by as much as 22 gigawatts and save $27 billion.

Exploiting Off-Peak Power

End-use efficiency is one way to conserve energy and forestall the construction of new plants. Another approach is for utilities to develop pricing strategies calculated to reduce the huge surges in demand that occur at certain times. Peak demand on summer afternoons is often from two to three times as high as the demand at night. Air conditioning accounts for one-third of the 500-gigawatt peak demand in the U.S.

Common sense and basic economics dictate that utilities should charge the highest rates for electricity at peak hours during the day and discount it at night, following the practice of other industries such as telecommunications and airlines. Yet until recently time-of-use electric meters have been relatively expensive, and so utilities have offered time-dependent rates mainly to large customers—buildings and factories that consume 500 kilowatts or more—even though residences and small commercial buildings account for two-thirds of the peak-power load. In the next 10 or 20 years inexpensive microprocessor-based meters will enable utilities to apply time-of-use rates to these customers as well.

Time-of-use pricing gives consumers an incentive to store energy in off-peak periods. In 1977, for example, Stanford University recognized that its daytime cooling needs were rising and that it needed to plan for three megawatts of new peak demand. Adding that much new air-conditioning capacity would have cost about $1.5 million. Instead, for only $1 million, the university built a four-million-gallon cold-water storage tank connected to the existing air-conditioning system. By cooling the water during off-peak hours and then drawing on the stored refrigeration, Stanford trimmed 3.5 megawatts from its peak demand for an additional saving of $200,000 per year.

Market Failures

Clearly there are many opportunities for boosting the energy efficiency of buildings. Yet improvements are not proceeding as fast as one would expect. The reasons can be traced to a number of market failures. The most important one stems from the different time horizons the various principals consider when making decisions. Investments in energy supply are made by utilities and other large companies that raise billions of dollars for huge projects and expect to pay off their investors over a decade or two. In contrast, most homeowners will not invest in efficiency if the payback time is 2.5 years, even though this represents a hefty 40 percent (nontaxable) annual return on investment. Large institutions such as governments, universities and corporations seldom consider paybacks longer than three years, thereby rejecting a 30 percent return on their own or taxpayers' money.

Utility pricing introduces another distortion. Electric companies are regulated and may only charge their average cost (plus a 10-to-15-percent return on investment) for the power they sell—about seven cents per kilowatt-hour. Yet the replacement cost for that kilowatt-hour is considerably higher—say 10 cents—depending on the utility's new sources of supply. Consumers may therefore reject an efficiency improvement because they do not perceive it to be cost-ef-

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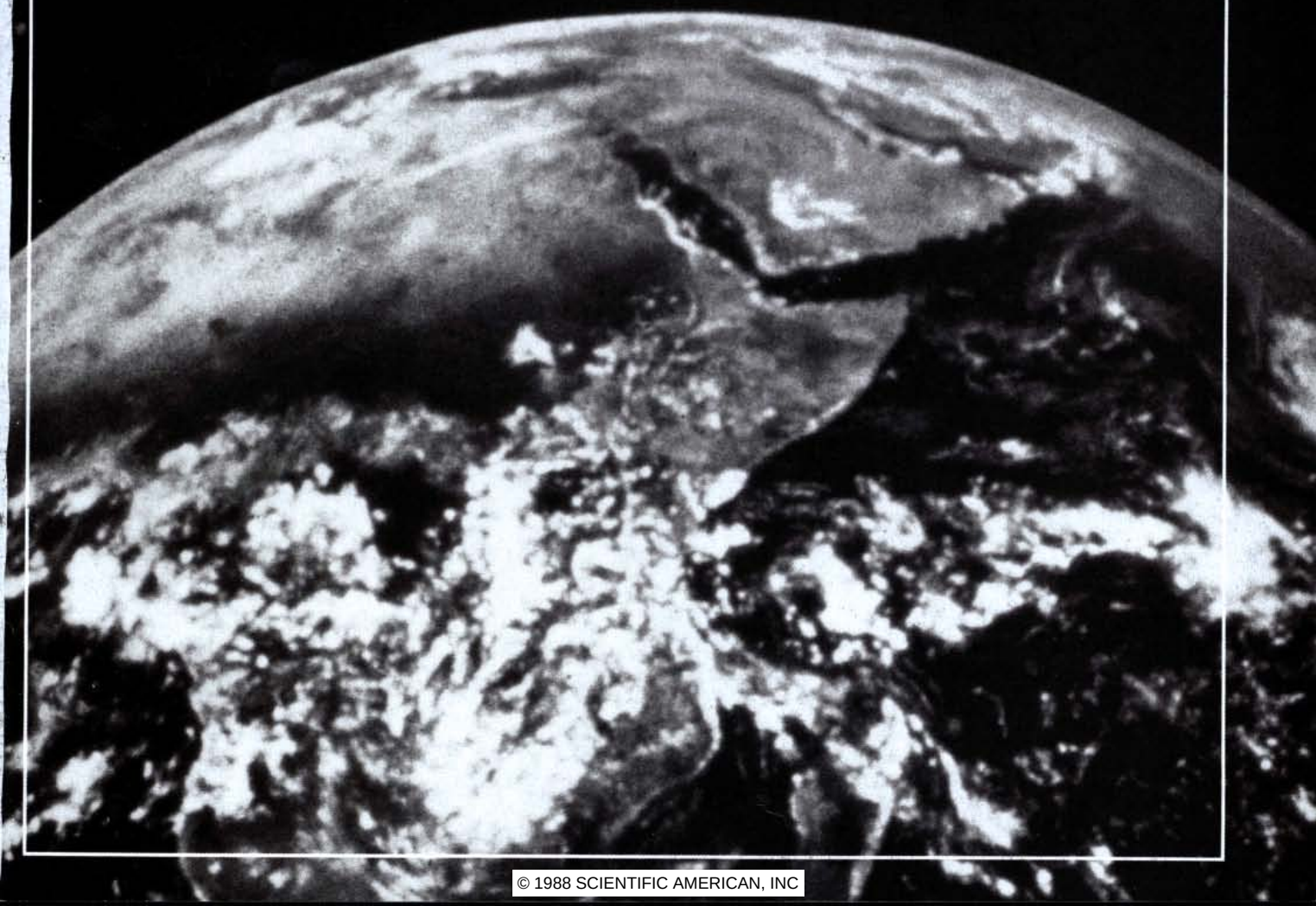

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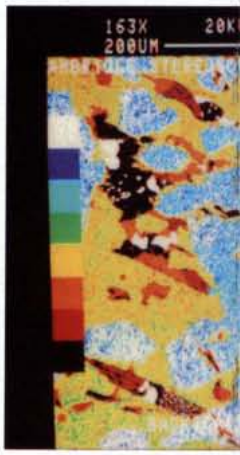
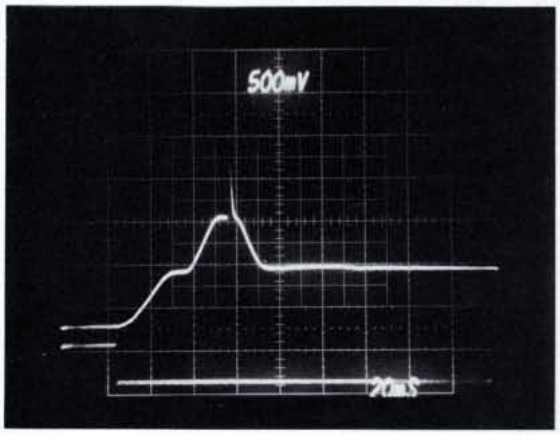
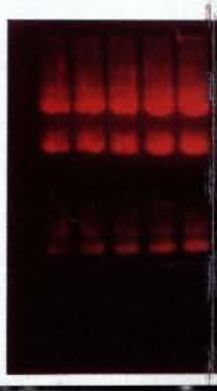


S.E.M. Image of a Heart Valve –
Type 55

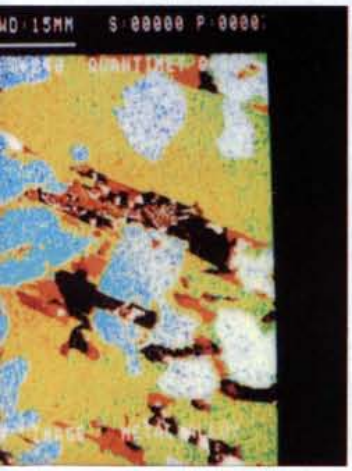
Oscillograph Image –
Type 667



Electrophoresis Pat
Enzyme Digestion of
Polacolor ER Type



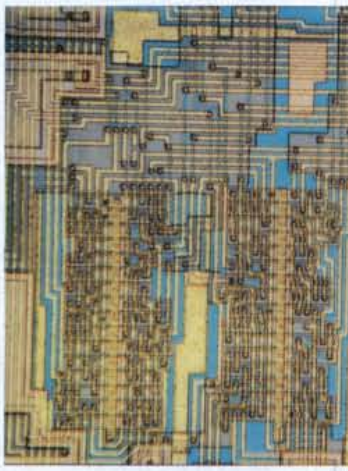
alysis of a Metal Alloy –
oFilm Type 339



CAD/CAM Image of a Ball Bearing –
PolaChrome Instant 35mm Film

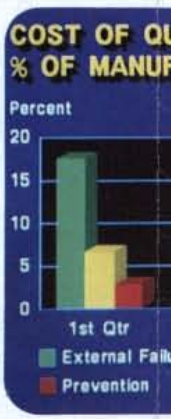
Molecular Structure of Galactosamine –
PolaBlue Instant 35mm Film

Photomicrograph of Integrat
AutoFilm Type 339

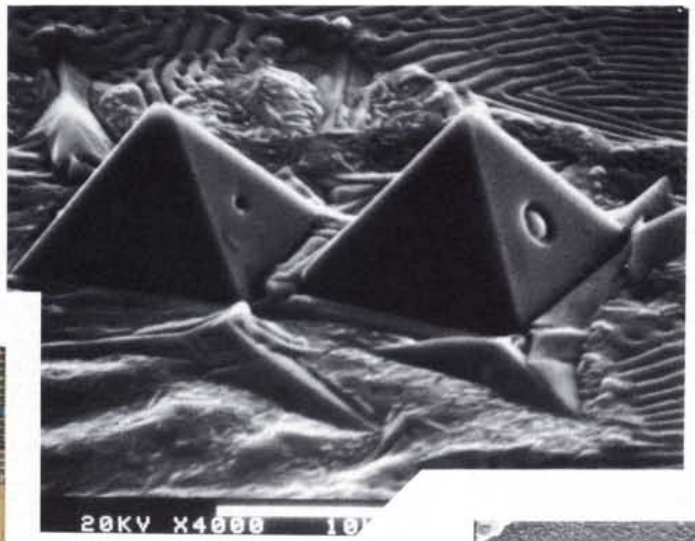


X-ray of Pens –
Type 53

rn from an
asmid DNA –
69 Film



S.E.M. Image of Inner Surface Cavity of a Nickel-Tin Eutectic Alloy Sphere – Type 55



ted Circuit –
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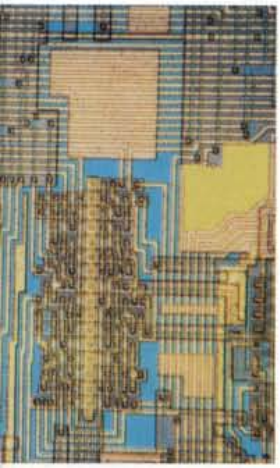
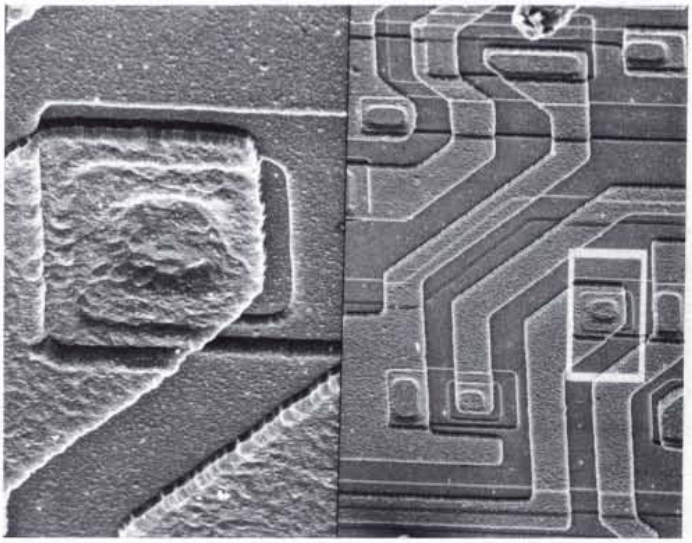
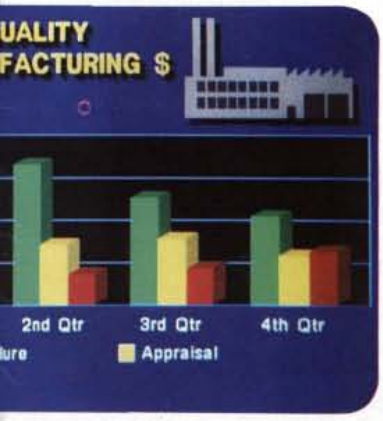
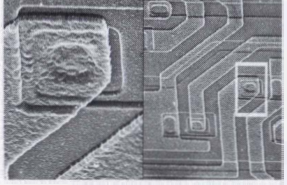


S.E.M. Image of an Integrated Circuit – PolaPan Type 52

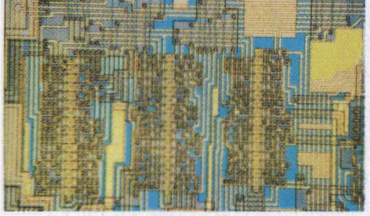


Cost Analysis Graph – Colorgraph Type 691

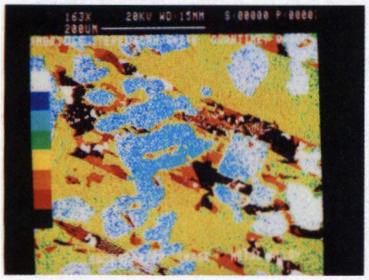




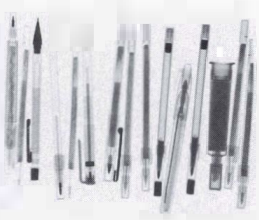
sheet film was used to capture this split-field S.E.M. of an integrated circuit. This black and white, fine grain print film offers a wide tonal range and provides superb detail.



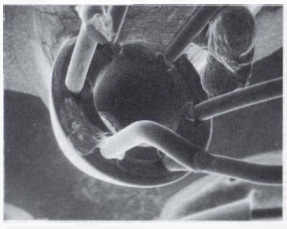
Polaroid AutoFilm Type 339 was used to produce this photomicrograph of an integrated circuit viewed through an optical microscope.



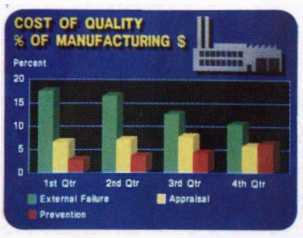
Quality Assurance. This particle analysis of a metal alloy, shown on Polaroid High Speed AutoFilm Type 339, displays consistent saturated color and requires no pulling, timing, or peeling. It was made with the Polaroid FreezeFrame Video Image Recorder.



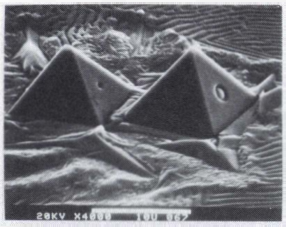
Non-Destructive Testing. This X-ray of a representative group of pens was made on Type 53 to view the alignment of the parts. This general purpose high speed film requires no print coating.



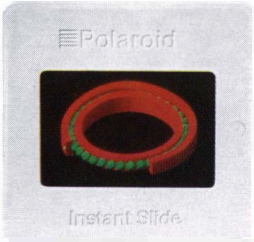
Failure Analysis. This S.E.M. image of a heart valve, magnified 18x, is on Type 55 instant film. This black and white sheet film provides you with a positive and negative to make high quality, professional images.



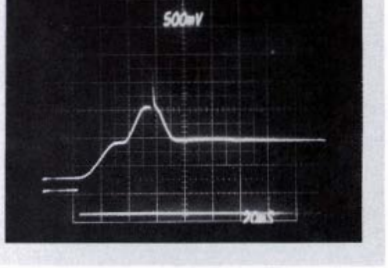
Presentations. An instant color overhead transparency, such as this cost analysis graph, can be made using Polaroid Colorgraph Type 691 film. This full color film creates small format overhead transparencies so the latest findings can be presented instantly. The actual graph was generated on a personal computer using the PalettePlus Computer Image Recorder.



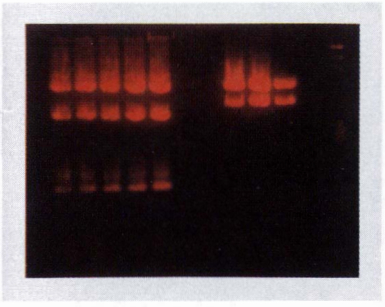
Metallurgy. This S.E.M. image magnified 4000x is of the inner surface shrinkage cavity formed on solidification of a nickel-tin eutectic alloy sphere levitated in microgravity aboard the space shuttle. To capture the fine detail, Polaroid Type 55 black and white instant film was used.



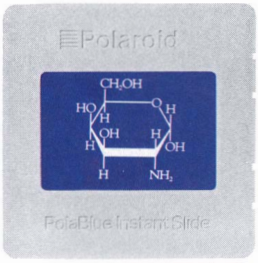
Graphic Design. To capture the subtle color differentiations in this CAD/CAM image of a ball bearing, new Polaroid High Contrast PolaChrome Instant 35MM Slide Film was used. New High Contrast PolaChrome provides bright, high quality, color slides in minutes for presentation or documentation.



Measurement. Polaroid Type 667 black and white high speed print film and Polaroid DS-34 Direct Screen Camera were used to document this oscillograph.



Biotechnology. Polaroid Polacolor ER Type 669 film and the Polaroid MP-4 Multipurpose Camera were used to produce this image of an electrophoresis pattern from an enzyme digestion of Plasmid DNA. Type 667 and Type 53 black and white films are also used for electrophoresis documentation.



Physical Science. This white on blue slide of the molecular structure of galactosamine was made with new Polaroid PolaBlue Instant 35MM Slide Film. New PolaBlue provides bright, high quality, white on blue slides in minutes for presentation or documentation. It's more cost effective than traditional methods of making blue slides.

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Result	Product	Format/Size	Speed ISO & DIN equivalents	Normal Development Time at 75°	Special Characteristics
Instant Color Prints	Type 779	Integral Pack 3½x4¼in.	ISO 640/29°	Self-timing	Balanced for daylight and electronic flash.
	Time Zero Type 778	Integral Pack 3½x4¼ in.	ISO 150/23°	Self-timing	Balanced for daylight. Image visible in 10-15 seconds.
	Type 909	Integral Pack 4x4in.	ISO 640/29°	Self-timing	Balanced for daylight and electronic flash.
	Type 339	Integral Pack 4.5x4.2 in.	ISO 640/29°	Self-timing	General purpose, high speed, medium contrast.
	Polacolor ER Type 669	Pack 3¼x4¼ in.	ISO 80/20°	60 seconds	Medium contrast; extended dynamic range. Balanced for daylight and electronic flash.
	Polacolor ER Type 559	Pack 4x5 in.	ISO 80/20°	60 seconds	Medium contrast; extended dynamic range. Balanced for daylight and electronic flash.
	Polacolor ER Type 59	Sheet 4x5 in.	ISO 80/20°	60 seconds	Medium contrast; extended dynamic range. Balanced for daylight and electronic flash.
	Polacolor ER Type 809	Sheet 8x10 in.	ISO 80/20°	60 seconds	Medium contrast; extended dynamic range. Balanced for daylight and electronic flash.
Instant B&W Prints	Type 331	Integral Pack 4.5x4.2 in.	ISO 400/27°	Self-timing	Medium contrast, automatic development.
	Type 612	Pack 3¼x4¼ in.	ISO 20000/44°	30 seconds	Ultra high speed for oscilloscope recording.
	Type 667	Pack 3¼x4¼ in.	ISO 3000/36°	30 seconds	General purpose, high speed film. No coating required.
	Type 52	Sheet 4x5 in.	ISO 400/27°	15 seconds	Wide tonal range, superb detail.
	Type 53	Sheet 4x5 in.	ISO 800/30°	30 seconds	Medium contrast film. No coating required.
	Type 57	Sheet 4x5 in.	ISO 3000/36°	15 seconds	General purpose, high speed film.
	Type 553	Pack 4x5 in.	ISO 800/30°	30 seconds	General purpose, high speed film. No coating required.
	Type 803	Sheet 8x10 in.	ISO 800/30°	30 seconds	Fine grain medium contrast film. No coating required.
Print & Negative	Type 55	Sheet 4x5 in.	ISO 50/18°	20 seconds	Negative requires brief clearing in sodium sulfite solution, washing and drying before use.
	Type 665	Pack 3¼x4¼ in.	ISO 80/20°	30 seconds	Negative requires brief clearing in sodium sulfite solution, washing and drying before use.
Instant Color Overhead Transparency	Colorgraph Type 691	Pack 3¼x4¼ in.	ISO 80/20°	4 minutes	Small format overhead projection use.
	Colorgraph Type 891	Sheet 8x10 in.	ISO 80/20°	4 minutes	For overhead projection use.
Instant B&W Radiographic Transparency	Type TPX	Sheet 8x10 in.	N/A	60 seconds	Medium to high contrast. High speed Orthochromatic sensitivity. No darkroom needed.
Instant 35mm Color Slides	PolaChrome CS	35mm Roll (12& 36 Exposures)	ISO 40/17°	60 seconds	General purpose, continuous tone color.
	High Contrast PolaChrome	35mm Roll (12 Exposures)	ISO 40/17°	2 minutes	High contrast color for text and graphic imaging.
	PolaBlue BN	35mm Roll (12 Exposures)	ISO 4/7° (Tungsten) ISO 8/10° (Electronic Flash)	4 minutes	White-on-blue negative film for word slides, charts and graphs.
Instant 35mm B&W Slides	PolaPan CT	35mm Roll (12 & 36 Exposures)	ISO 125/22°	60 seconds	General purpose, continuous tone black and white.
	PolaGraph HC	35mm Roll (12 Exposures)	ISO 400/27°	2 minutes	High contrast black and white. Ideal for line copy.

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fective at today's prices even though it would actually be cost-effective if they considered the higher prices the utility will charge when it is forced to build a new plant.

Remedies

Fortunately specific policies can be adopted to counteract these market failures. One of the most promising policies is for utilities themselves to sponsor conservation. Utilities can offer incentives, such as low-interest loans, rebates and outright grants, as a way of encouraging customers to make their homes and businesses more energy-efficient. In California the utilities pay commercial customers $300 per kilowatt saved as an incentive to reduce peak demand. In the Northwest utilities pay home builders between $3,200 and $3,800 for meeting the new construction standards of the region before 1990, when they will become mandatory. In Dallas last year a utility-sponsored rebate program induced 40 percent of the new large office buildings to install thermal-storage systems.

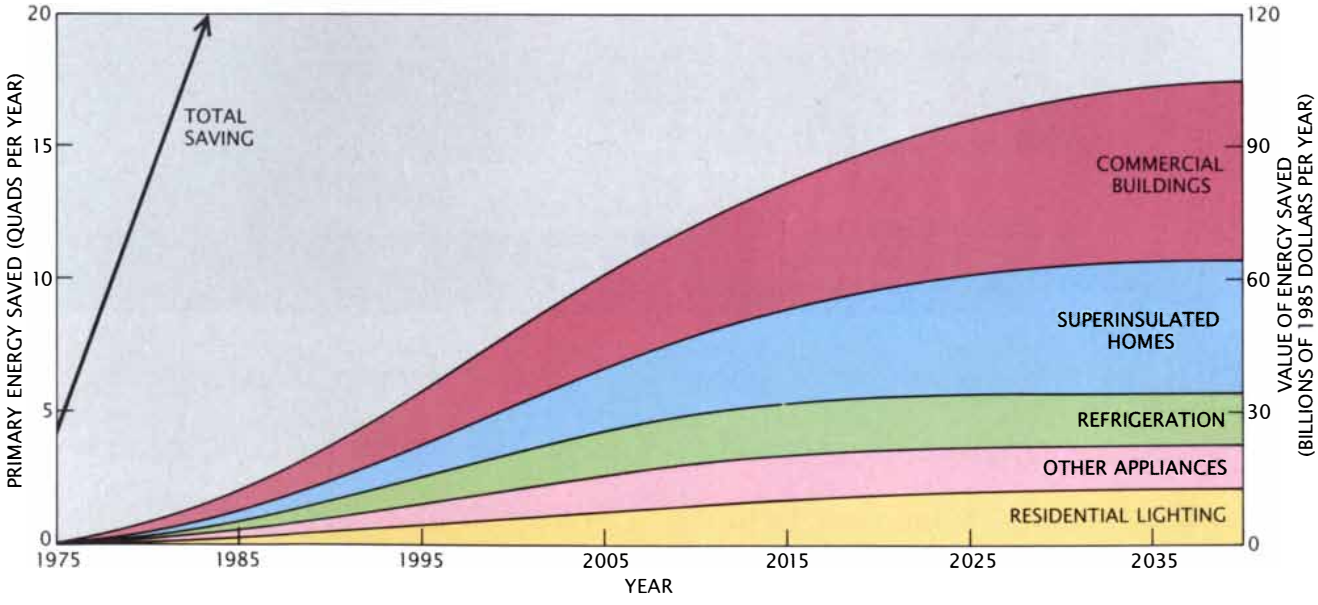
Some utilities have also changed to a progressive rate structure. Before the era of OPEC, the more one consumed, the less one was charged per kilowatt-hour. Utilities in California and elsewhere now do the opposite. Their rates are low for the first few hundred kilowatt-hours per month and go up as consumption increases. In the highest tier, customers must pay the cost of power from a new plant the utility would have to build if consumption increased any further. With such a rate structure, conservation can compete with energy purchases fairly. The next step could be to charge new buildings "compulsory utility bonds," which would reflect the cost of the new capacity that would be needed for the building and would more accurately convey the costs of electric demand to the builder and the buyer.

The Federal Government also introduces distortions in the economics of energy, by supporting research and development for energy supply (particularly nuclear power) much more generously than R&D for energy efficiency. The Government should either drop the supply incentives or level the playing field by providing equivalent incentives for conservation.

Already R&D in end-use efficiency has contributed mightily to reducing the nation's energy needs. For example, we estimate that Federal R&D funds hastened the commercialization of high-frequency fluorescent ballasts by five years. Those five years will save the country more than $25 billion. Yet the Federal program cost less than $3 million, of which half came from industry. That represents a benefit-to-cost ratio of 8,000 to one. Moreover, the research helped U.S. industry to retain its market share vis-à-vis Europe and Japan, both of which had independently developed high-frequency ballasts. Yet every year the Administration requests a 50 percent cut in research in energy efficiency. Given the decades necessary for new technologies to saturate the marketplace, it makes more sense to maintain the levels of research funding.

Finally, we argue for reasonable standards for appliances and buildings, an approach that has worked well in California. These could be aimed at keeping the worst appliances off the market and could be based on, say, a five-year payback period.

The U.S. has the means to reduce its energy costs by $220 billion per year, above and beyond the $150 billion it is already saving as a result of conservation. For the buildings sector the potential annual savings are from $50 to $100 billion. In order to achieve these goals it will be necessary to remove the market barriers we have described. This will require the concerted efforts of utilities and government. The penalty for not doing so is severe: money will continue to be wasted, remaining reserves of cheap energy will be squandered, the U.S. will wane in competitiveness with Europe and Japan, the country will remain dependent on foreign sources and the environment will continue to be degraded. The nation should take advantage of the opportunities at hand without delay.



ENERGY SAVINGS from five of the six examples described in the article save only a few billion dollars per year today, but 50 to 100 years from now, when the new technologies saturate the marketplace, they will save more than $100 billion per year. The savings shown are for commercial buildings (including most of the savings from improved lighting), superinsulated homes (including windows), refrigeration, other appliances and residential lighting. Thermal storage is not included because it saves peak power, not energy. The total-savings line shows all U.S. energy savings (*see top illustration on page 80*). The calculations are based on figures fixed at 1985 levels for the total number of households and area of commercial floor space in the U.S.

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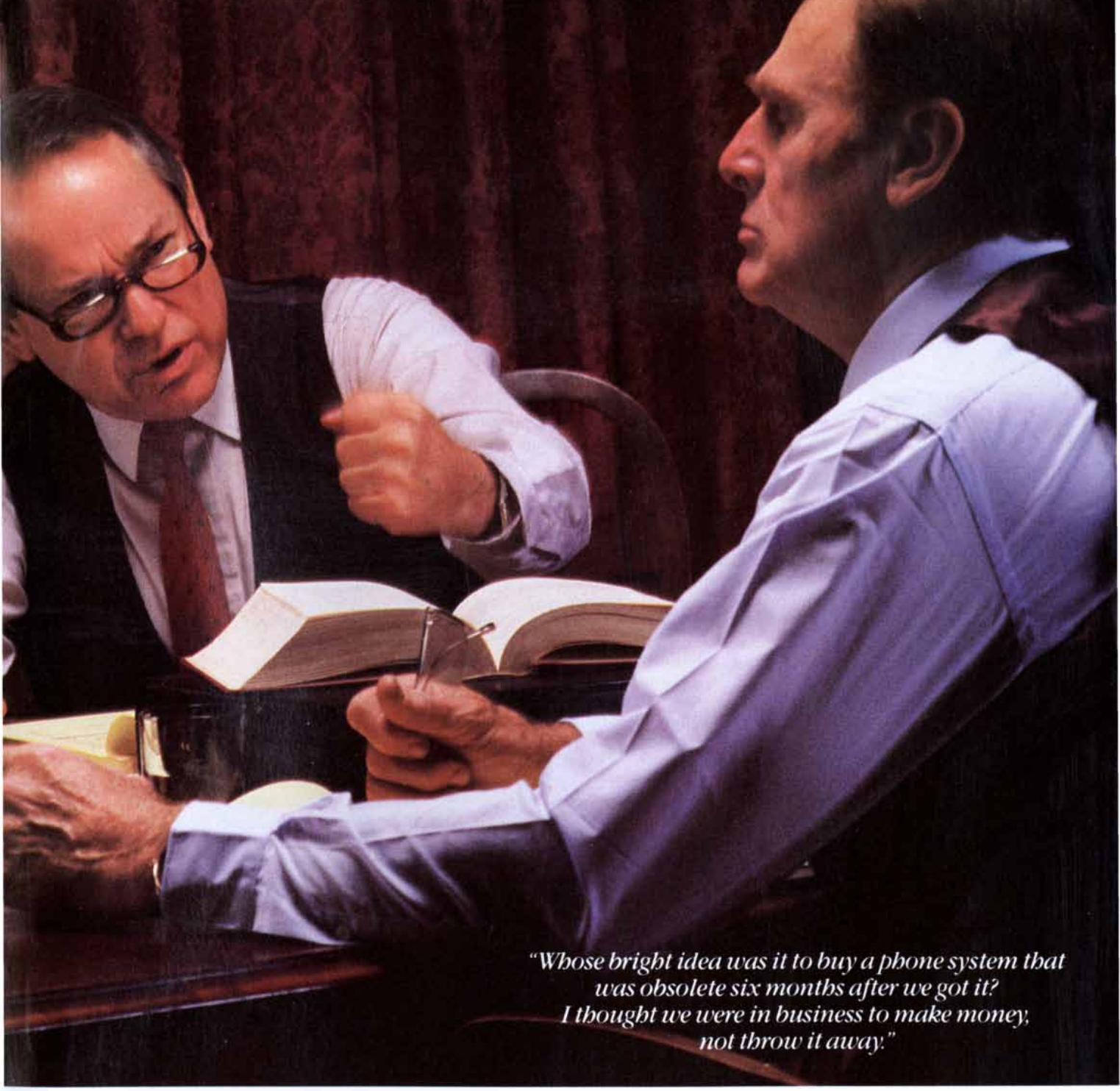

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Light Switches for Plant Genes

How do rays of sunlight plot the destiny of a sprouting seedling? Biologists have found segments of DNA that respond to light energy by turning on genes necessary for the development of living plants

by Phyllis B. Moses and Nam-Hai Chua

A green plant is a machine that runs on solar energy. Light powers photosynthesis, the process by which a plant converts carbon dioxide and water into sugars, starch and oxygen. In effect the plant captures the energy of the sun and converts it into the substances that directly or indirectly sustain most other forms of life on the earth.

It is a mistake, however, to think that to a plant light is no more than fuel. Even before a nascent shoot splits its seed coat, light or the lack of it rules a plant's life. Light can tell a plant how high to grow, how many leaves to sprout, when to flower and to set fruit and when at last to age. More than just a power supply for photosynthesis, light dictates a plant's very form through a process called photomorphogenesis.

To control the development of a plant, light must have some effect on the developmental blueprints, the genes. Yet whereas the biochemical reactions involved in photosynthesis have been described at length, it is not at all clear how light influences the expression of plant genes. Six years ago we set out to clarify the biochemical basis for photomorphogenesis by beginning with the light-responsive genes themselves. We wanted to identify precisely the gene sequences that respond to light. With the techniques of genetic engineering we have already found such sequences, which we call light-responsive elements, or LRE's.

Our group in the Laboratory of Plant Molecular Biology at Rockefeller University is but one of several studying the details of LRE control. In characterizing the elements we drew on strategies and information gathered in the past decade by dozens of other investigators. The enzymes with which we cut and splice genes, the vector we use to transfer genes to plant cells and the hormones that help us to regenerate whole plants from single cells reflect the legacy of methodology we inherited.

With that methodology we were able to construct genes that were amalgams of DNA from bacteria and plants and to shuffle the genetic material of peas, petunias and tobacco. Our experiments typify much of the ongoing work aimed at illuminating the molecular biology of plants. Although the complexity and elegance of plants' biochemical machinations make these investigations intrinsically fascinating, we hope that the knowledge gleaned in the laboratory will also pay off eventually in the field with healthier, more productive and more nutritious crops.

Photomorphogenesis can be divided conceptually into three parts: reception of light by means of pigments, transduction of the light signal from pigment to gene and the induction of development through genetic regulation [*see illustration on page 90*]. Of these parts, transduction has proved to be the most inaccessible. Little is known about the form the light signal assumes within living plant cells in order to interact, directly or through intermediate molecules, with the genetic regulatory apparatus.

More has been discovered about light reception. The green pigment chlorophyll traps energy from light in photosynthesis; in photomorphogenesis the photoreceptor is a blue-green pigment called phytochrome. Phytochrome is present in much smaller quantities in plants than chlorophyll is. It exists in two interconvertible forms, one of which absorbs red light having wavelengths near 660 nanometers and one of which absorbs "far red" light, which has wavelengths near 730 nanometers (one nanometer is a billionth of a meter). The two forms are called Pr and Pfr respectively.

Phytochrome is a kind of biological switch. When one pigment form receives light of the appropriate wavelength, it changes into the other: far-red light converts Pfr into Pr, and red light converts Pr into Pfr. Pfr is the phytochrome form that initiates the steps culminating in photomorphogenesis. Hence light in the red region of the spectrum is responsible for inducing the expression of some of the genes that control development.

The genes exert their influence through the proteins they encode. When a gene is induced, its double-strand DNA sequence, which consists of "nucleotides" designated by the letters *A, T, G* and *C,* is transcribed into a single strand of messenger RNA made up of four analogous nucleotides. The mRNA code is in turn translated into a particular protein. The protein may be part of a structure or may perform a function that helps to determine the form of the plant.

Many genes are themselves controlled by the DNA sequences immediately surrounding the genes. These regulatory regions govern expression of a gene by modulating its transcription into mRNA. It is these regions we examined in our studies of light induction. Our immediate goal was to learn what DNA sequences flanking a light-responsive gene are needed to govern the gene's activity in the course of development. Ultimately we hope to work out the chain of events by which light, acting

TOBACCO PLANT figures prominently in studies of gene regulation by light. Tobacco cells are amenable to genetic-engineering techniques and whole plants can be regenerated from cultures based on engineered cells (*see illustration on page 91*).

through photoreceptors such as phytochrome and probably in conjunction with a number of different proteins, gives its signal to these regulatory sequences.

In order to identify light-responsive regulatory sequences we had first to locate light-responsive genes. Dozens of plant genes are known to be affected by light and many of these are regulated by way of phytochrome. The amount of mRNA transcribed from such genes often changes directly in response to light. In some cases red light actually decreases the expression of a gene. For example, expression of the gene for phytochrome itself becomes depressed in red light; thus the pigment modulates its own gene in a kind of negative-feedback loop.

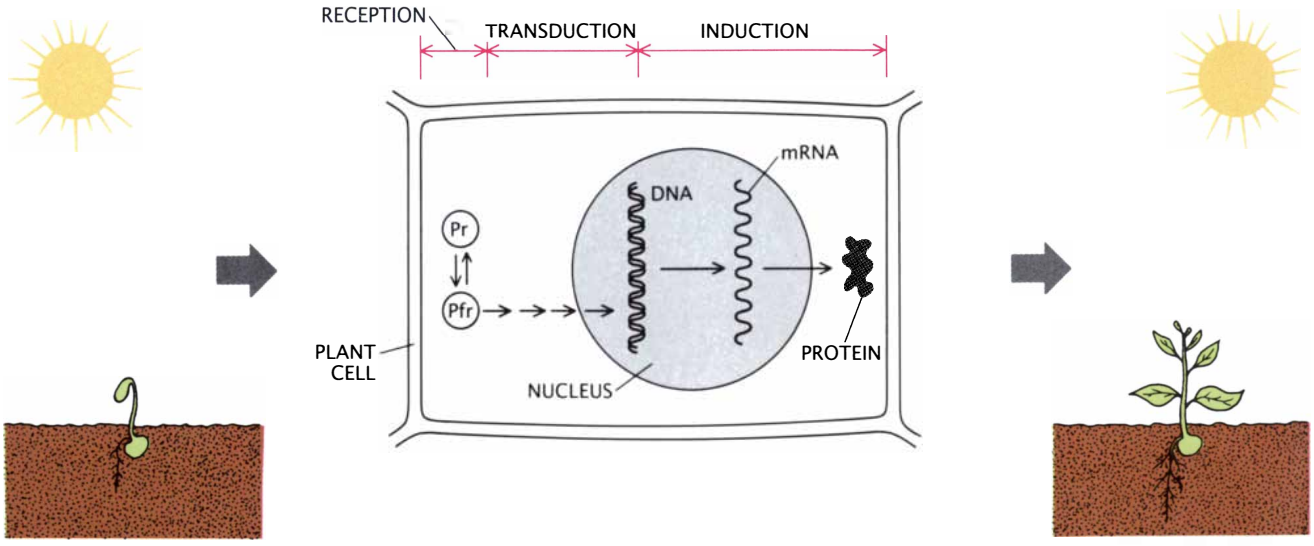
In contrast, red light is known to turn on the genes for an important photosynthetic enzyme called ribulose 1,5-bisphosphate carboxylase, or RUBISCO for short. RUBISCO is the primary enzyme involved in the fixation of carbon dioxide from the atmosphere, one of the most fundamental life processes on the earth. As such it is probably the most abundant enzyme in the world. The active RUBISCO molecule consists of two types of subunit that are encoded by separate genes.

We decided that the smaller RUBISCO subunit, known as rbcS, would make an ideal target for our investigations. For one thing, both the protein and its mRNA are easy to detect in normal green plants because they are produced in very large amounts in the leaves. Furthermore, the gene's response to light is quite dramatic, a sign that its regulatory sequences exert powerful control on mRNA transcription; plants grown in the dark contain less than a twentieth of the rbcS mRNA produced by plants grown in the light. Moreover, because the enzyme subunit is essential to most plant life, the rbcS gene is common to all species of higher plants, even species separated by widely divergent evolutionary paths. This commonality was crucial because we hoped to transfer genes among different plant species and wanted the foreign genes to be able to work properly in their new hosts.

The commonest vehicle for transferring genes into plants is the soil bacterium *Agrobacterium tumefaciens* [see "A Vector for Introducing New Genes into Plants," by Mary-Dell Chilton; SCIENTIFIC AMERICAN, June, 1983]. This microbe is a natural genetic engineer: in the wild it inserts a small segment of its own DNA into the chromosomes of plant cells, giving rise to a bulbous tumor called a crown gall. Within the bacterium the genes to be transferred are borne on a circular DNA molecule called a plasmid. The transfer is mediated by the DNA sequences bordering the tumor-inducing genes. Molecular biologists can replace the plasmid genes that cause the tumor with the gene of their choice; the border sequences then insert the foreign gene into plant chromosomes just as faithfully as they ordinarily insert tumor-inducing genes [*see illustration on opposite page*].

In the early 1980's biologists most often introduced an engineered plasmid into plant cells by mixing *Agrobacterium* with the isolated cells in culture. More often now the microbe is spread on wounds cut into a leaf and the leaf itself is cultured. In either case the cells that pick up the new gene pass it along when they divide. Whole plants regenerated from these cells have at least one copy of the engineered gene in every cell. Except for the presence of the so-called transgene, the plants are normal, and they produce seeds that contain the transgene as well.

Expression of a transgene can be gauged by measuring the amount of mRNA transcribed from it. The mRNA is quantified by a technique known as hybridization. Hybridization exploits the fact that a strand of mRNA will pair with a single-strand piece of DNA if the nucleotides on the two strands are complementary. In order to detect a piece of mRNA generated by a transgene, a biochemist prepares a probe—a strand of DNA that is complementary to the mRNA from the transgene and is labeled with a radioactive isotope. When a probe binds to its target, the target can be singled out by virtue of the radioactive label. Quantifying the radioactivity of bound probes, then, is akin to quantifying the mRNA generated by the transgene.



PHOTOMORPHOGENESIS, the process by which light influences a plant's form, takes place in three stages. Here the process is schematized in the cell of a pea plant. In the first stage, called reception, light prompts the conversion of a pigment (*Pr*) into its molecular alternate (*Pfr*) through a reversible reaction. The presence of Pfr initiates transduction, a series of steps that communicates the light signal to the plant genes in the cell nucleus. Some genes are induced, or activated, by the transduced signal; these genes undergo transcription to messenger RNA and translation into proteins that shape the developing plant.

Hybridization can be very sensitive: under certain conditions the sequences on two separate strands must be exactly complementary for binding to occur. It so happens that, in spite of the similarity of the rbcS proteins made by all plants, the corresponding mRNA generated by different plant species varies enough for transgene mRNA to be distinguished from the "native" version by hybridization techniques. This capability was vital for our experiments, because it provided us with a reliable way to quantify the expression of our transgene in host plants. Eventually, by manipulating the DNA sequences surrounding a transgene and measuring the mRNA transcribed from it, we hoped to close in on the regions that are critical to a gene's control: the regulatory sequences.

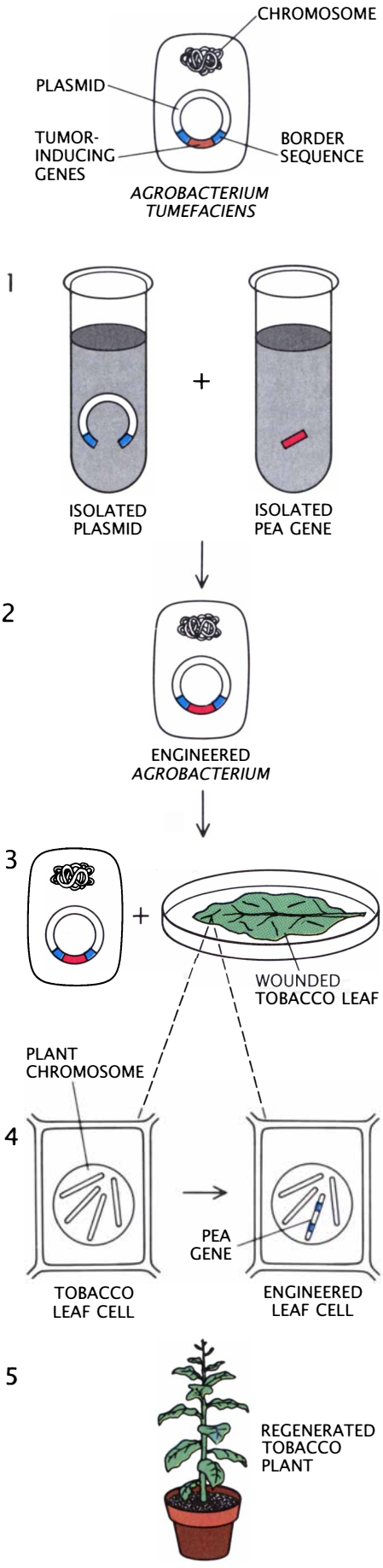
We carried out our initial gene-transfer experiments with cultured plant cells. In our laboratory Richard M. Broglie and Gloria M. Coruzzi isolated an rbcS gene from a pea plant and then, in collaboration with Robert T. Fraley, Steven G. Rogers and Robert B. Horsch of the Monsanto Company, put the gene into petunia cells. The cells correctly expressed the foreign gene, yielding rbcS mRNA and the rbcS protein itself. The pea rbcS subunit even combined with the petunia's own RUBISCO subunits to form RUBISCO enzyme. Anthony R. Cashmore at Rockefeller, Luis Herrera-Estrella at the State University of Ghent in Belgium and their colleagues obtained similar results, transferring the pea rbcS gene into tobacco plant cells.

Workers in our laboratory subsequently examined the sequences "upstream" of the pea rbcS gene, that is, the sequences preceding the gene in the direction of transcription. It is in the noncoding DNA region upstream from the gene that regulatory sequences are often found. Called promoters, these sequences usually contain two discrete subregions. One is a short sequence that indicates where transcription of the mRNA strand should begin. The sequence is similar in the genomes of bacteria, animals and plants and is called the TATA box for its commonest series of nucleotides. Farther upstream a more complex DNA sequence controls the conditions under which transcription takes place as well as the amount of mRNA that is made.

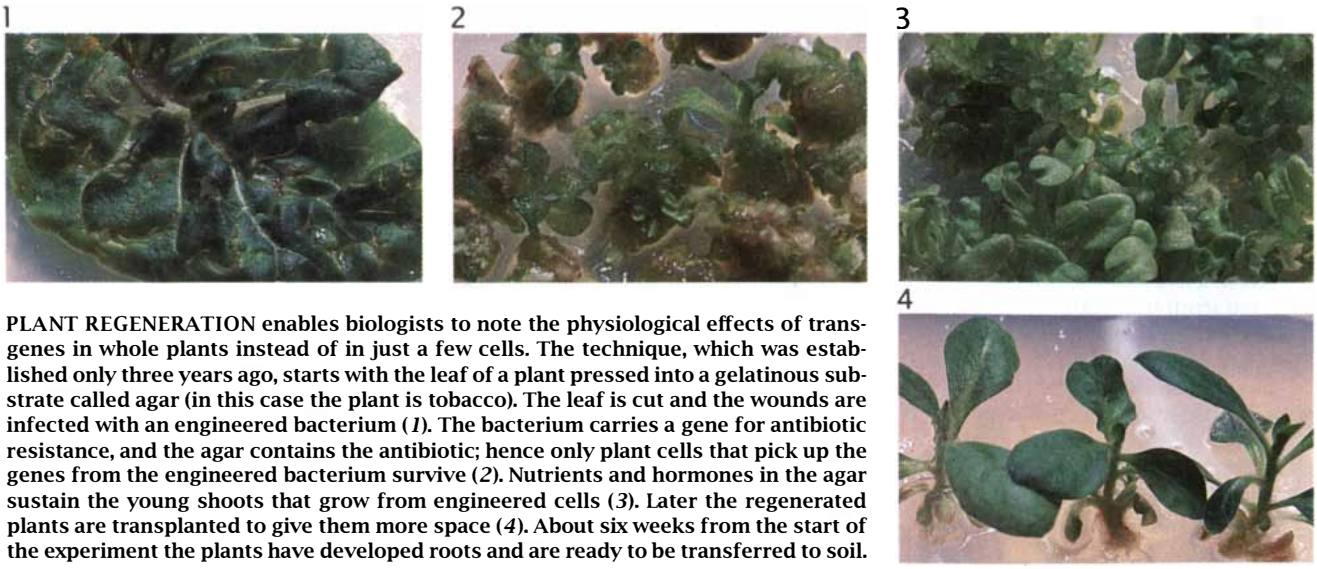
Giorgio Morelli and Ferenc Nagy wanted to define the promoter for the rbcS gene precisely; to do so they generated a series of "deletion mutants," in which progressively larger pieces of the region upstream from the rbcS gene were removed, and then tested the gene's activity in cultured petunia cells. The two workers succeeded in showing that a short sequence in the vicinity of the TATA box is involved in light regulation. Cashmore, Herrera-Estrella and their fellow workers corroborated these results and went on to demonstrate that the region upstream from the TATA box also takes part in the response to light. We introduced the term LRE to refer to this region.

As a means of gathering more pertinent physiological information, Robert Fluhr and Cris J. Kuhlemeier at Rockefeller regenerated whole petunia and tobacco plants from leaf cultures that contained the pea gene for rbcS. These "transgenic" plants showed remarkably faithful expression of the transgene in different organs and under various light conditions. The pattern of expression among the leaves, stems and roots conformed to that seen in normal plants: leaves had large amounts of mRNA, stems much smaller amounts and roots virtually none. Red light stimulated the transcription of mRNA from the foreign rbcS gene, and subsequent treatment with far-red light halted the stimulation. Plants grown in the dark contained little mRNA from the transgene.

This accuracy of expression is particularly surprising considering the wide evolutionary gap between the gene's sources and its new hosts. The lineages of pea and tobacco plants, for instance, diverged 70 million years ago. The functional integrity of the transgene is also exceptional because the *Agrobacterium* vector deposits the gene randomly in the



MOVING GENES from one plant species to another requires the assistance of the microbe *Agrobacterium tumefaciens*. The bacterium contains a circular piece of DNA known as a plasmid that ordinarily causes tumors in plants by transferring deleterious genes to its host. Plant biologists remove the tumor-inducing sequences and replace them with a gene isolated from, say, a pea plant (*1*). The plasmid thereby created is put back into *Agrobacterium* (*2*) and the engineered bacterium is introduced into plant cells of a different species through wounds in a leaf (*3*). The cells the bacterium infects acquire the pea gene (*4*). The medium in which the leaf is embedded encourages the growth of cells that have the "transgene" but kills cells without it. In a few weeks the "plantlets" are put into soil (*5*).



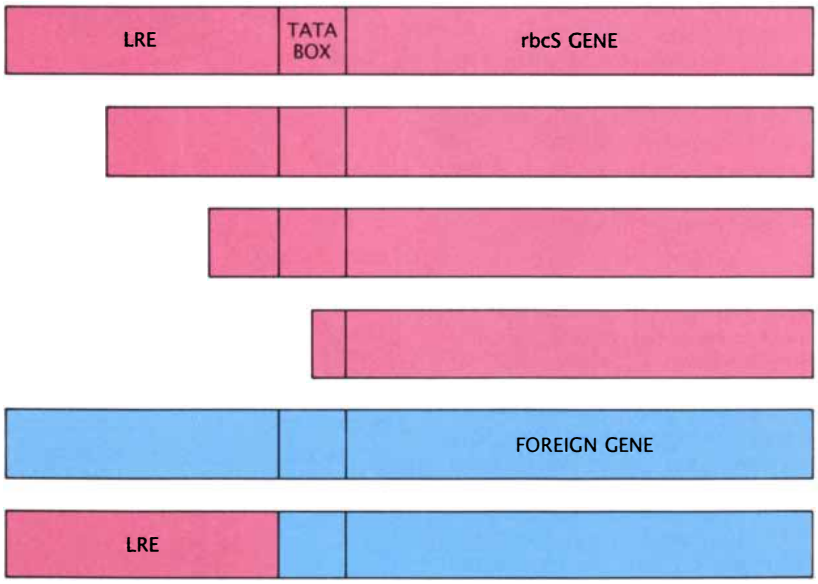
PLANT REGENERATION enables biologists to note the physiological effects of transgenes in whole plants instead of in just a few cells. The technique, which was established only three years ago, starts with the leaf of a plant pressed into a gelatinous substrate called agar (in this case the plant is tobacco). The leaf is cut and the wounds are infected with an engineered bacterium (*1*). The bacterium carries a gene for antibiotic resistance, and the agar contains the antibiotic; hence only plant cells that pick up the genes from the engineered bacterium survive (*2*). Nutrients and hormones in the agar sustain the young shoots that grow from engineered cells (*3*). Later the regenerated plants are transplanted to give them more space (*4*). About six weeks from the start of the experiment the plants have developed roots and are ready to be transferred to soil.

plant-cell genome. Correct regulation must therefore depend mainly on the guidance of the flanking LRE.

More elaborate manipulations of the rbcS LRE showed that the element can impose light sensitivity on a foreign TATA box placed in its sphere of influence: TATA boxes from genes that normally operate under all conditions became dependent on light for proper functioning when they were coupled with the LRE. Furthermore, the LRE can regulate foreign genes placed under its control. Experiments in which foreign genes were hooked up to the rbcS LRE revealed that the regulatory sequence confers organ specificity in addition to light responsiveness, establishing the pattern of high expression in leaves, low expression in stems and no expression in roots.

In the past two years our laboratory has begun to uncover the exact composition of the DNA sequences that make up the rbcS LRE. Pamela J. Green and Maria A. Cuozzo, working with Kuhlemeier, determined that the LRE consists of two shorter regions of DNA, each of which can mediate light responsiveness and organ specificity by itself. In other words, the genetic information contained in the LRE is repeated.

Why should a regulatory sequence in a plant genome contain redundancies? We speculate that during certain parts of a plant's life cycle multiple copies of light-responsive ele-



	LIGHT			DARK		
	LEAVES	STEM	ROOTS	LEAVES	STEM	ROOTS
	+++	+	–	–	–	–
	+++	+	–	–	–	–
	+	–	–	–	–	–
	–	–	–	–	–	–
	+++	+++	+++	+++	+++	+++
	+++	+	–	–	–	–

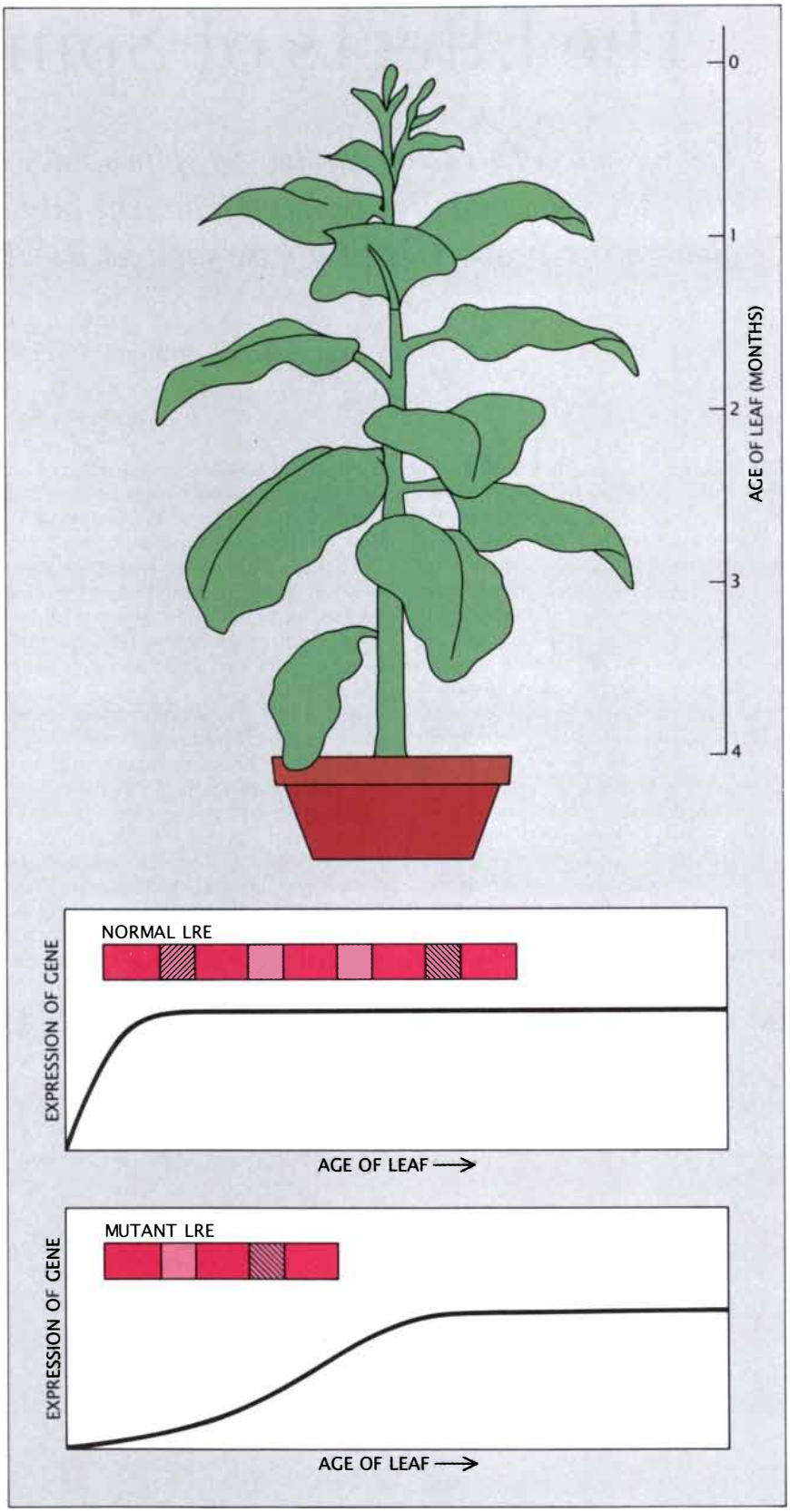
GENETIC MANIPULATION revealed that a segment of DNA "upstream" from the light-responsive rbcS gene regulates the gene's expression. At the top of this schematic diagram the rbcS gene with its regulatory region, including the "light-responsive element" (LRE) and the so-called TATA box, are shown along with the normal levels of expression found in leaves, stems and roots both in the light and in the dark. Below that three mutants are shown in which successively larger parts of the regulatory region have been deleted; because of redundancy in the region, the LRE can be halved without affecting expression in most of the host plant. The regulatory region also confers light responsiveness and organ specificity on a foreign gene whose expression is normally independent of those conditions, as is demonstrated by experiments placing an LRE upstream from such a gene.

ments may be needed for photomorphogenesis. In fact, Kuhlemeier recently found that both subregions of the LRE are required for full expression of the rbcS gene in the youngest budding leaves of tobacco plants [*see illustration at right*]. If this discovery is any indication, the role of LRE's in plant development ought to be quite complex.

Other hints of complexity come from what is known about similar regions in animal genes. These regions also control development, although they react to quite different signals. And like their analogues in plants, the sequences exert varying degrees of control depending on the organ type and developmental stage of the animal. For example, the expression of the gene for insulin in pancreatic cells of mammals is governed by a regulatory DNA sequence.

In general, animal regulatory sequences are better understood than their floral equivalents. Plant molecular biologists are studying LRE structures in finer detail in order to get a better grasp of how they operate and how their responses differ depending on the quality of light, the organ type and the stage of development of the plant. Many clues will probably come from investigations of the mechanisms for transducing the light signal. It is likely that the phytochrome pigment activates molecular intermediaries that convey the signal to the LRE. Indeed, Green and her colleague Steve A. Kay have already identified one candidate for such an intermediary, a protein factor found in the plant-cell nucleus. The protein binds to two specific DNA sequences within each subregion of the LRE; mutations in the LRE that decrease binding in the test tube also diminish expression of the rbcS gene.

Present knowledge offers just a glimpse of how light, with exquisite precision, governs the growth, development and aging of plants. More thorough acquaintance with the process of photomorphogenesis would have countless advantages for agriculture. Perhaps science will be able to make plants more efficient harvesters of the sun's energy or less demanding consumers of the earth's resources. The study of photomorphogenesis, however, has merit beyond its practical applications. Shaping as it does the primary source of oxygen and the very first link in the food chain, the relation between light and plants is one of the most important and intriguing aspects of life on this planet.



HALVING THE LRE of the light-responsive rbcS gene disrupts expression in the youngest leaves of a tobacco plant. The normal rbcS LRE shown in the top graph has two redundant subregions, each with two sites for protein binding (*pale and hatched boxes*). With this LRE maximum expression is achieved in almost all leaves of the plant. When only one subregion is present (*bottom graph*), the younger leaves do not exhibit full expression. These graphs are still largely speculative, but the experiments carried out so far hint that genetic redundancy could play an important role in development.

The Effects of Spin in Gases

The nucleus of an atom can have a spin, somewhat like a tiny top. How can that spin, which is isolated from the outside world, dramatically change the properties of a gas, such as its ability to conduct heat?

by Franck Laloë and Jack H. Freed

Low-density gases, in which atoms are separated by large distances, have long provided an enjoyable playground for physicists. Much of the enjoyment comes from the simplicity of the medium; since the atoms collide only occasionally with one another, a theoretical understanding of the gases' macroscopic properties is easily attained. A significant fraction of the current understanding, in fact, comes from contributions made late in the 19th century by James Clerk Maxwell and Ludwig Boltzmann. In contrast, many of the properties of liquids and solids—which consist of large numbers of closely spaced, simultaneously interacting particles—continued to be mysterious until the development of the quantum theory in the early part of the 20th century, and explanations of some of the properties still elude theorists.

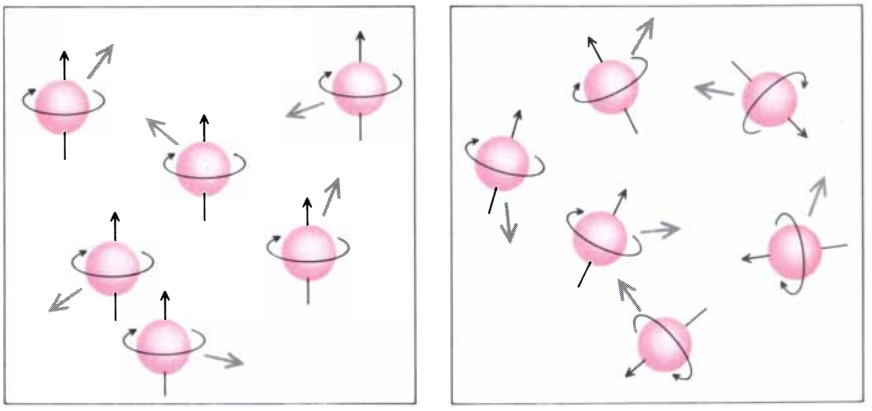
One might suppose the pleasure of the playground would by now have been exhausted by the very simplicity of low-density gases. Recent work by a number of investigators including us shows that this is not the case; low-density gases continue to serve up a rich variety of phenomena as well as counterintuitive surprises. In particular, the macroscopic properties of a gas composed of individual hydrogen or helium atoms can under special circumstances be changed dramatically by quantum-mechanical effects.

According to quantum theory, the nucleus of an atom behaves in a way similar to a rotating top, which has angular momentum about its axis of rotation; that is, the nucleus has spin, known more precisely as spin angular momentum. If the atoms of a gas are spin-polarized, so that their nuclei all have their spins pointing in the same direction, the viscosity of the gas can be changed enormously and so can its ability to conduct heat. Quantum-mechanical correlations among the nuclei called spin waves, which up to now had been observed only in certain liquids and solids such as magnets, can also arise. The changes are large enough for one to say the quantum-mechanical effects have caused the gas to take on entirely new properties.

In a certain sense it is amazing to think that polarizing the nuclear spins can have any effect on the macroscopic properties of the gas, since the nuclear spins are so weakly coupled to the outside world. Yet the observations are in full agreement with theory. Moreover, because spin-polarized gases are still fairly simple systems, they can be understood in terms of precise calculations made from fundamental principles, something that is still not possible to do in the case of liquids and solids.

Our work has involved two kinds of gases: atomic hydrogen and helium 3 (^{3}He). Atomic hydrogen, of course, consists of a single electron bound to a nucleus made of a single proton. Hydrogen gas in nature is generally diatomic, composed of two hydrogen atoms bound together (H_2). In recent years investigators have found that they can keep hydrogen atoms from binding and thereby prepare samples of atomic hydrogen gas by exploiting the effects of spin polarization [see "The Stabilization of Atomic Hydrogen," by Isaac F. Silvera and Jook Walraven; SCIENTIFIC AMERICAN, January, 1982]. Such samples represent yet another remarkable way in which quantum-mechanical effects come into play on a macroscopic level. Exactly how the effects make themselves felt will become clear as we discuss the effects of spin in general.

The other gas we have worked with, helium 3, has a nucleus consisting of two protons and a neutron. Two electrons are bound to the nucleus. Helium atoms are nonreactive, and so diatomic molecules of helium 3 never form. At sufficiently low temperatures—about 3.2 degrees Kelvin at atmospheric pressure—atomic he-



GAS OF ATOMS is said to be spin-polarized when the atomic nuclei have their spins, or spin angular momenta, aligned in the same direction (*left*). Here the spins are depicted pointing "up." When the gas is unpolarized, the spins point in all directions (*right*).

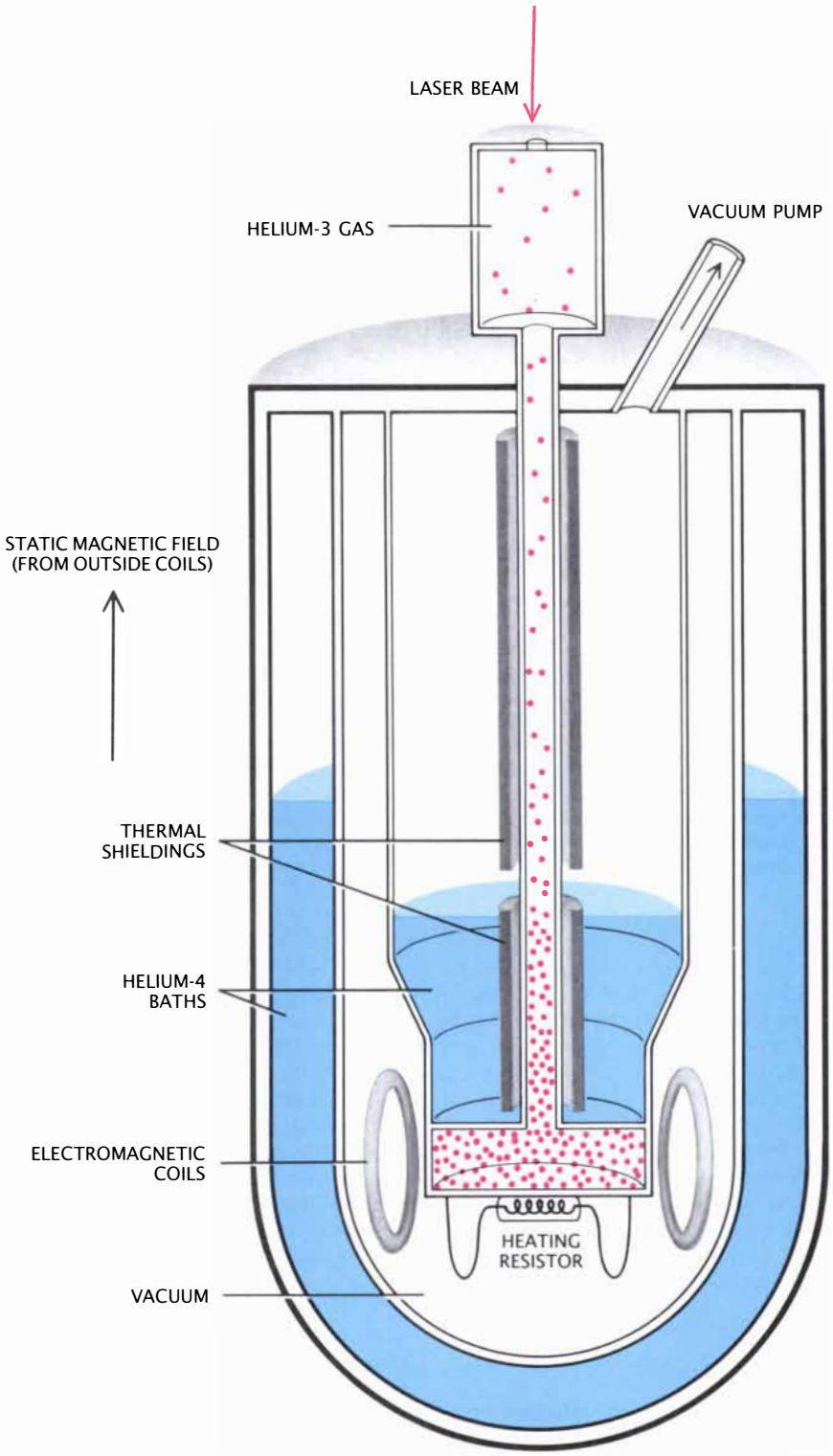
lium-3 gas does liquefy. Atomic hydrogen, on the other hand, is unique among all substances in that it is expected to remain a gas even at absolute zero (zero degrees K.).

As stated by quantum theory, there are important differences in the behavior of atomic hydrogen and helium 3. Atomic hydrogen is expected to belong to a class of particles called bosons and helium 3 is expected to belong to a class of particles called fermions. The contrast between bosons and fermions is considerable. Under certain conditions that we shall elaborate on, bosons tend to come close to one another easily, whereas fermions tend to avoid one another. Such behavior is the basis of the surprising effects observed in spin-polarized gases.

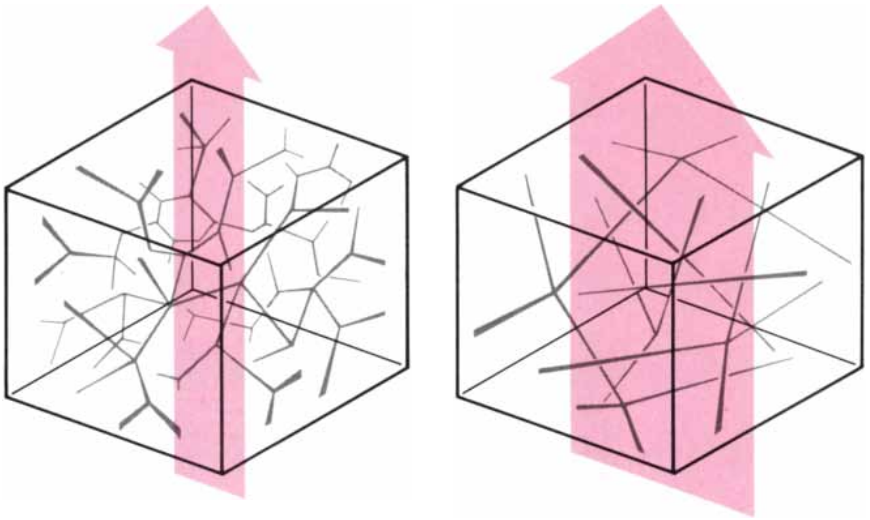
Whether a particle is a boson or a fermion depends on its spin. We have already mentioned that the nuclei of atoms have spin. It turns out that spin is an intrinsic property of every particle. Since every atom is a composite entity consisting of a nucleus and one or more electrons, it will in general have a composite spin.

The spin of a particle is somewhat like the spin of a ball, but there are important differences. The direction of the spin of a ball is given by the rule that if the fingers of the right hand curl in the same sense as the spin, the right thumb points in the direction of the spin. A quantum particle has spin, but the particle cannot be thought of as actually rotating or spinning in space. Also, unlike the spin of a ball, which can take on any angular momentum, the spin of an atom or a subatomic particle is quantized: the magnitude of the spin can take on only integer or half-integer values of the fundamental unit of angular momentum called Planck's constant. The proton, the neutron and the electron, for instance, have a spin of 1/2. The photon, or quantum of electromagnetic radiation, has a spin of 1. A particle that has half-integer values of spin, such as 1/2, 3/2, 5/2 and so on, is called a fermion, after the Italian physicist Enrico Fermi. A particle that has integer values of spin, such as 0, 1, 2, 3 and so on, is called a boson, after the Indian physicist S. N. Bose.

To determine the spin of a composite entity such as a nucleus or an atom, one must take the so-called vector sum of the spins of its components. (A vector is a quantity that has both a magnitude and a direction.) Since the nucleus of a hydrogen atom consists of a single proton, its spin is



EFFECTS OF SPIN POLARIZATION on heat conduction were measured at the École Normale Supérieure by a group of collaborators including one of the authors (Laloë). A gas of helium-3 atoms is spin-polarized by a beam of circularly polarized laser light, which injects angular momentum into the sample. The spin-polarized atoms travel down a pipe about a meter long into a chamber held at a temperature of a few degrees Kelvin. The bottom surface of the chamber has a resistor glued to it. By passing an electric current of known magnitude through the resistor, a known heat current can be made to pass through the gas. When the gas is spin-polarized, the temperature difference between the top and bottom surfaces is less than when the gas is unpolarized; spin-polarized helium 3 conducts heat better than unpolarized helium 3. The electromagnetic coils on each side of the chamber are employed to deliver a quick pulse of oscillating magnetic field to destroy the polarization for comparative measurements.



ENHANCED HEAT CONDUCTION of spin-polarized helium 3 can be accounted for by the laws of quantum mechanics. In ordinary, unpolarized helium 3 the atoms collide frequently, and the mean free path—the average distance traveled by one atom between two successive collisions—is rather short (*left*). Heat is poorly conducted (*colored arrow*). The enhanced conduction of spin-polarized helium 3 arises from the fact that the atoms belong to a class of particles called fermions; according to quantum mechanics, if one fermion occupies a certain state, all other identical fermions are excluded from that state. (The state of a particle is a complete specification of the characteristics of the particle, such as its energy, its position or momentum and its spin.) If two helium-3 atoms have identical spins, they cannot be found at the same point in space: the two atoms tend to avoid each other. In a spin-polarized helium-3 gas, therefore, atoms ignore one another and the mean free path approaches infinity (*right*). The longer the mean free path, the better the efficiency with which "hot," or fast, atoms can carry heat from a hot part of the gas to a cold part: the conduction increases dramatically.

simply 1/2. The net spin of the helium-3 nucleus, which consists of three spin-1/2 objects, turns out to be 1/2 also. The spin of the hydrogen atom as a whole assumes an integral value (either 0 or 1), because the atom's spin-1/2 nucleus and spin-1/2 electron "add" vectorially, and the hydrogen atom may be expected to act as a composite boson. The helium-3 atom, on the other hand, contains two spin-1/2 electrons, and so the total spin of the atom will always assume a half-integral value (either 1/2 or 3/2). Helium 3 may be expected to act as a composite fermion.

One of the most fascinating properties of bosons and fermions is that they can deviate from some of the predictions of classical physics. A key breakdown in classical theory stems from the incorrect assumption that individual particles are always distinguishable from one another. According to quantum mechanics, however, identical particles that have identical spins are in fact indistinguishable: no measurement can be made to determine which particle is which. Indistinguishable particles exhibit important nonclassical effects when they come together in a collision. The nature of such effects depends on whether the particles are fermions or bosons.

The basis for the behavior of fermions is the quantum-mechanical rule called the Pauli exclusion principle, named after the Austrian physicist Wolfgang Pauli. The principle requires that if one fermion occupies a certain state, all other identical fermions are excluded from that state. The state of a particle is a complete specification of its characteristics, such as its energy, its position or momentum and its spin. An important consequence of the exclusion principle is that if two electrons, say, are in identical spin states, they cannot be found at the same point in space. Under such conditions, which we alluded to above, the two electrons tend to avoid each other. (Electrostatic repulsion, which also tends to keep the two electrons apart, is a separate but important consideration.) It is the exclusion principle, applied to the electrons of atoms, that gives rise to the properties of all the elements, each with its own distinct and stable electronic configuration.

Let us now clarify what we mean by indistinguishability in a collision between two fermions. One can in principle observe the respective paths of the two fermions as they approach each other. The collision alters their directions, and one can then observe their paths as they recede from each other. If both fermions are in the same spin state, one cannot distinguish which fermion is which. If, however, they are in different spin states, they can (at least in principle) be distinguished by measuring the direction of their spins. This would enable one to determine the complete path of each fermion, that is, one would know which fermion is which. (The same statement applies to a collision between two bosons.) The tendency of two indistinguishable fermions to avoid each other is known to influence the way they interact during a collision.

Bosons, on the other hand, do not follow the Pauli exclusion principle. There is no limit to the number of bosons that can occupy the same quantum state. If two simple bosons, such as photons, have identical spins—and are therefore indistinguishable—they tend to come close to each other more readily than two distinguishable particles would. Composite bosons such as hydrogen atoms with identical electron spins will exhibit a similar effect when their nuclear spins are the same.

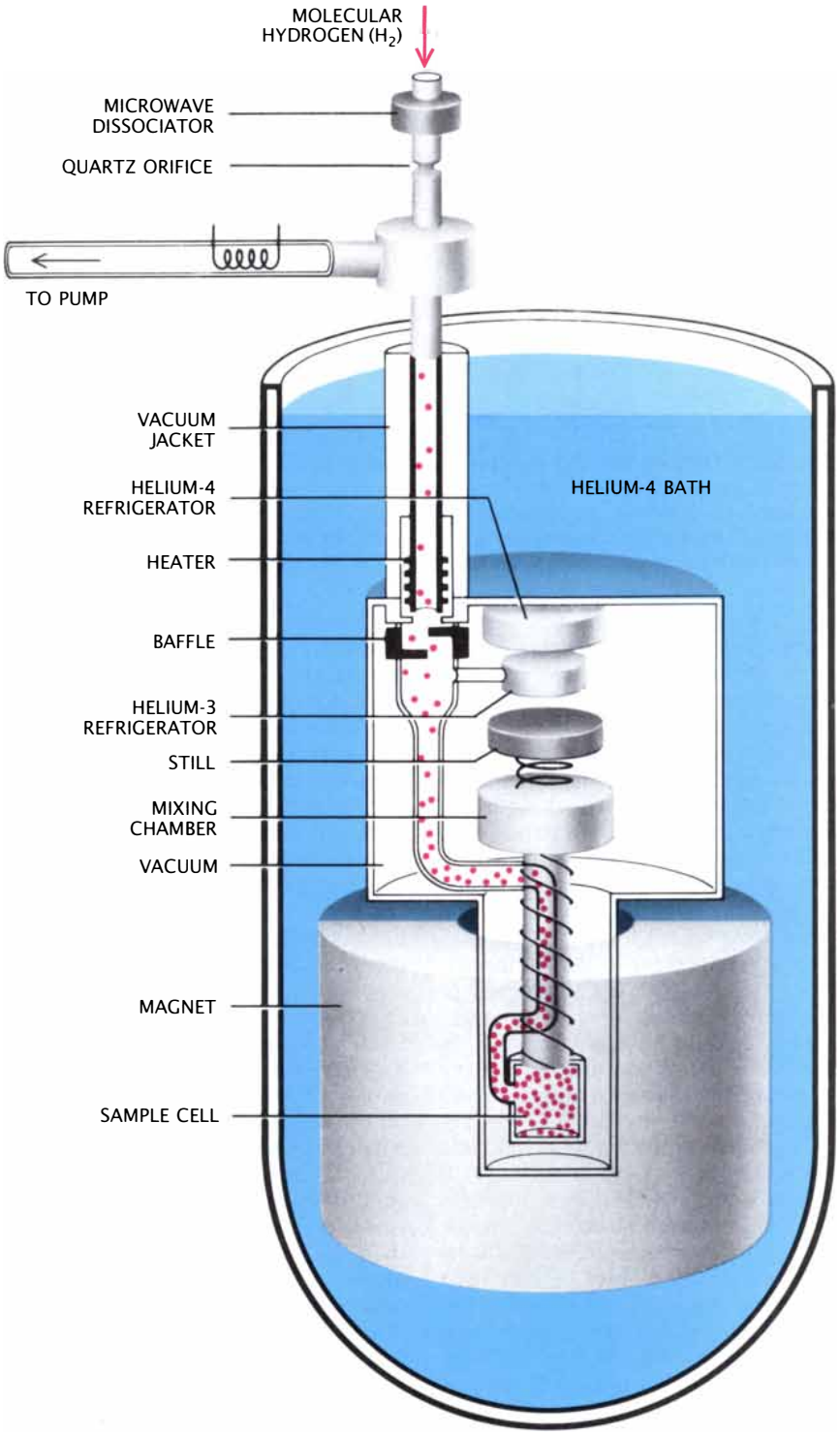
The exclusion principle can be exploited to keep individual atoms of hydrogen from combining to form molecular hydrogen (H_2) when they collide. Actually, although the hydrogen atom is a composite boson, its constituent proton and electron are fermions and therefore obey the exclusion principle. In ordinary, unpolarized gaseous hydrogen the spins of the electrons of the atoms point in all directions in a random manner. (In an applied magnetic field the spins can point in only one of two directions, either "up" or "down.") Two electrons that have the same spin state are indistinguishable and will tend to avoid each other. If each electron is part of a hydrogen atom, this would prevent the formation of a chemical bond between them. If the electron spins point in different directions, however, they are distinguishable and no quantum principle keeps them from being in the same place at the same time. If each elec-

tron is part of a hydrogen atom, it is energetically more favorable for the two atoms to bind together than for them to remain apart. Molecular hydrogen forms.

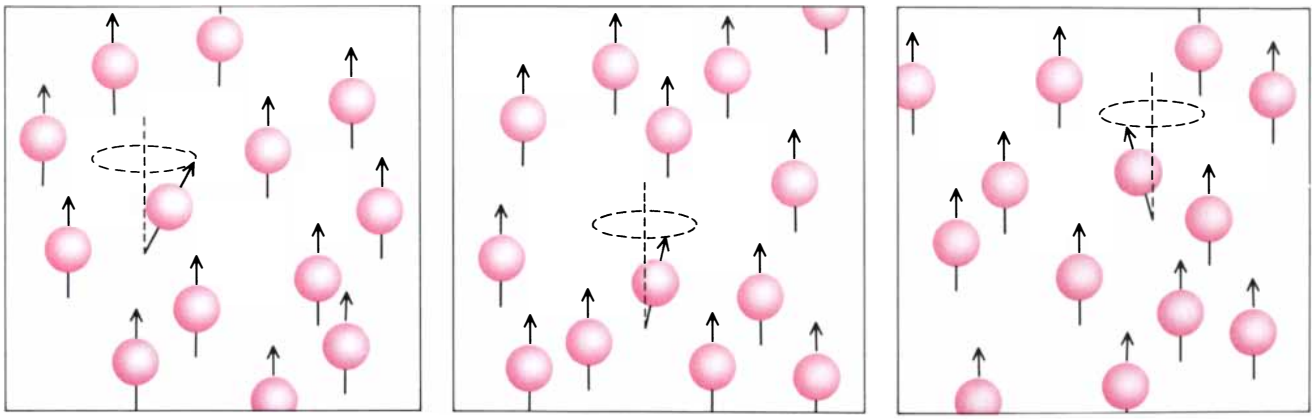
Now suppose the gaseous sample of hydrogen is polarized, so that the spins of all the electrons point in the same direction. In this case all the electrons are indistinguishable, and they will tend to avoid one another. Consequently the hydrogen atoms will not come together and bind into pairs during a collision; they separate instead. Under these conditions atomic hydrogen is stable and molecular hydrogen will not form. In recent years a number of laboratories around the world have produced stabilized atomic hydrogen gas by spin-polarizing the electrons.

In our work we have addressed the question of what happens when the nuclear spins of atomic hydrogen and helium 3 are polarized. (The hydrogen atoms are "doubly polarized": the electron and the nucleus are both polarized. In helium 3 in its ground state one does not need to be concerned about polarizing the electrons: each pair of electrons in an atom are in opposite spin states, yielding a composite electron spin of zero.) The effects of polarizing the nuclear spins are remarkable, particularly in the light of the fact that the tiny magnetic top associated with each nuclear spin is almost indifferent to the environment surrounding the atom. The reason the nuclear spin is isolated from the outside world is that the magnetic force associated with it is roughly 1,000 times weaker than the magnetic force associated with the spin of each electron of the atom. Of course, the effects of nuclear spin polarization do not come from the magnetic forces associated with the nuclear spins. Rather, the dramatic changes in macroscopic properties are built-in consequences of the quantum-mechanical description of identical particles.

An important aspect of all our work is that it has been done in very low temperatures, no more than a few degrees above absolute zero. Low temperatures are necessary because of the wave-particle duality of matter and radiation. A particle has associated with it a certain wavelength known as the de Broglie wavelength, which is inversely proportional to the momentum of the particle. The lower the temperature is made, the longer the de Broglie wavelength be-



ANOTHER SPIN PHENOMENON, called spin waves, has been observed at Cornell University by a group of collaborators including one of the authors (Freed). A spin wave in a polarized gas is a collective oscillatory mode of the nuclear spins, so that the spins precess, or rotate, about the average direction of polarization at a frequency that depends on the amount of polarization. To study the waves, hydrogen molecules (H_2) are first dissociated into hydrogen atoms by bombardment with microwave radiation. The atoms are then cooled and spin-polarized and allowed to fill a small chamber, which is immersed in a strong magnetic field. The spin waves are induced by a pulsed nuclear-magnetic-resonance (NMR) technique, in which a short pulse of radio waves is used to tilt the nuclear spins at some small angle from their initial direction, and so afterward they precess around the static magnetic field at a rate proportional to the strength of the field. The rotating spins create a rotating magnetization that is transverse, or perpendicular, to the main direction of polarization. This transverse magnetization induces a voltage that is amplified, detected and analyzed by its frequency spectrum.



ORIGIN OF SPIN WAVES, like the dramatic changes in heat conductivity, can be accounted for by quantum mechanics. Imagine that into a collection of spin-up atoms a test atom is introduced that has a slightly tilted nuclear spin (*left*). When the test atom collides with any of the atoms, the amount of tilt will be virtually unchanged, but the test spin will be rotated slightly around the vertical axis (*middle*). The effect on the test spin in subsequent collisions will be almost identical. As a consequence the random collisions among the atoms will eventually produce a cumulative rotation of the test spin around the vertical axis (*right*).

comes, since the particle moves more slowly and has less momentum. Because of the Pauli exclusion principle, two fermions in the same spin state cannot come any closer to each other than a distance on the order of the de Broglie wavelength. For the quantum effects of indistinguishability to become important in a collision between two fermions, the de Broglie wavelength must exceed the range over which forces between atoms are appreciable. The temperature must therefore be lowered to maximize the de Broglie wavelength.

The effect of spin polarization on heat conduction is relatively easy to understand. Suppose the nuclear spins of a gas of helium-3 atoms are polarized and the sample is held at a low temperature, say one degree K. If ordinary, unpolarized gaseous helium 3 is held under such conditions, atoms in the same spin state will ignore one another, since helium 3 is a composite fermion, but atoms in different spin states will collide and interact with one another. In fully polarized gaseous helium 3, in contrast, all the atoms will ignore one another almost completely and collisions will be much less frequent. It is as if a complete nuclear polarization "switches off" any interactions among the atoms.

The switching off of atomic interactions leads to significant changes in an important physical quantity called the mean free path: the average distance traveled by one atom between two successive collisions in a gas. In an ideal gas the atoms would have no mutual interaction at all, so that their mean free path would be infinite. The atoms, merely ignoring one another, would fly along straight lines directly from one wall of a gas container to another. In real gases atoms collide with one another and the behavior becomes truly ideal only in the limit of infinite dilution. Yet the ideal gas behavior is precisely what is expected for a completely polarized helium-3 gas sample at extremely low temperatures. Under such conditions helium 3 acts as an "artificial" ideal gas, and the length of its mean free path approaches infinity. Similar effects were predicted in 1977 by two Soviet physicists, E. P. Bashkin and A. Meyerovich of the S. I. Vavilov Institute of Physical Problems, for dilute solutions of liquid helium 3 in superfluid helium 4, a physical system that can be very similar to a gas in some ways. (The helium-4 nucleus, which is naturally more abundant than the helium-3 nucleus, consists of two protons and two neutrons; a superfluid flows with no resistance.)

Among the physical properties that depend on the mean free path is the ability of any gas to conduct heat. If two walls of a container filled with a gas are kept at different temperatures, the heat flow across the system is proportional to the mean free path: the longer the mean free path, the better the efficiency with which the "hot," or fast, atoms will carry their energy from the hot wall to the cold one. Consequently a polarized gas of helium 3 at low temperatures should have a much higher heat conductivity—it would approach infinity as the mean free path approaches infinity—than its unpolarized counterpart. The viscosity of the gas should also increase for similar reasons, although the effect is not as intuitive.

The effects of spin-polarizing the nuclei of hydrogen atoms, on the other hand, should be just the opposite. The reason is that hydrogen atoms are bosons (actually composite bosons made of two fermions, remember), and that as identical particles they therefore tend to come close to one another more easily. Spin-polarizing the nuclei should make the mean free path shorter and decrease both the viscosity and the heat conduction. Even in an unpolarized sample, however, bosons are largely free to interact with one another anyway, and so the effects of polarization should be less pronounced than they are for fermions and less interesting to investigate experimentally.

The effect of spin polarization on heat conduction in gaseous helium 3 was observed and measured by a group of collaborators including Pierre-Jean Nacher, Geneviève Tastevin, Michèle Leduc, Stuart B. Crampton, David S. Betts, James M. Daniels and one of us (Laloë) at the École Normale Supérieure in Paris. It is first necessary to polarize the helium nuclei. To do so a technique called laser optical pumping was used. Optical pumping is a general method, invented in 1950 by Alfred Kastler, then at the École Normale, in which a beam of circularly polarized light (light in which the associated electric field rotates about the direction of travel) is employed to inject angular momentum into a gas of atoms and polarize their spins. Many atoms can be polarized this way, but helium raised spe-

cific difficulties that were solved in 1963 at Texas Instruments Incorporated by Forrest D. Colegrove, Laird D. Schearer and G. King Walters in an approach that was further refined by Leduc and her colleagues at the École Normale.

The second problem is to create the nuclear polarization in a cold gas, at temperatures of a few degrees Kelvin, where the quantum effects are significant. At the École Normale this was done by using a special container called a double cell. The container has two chambers: one held at room temperature, where the helium nuclei are polarized by optical pumping, and one held at a low temperature, where the measurements are made. The two parts are connected by a pipe about a meter long in which the atoms diffuse under the effect of their random thermal motion. The diffusion transfers polarization from the room-temperature cell to the cold measurement cell. To minimize the sticking and interaction of the atoms with the cold cell, the walls are coated with solid molecular hydrogen.

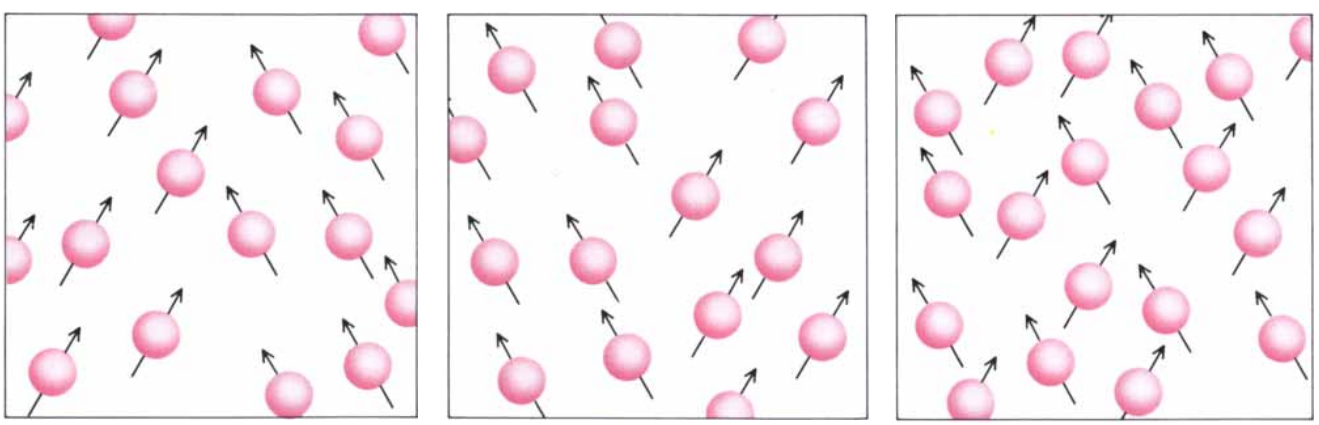
The measurement cell itself has the shape of a cylinder, about a centimeter high and a few centimeters in diameter. The upper flat surface is in contact with a helium-4 bath, which acts as a refrigerant. The temperature of the bath can be adjusted between one and four degrees K. The lower flat surface has a resistor glued to it and is in contact with a vacuum. An electric current of known magnitude passing through the resistor causes a known heat current to pass through the gas; a simple measurement of the temperature difference between the two flat plates provides a measurement of the heat-conduction coefficient of the gas.

The experiment consists of recording the temperature difference when a spin-polarized sample of helium-3 gas fills the cell and then applying an oscillating magnetic field in a quick pulse to destroy the polarization suddenly. A change of nuclear polarization does indeed trigger a macroscopic temperature change; the temperature difference between the top and the bottom of the cell is less when the gas is polarized. The observed change matches the predicted change, and the peculiar implications of quantum theory are upheld.

We have mentioned above that the quantum effects of spin-polarizing the nuclei of a gas are not limited to heat conduction. Another phenomenon was actually observed earlier: spin waves. These waves arise from the cooperative interaction of particles with spin and are perhaps best known for their role in permanent magnets. In a permanent magnet large numbers of electrons have their spin in the same direction. Since each electron spin behaves like a tiny magnet, the cumulative effect is to produce the permanent magnetization. Now suppose (with the aid of an external magnetic field if necessary) all the electrons are made to spin in the same direction, say up, except for one, which points down. This single down spin, which can be thought of as a "spin-down excitation," can propagate rapidly through the magnet: by interacting with the spins of the surrounding electrons, the spin-down excitation flip-flops its way through the magnet. Such delocalization is a simple example of a spin wave.

The origin of spin waves in a gas is somewhat different, because the atoms are not fixed; they move constantly in all directions. Moreover, the spin waves that have been observed involve the spins of atomic nuclei, which are shielded quite well from the outside world. How can occasional random collisions in a gas lead to correlations among the spins of many atoms to make spin waves possible?

The answer once again is found in the quantum behavior of identical particles. As we have mentioned, the result of a collision between two identical atoms depends on the spin directions of their nuclei, even though the forces of interaction between the two atoms have nothing to do with the nuclear spins. Suppose, for example, one introduces into a collection of identical spin-up atoms a test atom that has a nuclear spin tilted slightly with respect to all the other nuclear spins. (Such a spin can be expressed as a vector sum of a spin-up state with a small amount of spin-down character.) When the test atom collides with any of the atoms, the amount of downward tilt will remain virtually the same, but the test spin will be rotated slightly around the vertical axis. (This is a consequence of the spin-up part of the test atom's being indistinguishable in a collision with a spin-up atom, whereas the spin-down part engages in a distinguishable collision.) The effect on the test spin in subsequent collisions will

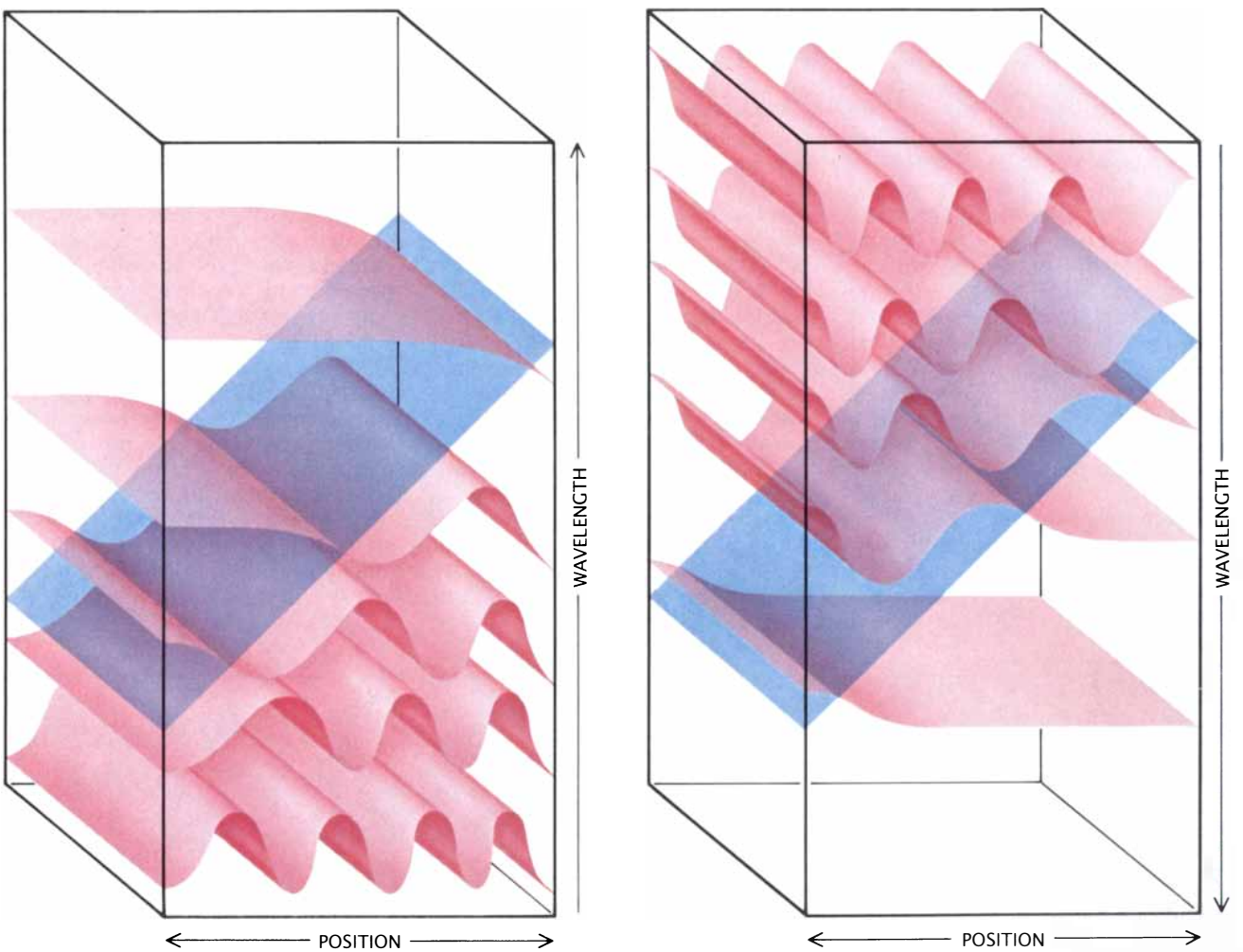


SPIN WAVES in a gaseous sample typically arise when the nuclear spins in one region of the sample are tilted differently from the nuclear spins in another (*left*). The transverse magnetization in each region can be transmitted coherently through the sample by the cumulative effect of the successive collisions of the atoms, a behavior that constitutes the spin waves (*middle*). The same random thermal motions that create the spin waves ultimately destroy them as well; the motions transfer atoms randomly from a region where the transverse magnetization points in one direction to a region where it points in another (*right*).

be almost identical, because the collisions are always with spin-up atoms, and so the random collisions among the atoms will produce an overall cumulative rotation of the test spin around the vertical axis.

Now suppose the nuclear spins in one region of a sample are tilted differently from the nuclear spins in another region. The macroscopic effect of tilting spins in one region of the sample is first to create some magnetization in a direction that is transverse, or perpendicular, to the main direction of polarization. This transverse magnetization is then transmitted coherently through the sample by the cumulative effect of the successive collisions of the atoms. The spins tend to rotate about the average direction of polarization and at a frequency that depends on the amount of polarization. Such a collective oscillatory mode in the gas is the spin wave. The more pronounced the quantum effects are, the more rapid the oscillation is.

An interesting aspect of spin waves in gases is that the same thermal motions that create the spin waves in random collisions are also responsible for destroying the waves. Typically, a gaseous sample containing spin waves will have several regions of different transverse magnetizations. The thermal motions of the atoms eventually transfer the atoms by a diffusional process from a region where the magnetization points in one direction to a region where the transverse magnetization points in another direction. In time the mixing of regions will randomize the overall transverse magnetization, so that there will be no preferential direction of the magnetization in the sample. The effectiveness with which spin waves are transmitted in a gas versus the randomization of the transverse magnetization by thermal motions is proportional to the de Broglie wave-



ANALOGUE OF HEISENBERG UNCERTAINTY PRINCIPLE occurs in spin-polarized atomic hydrogen gas. The uncertainty principle holds that the position and momentum of a quantum particle cannot be simultaneously measured: if one attempts to measure the position of a particle, the measurement itself will change the state of the particle, so that after the measurement the particle will be more localized in space. Similarly, spin waves in a measurement cell are localized by immersing the cell in a constant magnetic field gradient, the strength of which is low at one side of the cell and increases linearly across the cell to the other side, where it is high. The gradient localizes the spin waves in one of the two sides of the cell, depending in part on whether the spin waves are associated with spin-polarized fermions or particles called bosons. The spin waves associated with doubly spin-polarized hydrogen atoms, which act as composite bosons, should be trapped at the side that has the high field gradient (*left*). If the particles were instead to act as fermions, they would be trapped at the side that has the low field gradient (*right*).

length of the atoms and inversely proportional to the range over which the atoms interact (multiplied by the magnitude and direction of the nuclear-spin polarization).

The observation of spin waves in a gas was made at Cornell University by a group of investigators including Burgess R. Johnson, John S. Denker, Nicholas P. Bigelow, Laurent P. Levy, David M. Lee and one of us (Freed). The work involved atomic hydrogen gas, because it has the least mass, yielding the largest de Broglie wavelength. This maximizes the effectiveness with which spin waves are transmitted as compared with the diffusional randomization. The gas is generated by dissociating molecular hydrogen with microwave radiation. The individual atoms of hydrogen are then made to travel through a tube lined with Teflon, the nonstick coating found on many frying pans, and subsequently in a low-temperature section of the tube, a film of superfluid helium 4. The Teflon and liquid-helium coatings are employed to minimize the recombination of the hydrogen atoms back to molecular hydrogen on the walls of the tube, since atomic hydrogen does not stick as well to these coatings as it does to other materials.

The atomic hydrogen gas then enters a cell, which has a volume of .3 cubic centimeter, in which the temperature is extremely low—only a few tenths of a degree above absolute zero. The sample cell is immersed in a high magnetic field, which attracts atoms that have electron spins antiparallel to the field (down spins) and repels atoms that have electron spins parallel to the field (up spins). As a consequence the cell contains only atoms that have spin-down electrons. In other words, the electrons in the gaseous sample are spin-polarized. As we discussed above, molecular hydrogen will not form in such a gas. The atomic hydrogen gas is thereby made stable.

Now, the nuclear spins of the hydrogen atoms can be either parallel or antiparallel with respect to the spins of the polarized electrons. Atoms with nuclear spins that are antiparallel—that is, up—become slightly depolarized, and they recombine with one another and deposit on the walls of the cell, so that a layer of solid molecular hydrogen gradually forms. After a few minutes the cell contains only doubly polarized atoms: atoms with nuclear spins that are parallel to the electron spins. (Both are antiparallel to the magnetic field.) The effect was first shown by Thomas J. Greytak and Daniel Kleppner of the Massachusetts Institute of Technology.

The polarized atomic nuclei have been made to exhibit spin waves by a pulsed nuclear-magnetic-resonance (NMR) technique developed by the Cornell workers. In this technique a short pulse of radio waves is used to tilt the nuclear spins at some small angle from their initial direction, so that afterward they precess, or rotate, around the static magnetic field at a rate that is proportional to the strength of the field. The rotating spins create a rotating transverse magnetization, which induces a voltage that is amplified, detected and then analyzed in terms of its frequency spectrum.

An important feature of the Cornell experiment is that a constant magnetic field gradient is applied to the static magnetic field: the combined field strength is low at one side of the sample cell and increases linearly across the cell to the other end, which has a high value. As a result nuclear spins in different parts of the sample cell precess around the field at different rates. Normally the range of different rotation frequencies of the nuclear spins in the different parts of the sample cell would produce a frequency spectrum that consists of a broad resonance line. Such a characteristic spectrum is in fact exploited in other NMR applications to obtain spatial images of materials, and it is the basis of the magnetic-resonance-imaging (MRI) technique employed by hospitals. But the unique feature of the Cornell experiment is that superposed on the broad resonance line is a series of prominent, narrow resonance peaks. The peaks correspond to the spin-wave modes in the sample cell.

The magnetic field gradient also produces another remarkable effect. The effect is an analogue of the Heisenberg uncertainty principle, which states that both the position and the momentum of a quantum particle cannot be determined simultaneously. A consequence of the uncertainty principle is that if one attempts to measure the position of a particle, the very act of the measurement itself will change the state of the particle in such a way that after the measurement the particle will be more localized in space.

Similarly, the spin waves in the sample cell are localized in space by applying the field gradient to determine their location. In the absence of the field gradient the waves are delocalized, but in the presence of the gradient the spin-wave modes are localized in one of the two sides of the sample cell. The field gradient both traps the spin waves and allows them to be imaged, that is, detected by the NMR technique.

The spin waves are trapped either at the side of the cell that has the low combined magnetic field strength or the side that has the high value. One of the factors in making the determination is whether the atoms in the gaseous sample act as fermions or as bosons. According to theory, much of which was developed at Cornell by Levy and Andrei E. Ruckenstein, the spin waves associated with the doubly spin-polarized hydrogen atoms, which generally act as composite bosons, should be trapped at the side that has the higher field strength. The experimental evidence supports the theory and dramatically confirms the fact that under the proper conditions hydrogen atoms act as composite bosons.

As a final note, the existence of spin waves has also been observed in gaseous helium 3. The work was done by the collaboration at the École Normale. Although the spin waves are not as spectacular as those in atomic hydrogen, their existence is just as significant. The observations are in good agreement with the theoretical predictions of Claire Lhuillier of the École Normale and one of us (Laloë).

As more experiments are done with spin-polarized gases, it is quite probable that the techniques developed in working with the gases will spawn practical applications. Already, for instance, some of the techniques have been successfully exploited by a number of groups to build a new low-temperature hydrogen-atom maser, which could prove to be an extremely accurate atomic clock. Nuclear physicists are working on the use of spin-polarized helium 3 as targets for particle collisions. In the near future, however, it seems likely the real significance of spin-polarized gases is that they will continue to offer the opportunity to investigate, from first principles, a wide range of quantum phenomena including interesting hydrodynamic effects.

The Behavior of Baleen Whales

These marine mammals have diverse social and feeding behaviors that are reminiscent of the terrestrial grazers from which they evolved about 55 million years ago

by Bernd Würsig

More than 50 million years ago the ancestors of modern whales—relatives of terrestrial ungulates such as deer and antelope—left the land and entered the sea. As millions of years passed, they slowly diversified into more than 90 species and spread throughout the world's oceans; today they can be found as far south as the Antarctic continent and as far north as the ice edge of the Arctic. Biologists are only now beginning to realize that these majestic navigators of the deep have behavioral repertoires as varied and complex as some terrestrial mammals. Indeed, whales are emerging as highly social animals, similar to grazing ungulates and in some ways to primates and terrestrial carnivores.

The picture of whale behavior that has begun to emerge is the result of intensive research efforts over the past decade, stimulated in part by their threatened extinction by the whaling industry. Before the 1970's most of what was known about whales came from the journals of 19th- and 20th-century whaling-ship captains. In some cases these accounts provide surprisingly detailed information on the feeding and social behaviors of the different species, but for the most part they are accounts of animals under stress, being hunted or harpooned by whalers.

Unlike terrestrial animals that can be observed for days or years at a stretch and tracked over many miles, whales are generally visible only when they are at the surface, often less than 20 percent of the time. Indeed, it has been said that the behavioral study of cetaceans is akin to studying mice by watching their tails move. Nevertheless, with the advent of new techniques remarkable progress in whale research has been made in recent years.

The work I have done for the past seven years on bowhead whales at the edge of the polar ice fields in the Beaufort Sea (in collaboration with my colleagues at the Moss Landing Marine Laboratories and with W. John Richardson of LGL Ltd., environmental research associates, near Toronto) is dependent on a variety of recent technological developments. From a bird's-eye vantage in a twin-engine aircraft 500 meters above the ocean (the minimum altitude possible without disturbing the whales) we were able to describe and videotape the various social interactions and feeding strategies of bowhead whales. We also recorded their sounds with hydrophones (underwater microphones) attached to floating buoys called sonobuoys. By listening to the whales from the airplane we could correlate their sounds with specific behaviors. By photographing each whale (a technique developed by Roger Payne of the World Wildlife Fund) we were able to track and follow individual animals.

Some of the more exciting discoveries of the past decade concern the feeding behavior of baleen whales. These whales belong to the suborder Mysticeti, one of two suborders in the order Cetacea. The other suborder, the Odontoceti, is composed of the toothed whales (sperm and killer whales, dolphins and porpoises), all of which have teeth and feed on relatively large prey such as fish and squid.

The Mysticeti is composed of species that have finely fringed comblike plates, called baleen, hanging from their upper jaw in place of teeth. The whales feed by taking in large quantities of water and prey and then forcing the water out through the baleen. The baleen acts as a sieve, trapping food, which is then swallowed. This specialized method of feeding allows the whales to collect large volumes of prey—ranging from zooplankton a few millimeters long to squid and small fish. The immense quantity of prey consumed is converted into blubber, which provides the whales with the energy stores required for long-distance migration. Most baleen whales spend about six months a year feeding at high latitudes, where food is abundant, and then migrate to lower latitudes, where the water is warmer and more conducive to mating and calving.

Although all baleen whales are filter feeders, the design of the baleen plates varies from family to family, reflecting the diversity of feeding behaviors in the suborder. Three families of baleen whales are recognized today: the Eschrichtiidae, Balaenidae and Balaenopteridae.

In the family Eschrichtiidae, represented by one species, the gray whale, the baleen is short and coarsely fringed. These whales occasionally feed on small prey suspended in the water column; more frequently they scoop up large quantities of small crustaceans called amphipods from the bottom. After ingesting mouthfuls of muddy substrate, the whales will often swim to the surface before forcing the water from their mouths. There they alternately open and close their mouths, emitting a distinctive trail of mud. They leave traces on the bottom as well; in areas where gray whales are feeding, characteristic pits have been found [see "Whales and Walruses as Tillers of the Sea Floor," by C. Hans Nelson and Kirk R. Johnson; SCIENTIFIC AMERICAN, February, 1987].

In the family Balaenidae there are four species: northern right, southern right, pygmy right and bowhead

whales. All have baleen plates that are long and finely fringed, well suited for capturing clouds of free-swimming copepods and other crustaceans. They usually feed by moving slowly through the water with their mouths wide open.

While observing bowheads my colleagues and I became aware that they vary their feeding habits considerably depending on the availability of prey. They can sometimes be seen feeding alone; at other times they feed in highly synchronized groups. Moreover, we have evidence that they feed in the water column, on the ocean floor or at the surface depending on such factors as changing winds, salinity, temperature, turbidity and nutrient content of the water.

Water-column feeding, which takes place underwater, is suggested by the bowheads' behavior at the surface. They dive for prolonged periods (up to 30 minutes at a time), return to the surface to breathe and then dive again. While they are at the surface they frequently defecate, a behavior closely associated with feeding. As many as 20 to 30 whales have been observed feeding simultaneously in the water column in an area from 50 to 100 square kilometers in size.

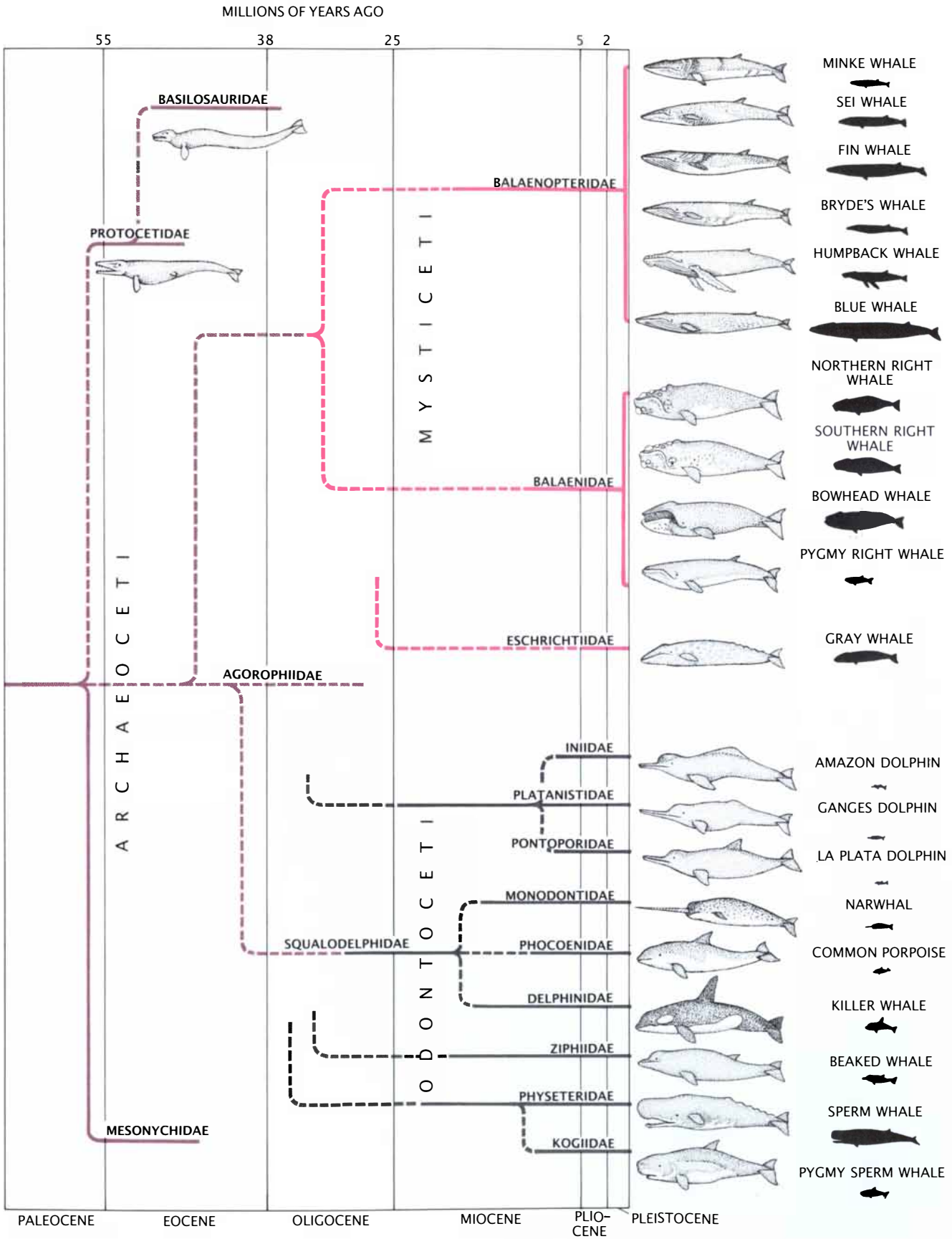
Bowheads are also believed to feed at the bottom (usually at depths of less than 60 meters), but it is not clear how, equipped with long and finely fringed baleen, they are able to do so. We have seen bowheads surfacing with muddy water streaming from the sides of the mouth, a behavior that in gray whales is clearly associated with bottom feeding. Although signs of substrate disturbance such as the pits made by grays have not been found where bowheads feed, analyses of stomach contents have revealed bottom-dwelling prey.

Bowheads do frequently skim-feed at the surface: they swim slowly and deliberately with the head just above the water and the mouth wide open. The lower jaw is dropped to varying degrees, sometimes forming an angle as great as 60 degrees with the upper jaw. They often skim-feed in groups of from two to 14 individuals and form echelons reminiscent of geese in flying formation: each whale is aligned behind the one preceding it, offset laterally by from one-half to three body lengths.

We have seen bowheads feeding in formation for more than three hours (the maximum time we were able to circle before refueling) and we believe they may continue to do so for several days. Sometimes the composition of the echelon changes as animals split off to join other groups and new ones enter, but its shape remains more or less constant.

Echelon feeding probably enables bowheads to exploit prey that would otherwise be unavailable. According to a survey of stomach contents, the bulk of the prey in a bowhead's stomach consists of copepods and euphausiids—small, rapidly swimming

FEMALE HUMPBACK and her calf were photographed in shallow waters near Hawaii. Less than three months old, the calf stays close to its mother. Like all whale calves, it is precocious at birth: able to swim about on its own, its senses functional.



WHALES have diverged since their origin about 55 million years ago into the suborders Mysticeti (the baleen whales) and Odontoceti (the toothed whales). The Mysticeti comprise 11 species, including the blue whale, the largest animal known; the Odontoceti comprise about 80 species, including toothed whales, dolphins and porpoises. Relative sizes are shown at the right.

crustaceans collectively known as krill. The fact that bowheads, which are slow swimmers, can catch such large numbers of these tiny crustaceans implies that there must be an advantage to echelon feeding.

In the family Balaenopteridae there are six species: minke, sei, fin, Bryde's, humpback and blue whales. These whales have baleen that is of medium length and fineness; when they feed, they open the mouth wide and lunge forward, expanding the throat (which has accordianlike grooves) as they do so. Feeding in these whales is very active, and the swiftness with which they lunge forward is undoubtedly related to their sleek, streamlined bodies.

A specialized style of lunge feeding, called bubble netting, is characteristic of humpback whales in the North Pacific. When these whales lunge, they sometimes emit a succession of bubbles while rapidly circling under and around a school of prey. The bubbles act as a net to corral the prey and the whales scoop the prey into their mouths as they rise.

Bubble netting is fascinating to watch: all that is visible initially is a ring of bubbles (from about 10 to 15 meters in diameter) rising up from below. A few seconds later an open-mouthed whale breaks through the surface, corralling several hundred pounds of food as it does so. Several whales sometimes bubble net at the same time, but whether their behavior is cooperative or simply a response to an abundant food supply is not known.

After feeding, whales migrate to lower latitudes, where much has been learned about their social behavior. Not surprisingly, whales display many of the same mating, mother-calf and communication behaviors their relatives on land display.

Roger Payne was one of the first biologists to undertake a long-term research project on the social behavior of baleen whales. In 1970 he began a study of right whales off the coast of Argentina, which involved photographing the distinctive physical characteristics of each one. Over a 17-year period he and his colleagues identified more than 600 individuals and were able to sex them and follow their social interactions for extended periods of time.

While he was studying their courtship Payne noticed that female right whales appear to exercise female choice, that is, they tend to discriminate among males, rejecting the advances of most in favor of one. A female that is pursued attempts a variety of escape maneuvers: swimming rapidly away, diving to the shallow bottom, violently lashing her tail, or swimming close to other females, which may serve to distract or block her suitors. If those maneuvers fail, the female will turn belly up at the surface, keeping her head down and her genitalia and tail in the air. In this position it is virtually impossible for a single male to mate with her. During her efforts to escape, however, a female may repeatedly orient toward a particular male, and it is with him that she is most likely to mate.

Sometimes a female is surrounded by several aggressive males. Payne has observed one or more males pushing a belly-up female below the surface and positioning her so that copulation is possible. Sexual behavior involving an unwilling female is considered forced copulation; first described in mallard ducks, it has since been observed in many animal species. Similar behavior has also been observed in groups consisting of one to three females and up to seven males. Payne interprets it as a form of male-male cooperation: by cooperating with one another, males increase the chance that at least one of them will successfully reproduce.

Cooperation among males, where an individual will engage in an act that directly benefits another individual with no apparent benefit to himself, is known as altruism. If a male increases his chances of reproduction through this type of cooperation because the favor is returned later on, the behavior is referred to as reciprocal altruism. In many species reciprocal altruism appears to have evolved in response to situations where it is difficult, if not impossible, for a solitary male to successfully mate with a female.

This interpretation is not universally accepted. Scott Kraus and John H. Prescott of the New England Aquarium and Randall Reeves of the Arctic Biological Station in Quebec suggest, based on studies of mating behavior of the northern right whale, that the males are not cooperating but rather are competing with one another for access to the female. According to their hypothesis, the jostling and display of physical strength that take place among the males may be the means by which a female assesses the relative attractiveness of her suitors. In most animal species competition (particularly among individuals that are not closely related) is far commoner than cooperation.

Additional evidence that the males engage in competition comes from the discovery that sexually active groups consisting of one or two females surrounded by as many as six or seven males have also been seen in bowhead, gray and humpback whales. Among the humpbacks the males are highly aggressive: there is much pushing and shoving, and they may draw blood when they abrade one another, which suggests they are competing for the female.

Payne agrees that male-male competition may occur sometimes and has reported that males show more scrape marks from aggressive interactions than females do, but he nonetheless maintains that cooperation is also an important social interaction. I must emphasize that although different mating strategies may indeed coexist, none of them has been proved in right or other whales, and so they remain intriguing hypotheses in need of further study.

Robert L. Brownell, Jr., of the U.S. Fish and Wildlife Service and Katherine S. Ralls of the Smithsonian Institution believe that in some whale species males may depend on sperm competition for reproductive success rather than on outright physical competition. They base their theory on work by G. James Kenagy and Stephen C. Trombulak of the University of Washington, who determined that in mammals the testes are larger (in relation to body weight) in species in which both males and females are promiscuous than they are in monogamous species. Larger testes produce more sperm, and the more a male produces during ejaculation, the greater the chance is that his will displace the sperm of rival males.

Right and gray whales have large testes in relation to the rest of the body, and Brownell and Ralls predict that mating behavior in these species is promiscuous. In contrast, they predict that whales such as the blue and the bowhead, which have smaller testes, are more monogamous. In support of their theory they suggest that right and gray males are less aggressive toward one another (an indication that they are not in competition for females). It is known that male humpbacks, whose testes are rather small, compete fiercely. Brownell and Ralls do not as yet have data on right and gray whales to back their assertion, however.

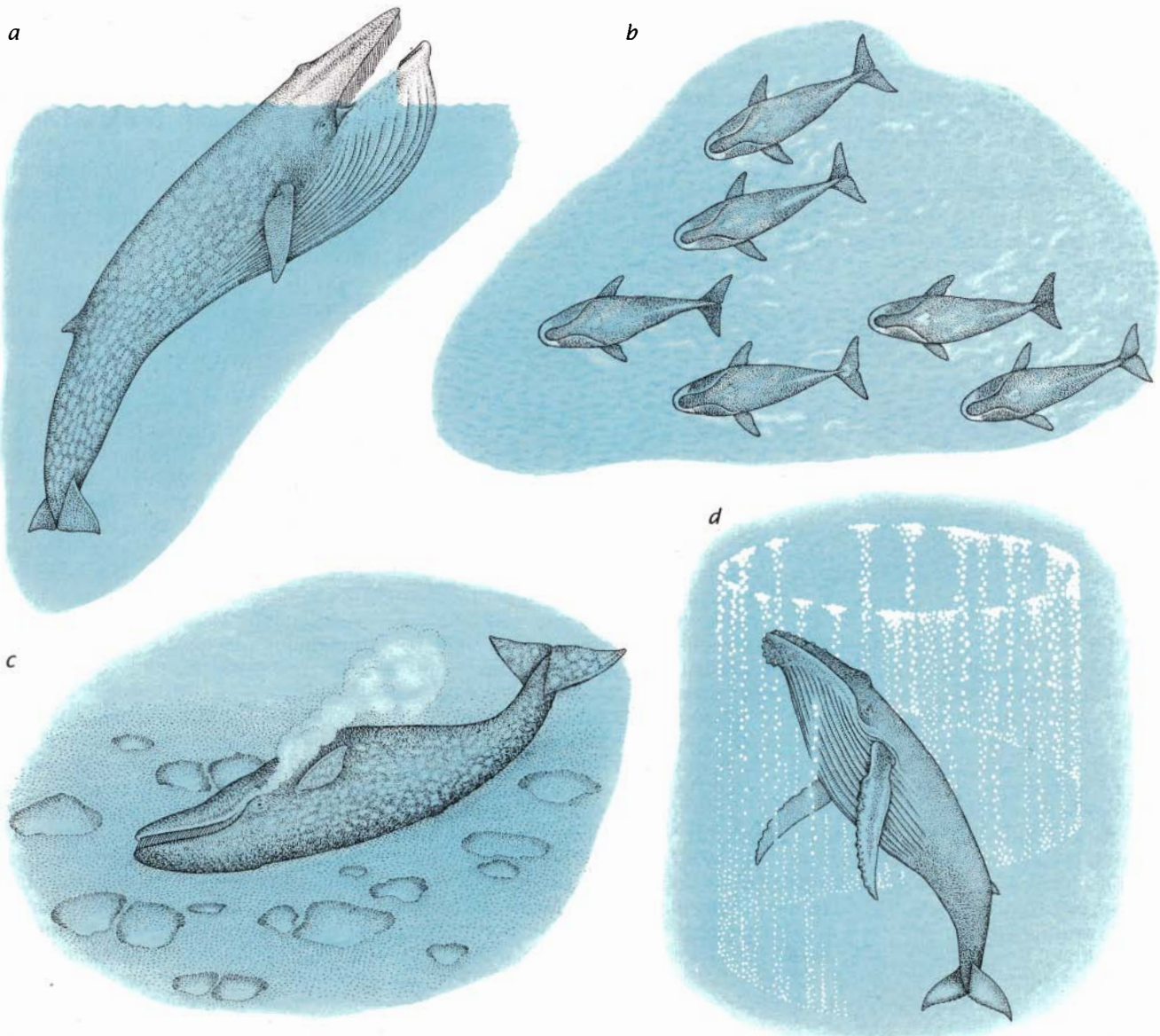
An alternative mating strategy has been observed in humpbacks. Fe-

males, when not surrounded by a corps of males, are often in the company of single males. Although the role of the escort male is not clear, Deborah A. Glockner-Ferrari, an independent investigator, believes the escorts may increase their chances of mating by staying with the female and therefore having sole access to her when she enters estrus. If a female is approached by other males, the escort male becomes aggressive, interposing his body between the intruder males and the female.

The fact that humpbacks also take part in group mating activity at the surface suggests males engage in several mating strategies in order to gain access to females. Although not all whale researchers would agree with such an interpretation, I believe multiple mating strategies are perfectly consistent with this behaviorally flexible mammal. Alternative mating strategies have been documented in tree frogs and the field cricket; in these species silent males are sometimes able to locate females more quickly than calling males are.

Another sexual behavior observed in whales that is also seen in human beings, chimpanzees and other terrestrial mammals is homosexuality. It occurs frequently in the three species of toothed whales I have studied (dusky, bottlenose and spinner dolphins) and is also seen in right and gray whales. It is most prevalent among young males, which may be denied access to females because of their smaller size and lower status.

The interactions between mothers and calves in southern right whales are surprisingly similar to those of terrestrial mammals, such as reindeer and caribou, that also migrate long distances. Sara Taber and



FEEDING STRATEGIES vary considerably within and among the different species of baleen whales. Whales that have greatly expandable, accordianlike throats, such as the giant blue, lunge-feed (*a*), by rapidly opening their mouths as they move suddenly forward. This enables them to take in large quantities of water, which can then be filtered through their baleen plates. Bowhead whales sometimes skim-feed at the surface in echelon formation (*b*), an arrangement thought to maximize feeding efficiency in this relatively slow-swimming species. Gray whales are frequent bottom feeders (*c*): they scoop prey from the ocean floor, leaving behind characteristic furrows in the muddy sediment. Humpback whales sometimes form bubble nets: they emit strings of bubbles as they circle under and around prey, a move that effectively corrals the prey and prevents it from escaping.

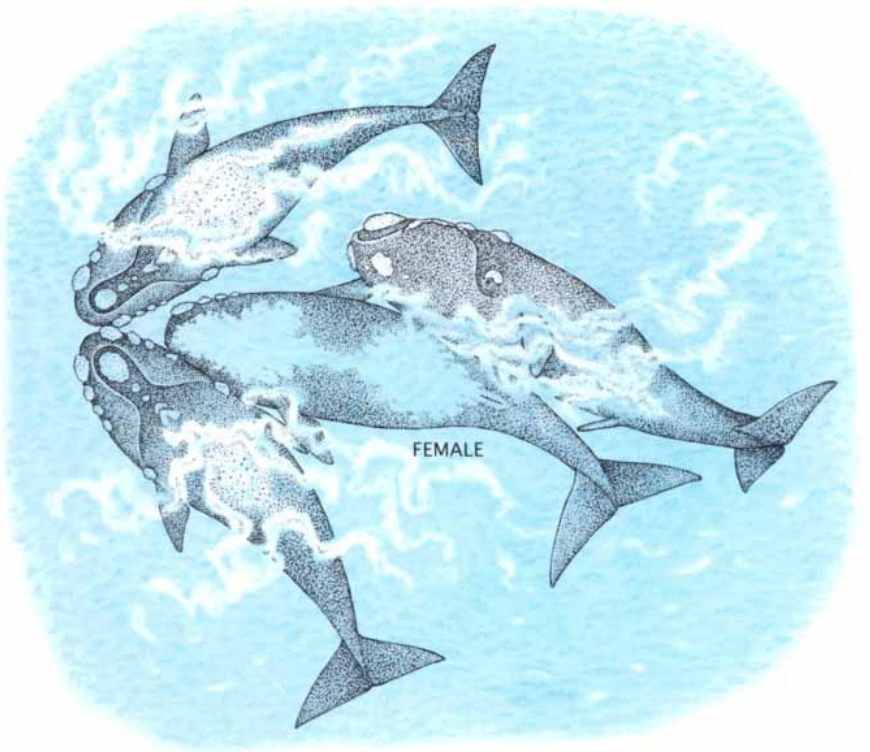
Peter Thomas, then at the University of California at Santa Cruz, found that during the first month of life a calf is totally dependent on its mother and follows her instinctively, periodically suckling from her mammary glands. The two are rarely out of touch; if they do separate by one or more body lengths, the mother immediately closes the distance by moving toward her calf. That act presumably protects the calf from predators and may also provide it with hydrodynamic lift, preventing it from tiring easily.

Between the ages of one and three months, a calf becomes increasingly active, often moving away from its mother and circling her at a distance of from one to three body lengths. Taber and Thomas suggest that such activity serves to increase the calf's muscle strength and coordination before migration in the spring to feed at higher latitudes.

One week before they migrate the activity level of the calves decreases sharply and they return to the protective custody of their mothers. Taber and Thomas speculate that the renewed association is an adaptive strategy that increases the likelihood of a calf's survival in the open ocean, where orcas, or killer whales, are primary predators of young right whales. Other dangers, such as sharks or the onset of violent storms, may also play a part in keeping mother and calf together.

After spending from five to seven months feeding in the open ocean, mothers and calves return to shallower waters. Although the calf still nurses from its mother (and continues to do so until it is more than a year old), it is decidedly more independent and active than it was before migration. For the first time since the calf's birth the mother displays signs of independence, leaving the calf more than she approaches it, but the calf stays close beside her and nurses frequently.

Such behavior is an expression of parent-offspring conflict. When the offspring are young and helpless, a female invests heavily in their care to ensure their survival. When they are older and less vulnerable, however, it is to her advantage to wean them quickly so that she can direct her energy to the production of additional offspring. Parent-offspring conflict has been documented for baboons, monkeys, moose and caribou (as well as other mammals) but had not been described in whales prior to the study by Taber and Thomas.



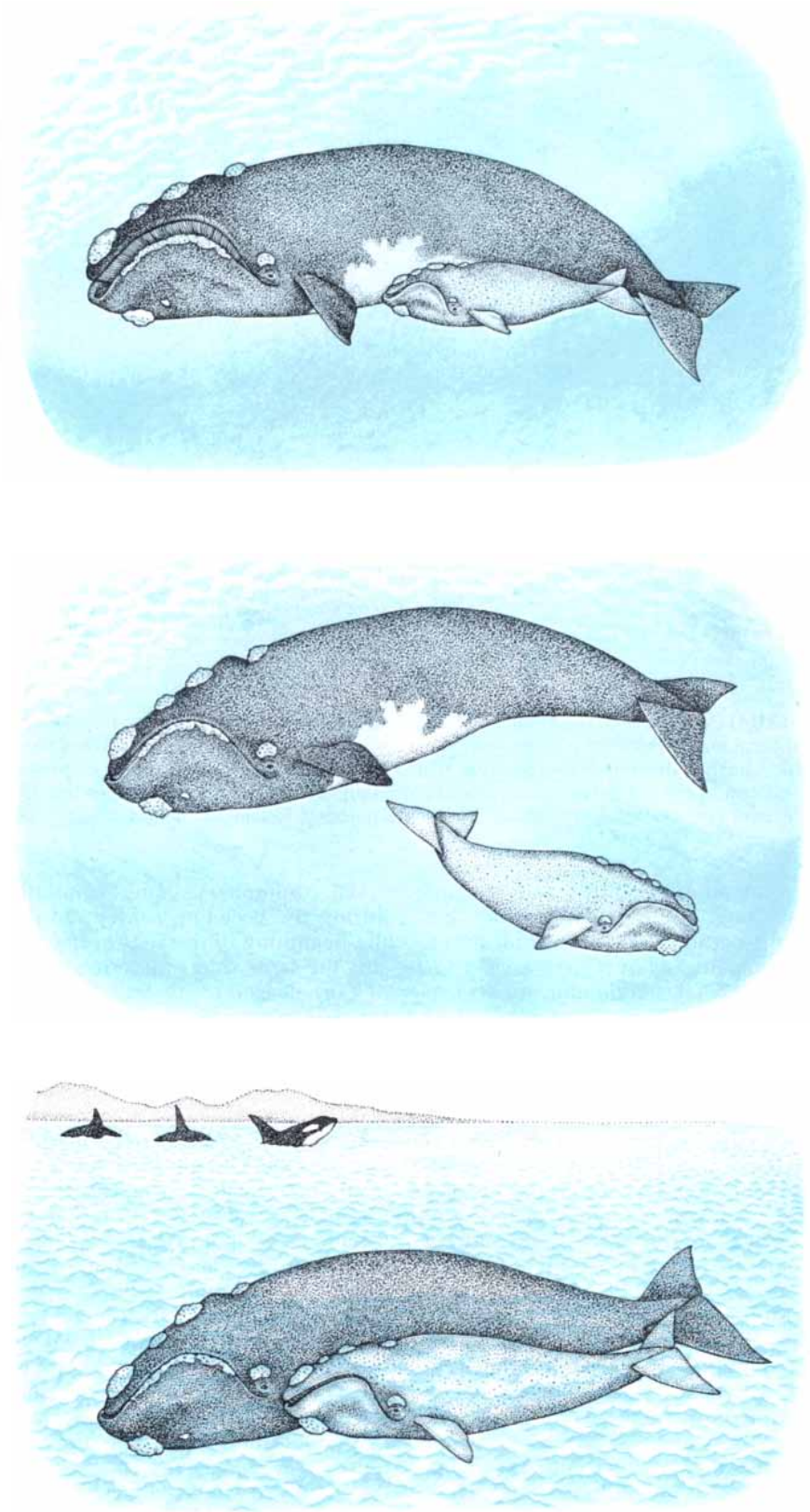
SEXUAL ACTIVITY in right whales often occurs in groups of one or more females and several males. Here three males have surrounded a single female (*center*). Two of them have pushed the female into position, which enables the third male (*right*) to align himself and insert his penis into her genital opening. Some researchers believe this is a form of cooperation among males but that hypothesis has not yet been substantiated.

Whale communication has had considerable attention from marine mammalogists over the past 15 to 20 years. Whales communicate acoustically, although the means by which they do so is not known: they have no vocal chords. The sounds are thought to be important in sexual and social communication; they also keep individuals in loose herds of whales in contact with one another, and they possibly signal danger. An analogous situation has been described for timber wolves: individuals are often miles apart for long periods, but they keep in contact through various calls.

Humpback whales are known for their melodious sounds, first described by Roger Payne and Scott McVay, who was then at Princeton University. Divided into recognizable themes and phrases that repeat themselves in regular fashion, their complex songs may last for more than half an hour at a single stretch. When the song is finished, the whale usually begins again, repeating the same sequence in a pattern that may last for several days.

Male humpbacks sing primarily during the breeding season, and at the beginning of the season they all sing the same song. Katherine Payne of Cornell University found that as the season progresses, however, the song gradually changes, and by the end of winter the one they are all singing is no longer recognizable as the one sung at the beginning. Little or no singing takes place during summer feeding at higher latitudes, away from the breeding grounds. When humpbacks return to the breeding grounds the following year, they start with the same song they were singing at the end of the previous season. By the end of the second season that too has evolved into a song that is distinctly new.

Peter Tyack of the Woods Hole Oceanographic Institution and James D. Darling, then at the University of California at Santa Cruz, set out in the late 1970's to study the role singing plays in the social behavior of humpbacks in the Hawaiian Islands. They found that males sing only when they are alone, suspended in the water column as much as 20 meters below the surface, with their heads directed downward. Their songs are so



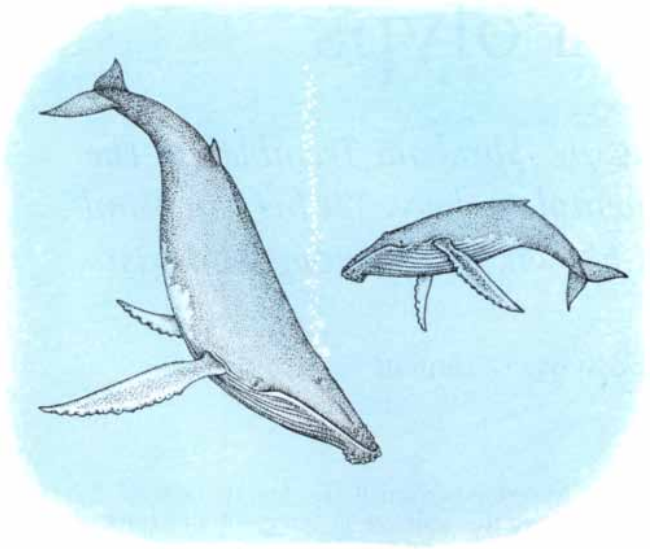
DURING THE FIRST MONTH of life a southern right-whale calf remains close to its mother (*top*) and its overall activity level is low. When the calf is one to three months of age (*middle*), it becomes much more active, often circling its mother and swimming a few body lengths away from her. At three months its activity level again decreases and the calf stays close to its mother's side (*bottom*). The change in behavior occurs approximately one week before migration from the calving area in the spring and is thought in part to protect the calf from its primary predators: killer whales in the open ocean.

loud that they can be heard underwater as much as five kilometers away. Occasionally a singing male is approached by another male. When that happens, the two swim silently side by side for several minutes; when they separate, one of the two males typically will begin singing again. Tyack thinks that by disrupting the singing the intruder male lessens the chance that a female will choose the singer as a mate.

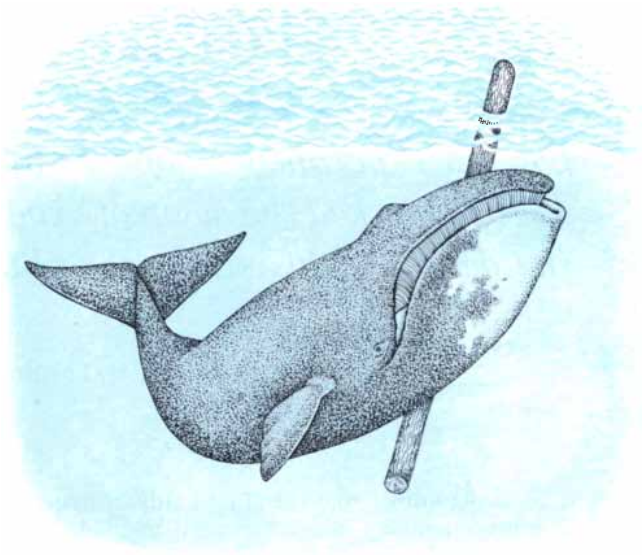
Darling believes the songs are the equivalent of male-male competition on land—where, for example, two mountain-goat bucks may test each other's strength with their horns. Singers are dominant males that display their strength through song in much the same way as the horns on a buck serve to advertise the attractiveness of their bearer to sexually receptive females.

Christopher W. Clark of Cornell and his wife Jane Clark began investigating the sounds of right whales in the late 1970's. At first the sounds seemed monotonous and repetitive, not unlike the mooing of a cow, but with time the Clarks were able to distinguish subtle and complex variations. In addition, with the aid of special hydrophones, which give directional information, they were able to locate individual vocalizers and link certain sounds to specific behaviors.

Six distinct calls have now been recognized in right whales: up, down, high, hybrid, pulsive and constant. Up calls (low-frequency calls that rapidly increase in frequency over the period of one second) are the commonest and serve to bring calling whales together. Down calls (low-frequency calls that rapidly decrease in frequency) are less common and function as a form of long-distance communication for whales that are spaced from several hundred meters to several kilometers apart. High calls (of higher frequency than the others) increase disproportionally as the size of the calling group increases; they reflect rising levels of excitement usually associated with sexually active groups of whales. Hybrid calls (of mixed frequency and amplitude modulation) and pulsive calls (harsh or growling noises) are almost invariably associated with groups of three or more whales and increase with rising physical aggression in a group. There is some evidence that pulsive calls are made by only one or two members of an active group, possibly the most ag-



SINGING IN MALE HUMPBACKS is not well understood, but it is thought to be a means by which males attract females and establish dominance hierarchies. The male here has assumed the typical singing pose: he is suspended in the water column some 20 meters below the surface with his head oriented downward. On his right is an intruder male that is about to disrupt the singing.



PROLONGED PLAY ACTIVITY has been recorded in several species of whales. Here a bowhead adult male, observed off the Alaskan coast, is trying to force a log below the surface with his chin. The same whale was seen repeatedly lifting the log at least three meters into the air and pushing it with a flipper or other parts of his body, an activity observed for more than an hour.

gressive ones. Constant calls (tonal sounds with little frequency change) are rare and have yet to be associated with specific behaviors.

It is interesting that these sound patterns—in which high calls indicate excitement and hybrid and pulsive sounds indicate aggression—are analogous to those made by land animals: high-frequency sounds are generally nonhostile whereas pulsive ones are typically antagonistic.

The Clarks also found that right whales communicate by means of nonvocal sounds. Blow sounds, usually made when the whales exhale forcefully through their nostrils at or slightly below the surface, are believed to indicate aggravation, as when dolphins circle around and in front of the whales. Slap sounds made by slapping flippers against the surface seem to indicate that an individual is aroused or excited by some event, such as a passing motorboat. When slap sounds are made within a group, they usually signal aggression toward other group members.

While studying bowhead whales in the Beaufort Sea, my colleagues and I were surprised to find apparent play behavior among both young and adult whales. A bowhead calf may be alone at the surface for as long as 30 minutes while its mother dives below for food. Calves separated from their mothers in this way apparently communicate with them by issuing an exchange of up and down calls, which we recorded with hydrophones dropped from our airplane. Similar calls have been recorded between Bryde's females and their calves by my graduate student Bernie Tershy.

Twice we observed lone calves "playing" with surface debris, orienting toward it and then swimming around and under it for perhaps 30 minutes. In one case the debris was flotsam; in the second case it was a patch of green dye we had thrown from the plane to mark the location of the whales. Play in young mammals is thought to be important for the development of foraging and social skills, and it may serve an adaptive purpose in young bowheads: playing may be the means by which calves learn to orient toward a food source such as a cloud of copepods.

We have also observed prolonged play behavior by juvenile and adult bowheads encountering logs that had floated down the MacKenzie River into the Beaufort Sea. One male was observed for more than an hour and a half, repeatedly tossing a 10-meter log into the air and then forcing it below the surface with one of his flippers. Another whale, a female, was seen balancing a log on her back with both ends out of the water. She would then roll the log off her back and repeat the balancing act.

Roger Payne observed similar play behavior in adult right whales that draped large fronds of free-floating kelp over their head and back. Although play behavior has also been observed in dolphins, it is not often exhibited by terrestrial adult mammals (chimpanzees and human beings are an exception), and the adaptive value, if any, is unclear. It seems possible to me that the whales are simply having fun in an otherwise featureless ocean.

This is an exciting time in whale research. As the techniques for studying whales improve, it is likely their behaviors will prove to be more complex than I have described here. Already we know that baleen whales are not mere grazers of the ocean but social mammals whose mating behaviors are varied, with hints of both competition and cooperation. In feeding, mating, mother-calf interactions and communication, they show patterns strikingly similar to those of terrestrial animal species.

Whales are difficult to follow underwater and progress is therefore sometimes maddeningly slow; nonetheless, I am confident that as the amount of research on great whales increases over the next decade, biologists will know almost as much about their behavior as they do about the behavior of some of their relatives on land.

Trembley's Polyps

Elegant experiments done on hydras by Abraham Trembley in the 1740's marked the dawn of experimental zoology. Yet his name and the details of his studies are little known, even among biologists

by Howard M. Lenhoff and Sylvia G. Lenhoff

Any biologist knows that certain primitive animals reproduce asexually by budding, that complete animals of some species can regenerate from cut pieces of a whole one and that tissues from two individuals of the same species can be grafted together. Yet few investigators stop to think that these facts were not always obvious. Fewer still know that the discoverer was Abraham Trembley of Switzerland, an obscure tutor whose many startling revelations about the curious invertebrates called hydras disturbed and intrigued Enlightenment Europe in the early 1740's and, in the eyes of some authorities, earned him the title "father of experimental zoology."

It is not surprising that Trembley is relatively unknown today. Reference books, if they mention him at all, usually say little about his life, his innovative methods, the impact of his work on his contemporaries or the considerable significance of his approach and his discoveries for modern science. We believe the time has come for Trembley to emerge from anonymity.

Who was Abraham Trembley and what led him to take an interest in hydras, or as he called them, "polyps of fresh water with arms shaped like horns"? He was a member of a prominent Genevan family. Born in 1710, he grew up in a period when many intellectuals in his native city had turned their attention to natural history. His own academic interest initially centered on mathematics rather than on animals, and as a university student he prepared a thesis on the calculus.

Having finished his education, the young man sought work in Holland. It was there, as a tutor at the estate near The Hague of Count William Bentinck, that Trembley made the observations and did the experiments that were to revolutionize the study of living organisms. Amazingly, he made scores of findings in the short span of four years from 1740 to 1744. Moreover, he did it long before the development of sophisticated tools, relying mostly on a magnifying glass and occasionally on a simple single-lens microscope.

Trembley first became intrigued by hydras—which are members of the Coelenterata, the same phylum as jellyfish and corals—in the course of observing aquatic plants and animals collected from ditches on the count's estate in his spare time. He found his glass jars "populated with little creatures" as "good company with which to relax from more serious occupations."

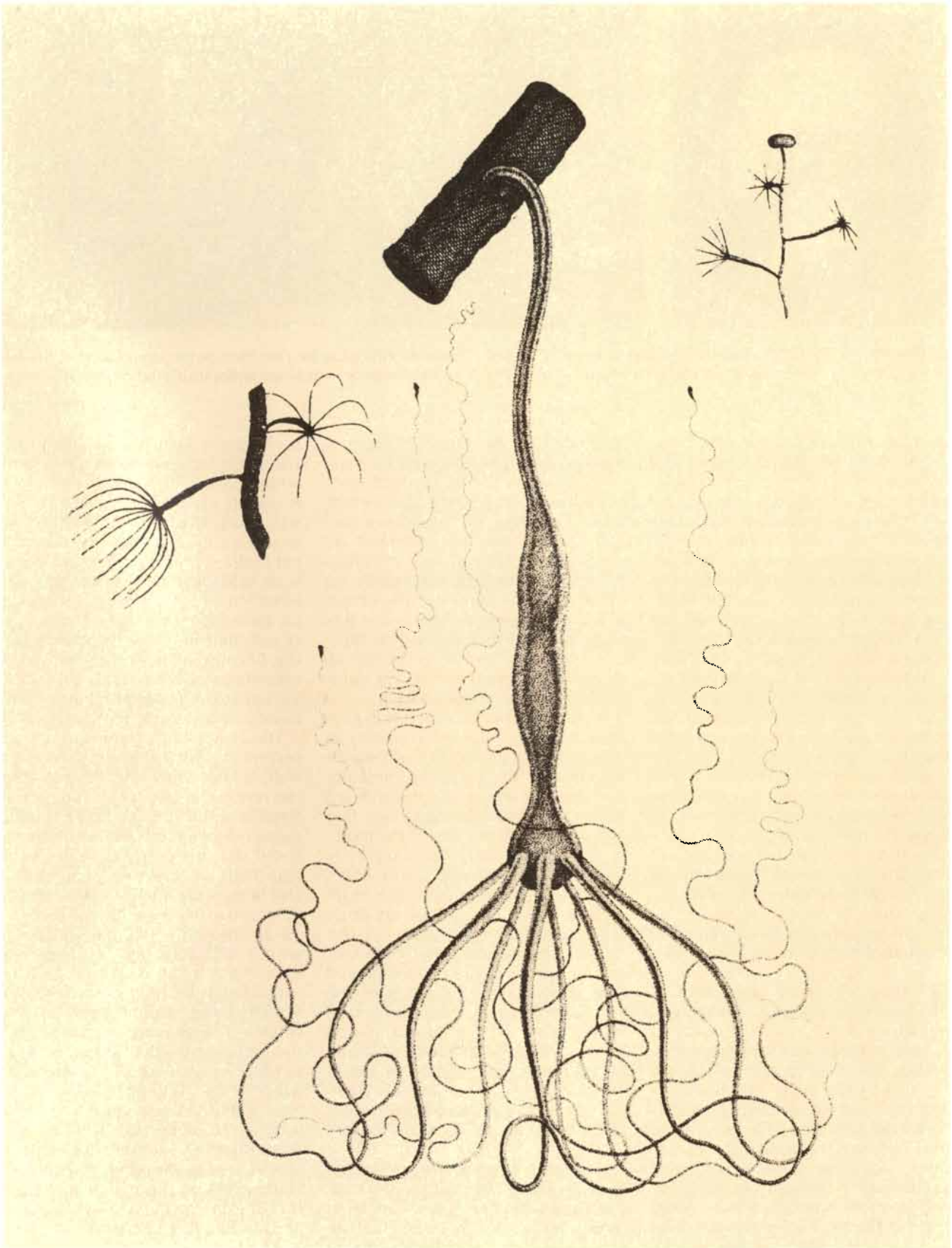
At first he was attracted more by the lively moving inhabitants of the jars than by the stationary green hydras there. The organisms, which were less than half an inch long and looked like tubes adorned with a crown of tentacles at one end, were apparently immobile, leading him to assume that they were simple plants. Yet one day in June of 1740 he saw them contract and extend. Astonished, he watched for other evidence of animal behavior until, after observing them for several days, he saw his subjects take steps.

Satisfied that the tiny creatures were animals, Trembley paid them little heed for the next month or so. Then by chance he noted that they had a propensity for light. At a time when many naturalists did little more than describe the organisms they observed, he decided to explore his observation further by experiment. He proceeded to demonstrate for the first time that eyeless animals can exhibit phototaxis, or movement toward light. In one study, for example, he covered a jar of polyps with a cardboard sleeve in which he had cut a small opening. He then rotated the sleeve at intervals and tracked the migration of the specimens, which was always toward the light coming in through the opening.

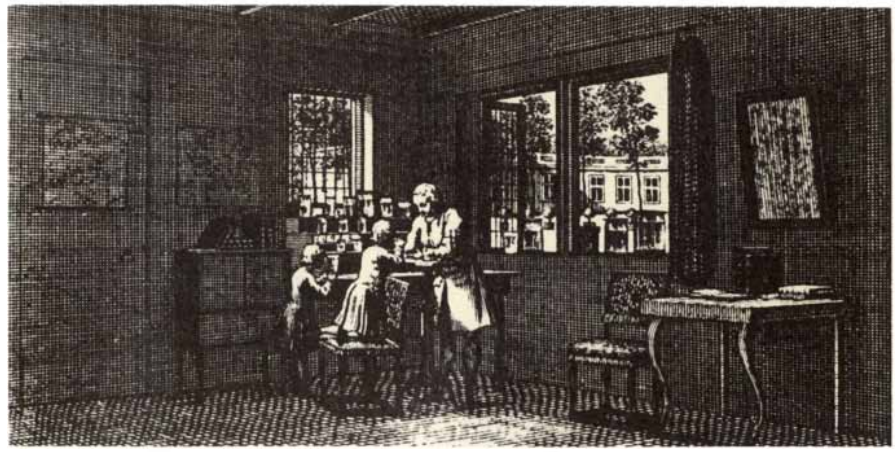
The tutor's interests were now irretrievably focused on hydras, and he decided to investigate them seriously and thoroughly. One of his first accomplishments was proving that a whole organism can regenerate from a small piece cut from an animal. He began to study this phenomenon after he noticed that hydras varied in the number of tentacles, or "arms," they had—a decidedly odd characteristic for an animal. The oddity made him think of bisecting a specimen to see whether the halves would develop into complete organisms. If they did, the finding would suggest the polyps were plants. It turns out that Trembley soon found definite evidence that hydras were animals: he saw a brown species seize and eat prey. Fortunately, however, he did not make this observation until after he had conclusively shown that hydras could regrow missing parts. As Trembley said, if he had seen his subjects eat earlier, he might never have decided to study regeneration.

To begin the studies, he divided a hydra transversely and then examined both parts under a magnifying glass several times a day. Within a few days he thought he could detect the excised posterior half regrowing tentacles. Soon he had no doubt: the segment had developed into a whole hydra.

"When I examined the two parts through a magnifying glass with all the attentiveness of which I was capable," Trembley reported, "both of them appeared to be demonstrably complete polyps performing all the functions of these organisms known to me: they elongated, contracted and took steps." In later studies he



THREE SPECIES OF HYDRAS—or polyps, as they were originally called—yielded their secrets to Abraham Trembley in the early 1740's. Carl Linnaeus named the animals "hydras" in 1746. Trembley discovered and initially studied the green variety, *Hydra viridissima* (*right*). Later he worked with two brown species, *Hydra vulgaris* (*left*) and *Hydra oligactis* (*center*). The naturalist Pierre Lyonet drew the images, which are reproduced here from two plates in Trembley's 1744 *Mémoires,* his book on the hydra.



PORTRAIT AND VIGNETTE show Trembley at age 68 (*left*) and as a young tutor. The portrait is from the frontispiece of a 1783 book on education by Trembley. In the vignette, from the *Mémoires,* the tutor is turning a hydra inside out as students watch.

also saw regenerated specimens eat.

The discovery of regeneration in animals was one of the first major challenges to the accepted "natural law" that mating was required for animals to reproduce. Trembley's finding was arguably even more dramatic than that of his kinsman Charles Bonnet, who in the course of studying aphids the year before had discovered parthenogenesis, the development of eggs without fertilization.

At about the time Trembley did the work on regeneration he also observed a "polyp that was beginning to produce a little one" in a manner that was "very closely akin to the way plants multiply when they give off *shoots.*" He became excited as he watched a small protrusion from the body of a polyp grow, develop tentacles and detach to become a small replica of its "parent." Experiments he then devised helped to elucidate the nature of asexual reproduction by budding, proving for example that the buds did not develop from eggs.

Trembley's other extraordinary discovery, grafting, was the culmination of a circuitous chain of events. While he was studying regeneration, he noticed that whenever he cut a hydra, many "granules," or grains, oozed out of the cut part of its body wall, which he called skin. For a time the young investigator explored the role of these granules in spreading nutrients through the body. At one point he wondered if he could nourish the hydras by turning them inside out and placing them in a nutrient-rich solution. The granules of the inner skin would then be on the outside, where the nutrients were.

In a truly impressive feat, accomplished while holding a hydra in a drop of water on his palm, he managed to invert the tiny animal without killing it. He pushed a boar's hair against the foot, or base, of the animal so that the foot, followed by the rest of the hydra, eventually emerged through the mouth, an opening at the center of the crown of tentacles. Animals inverted in this way survived and seemed to function normally in all respects, although they could not accept nutrients from the external solution.

It was a complication of turning hydras inside out that led Trembley to observe his first graft. In one instance he saw that the tip of an immature bud that was now inside the inverted parent had poked through a hole that had been cut in the skin of the mother; the bud seemed to be completely united to the mother at the new site. The discovery prompted him to do an orderly set of experiments proving conclusively that pieces of two different hydras from the same species could be grafted together and that grafts between hydras of different species would be rejected. In several such experiments he placed one hydra inside the body of another, gave them time to fuse and then fed prey to the inner animal. When pieces of the prey spread to the outer animal, Trembley knew the bodies had united.

The discoveries we have described were probably Trembley's most important achievements, but they were by no means his only ones. When he was still working with hydras, he invented the first "vital staining" technique, a process by which living tissues are colored for study. Trembley may also have been the first to describe protoplasm, the gel-like material that is fundamental in the cells of all organisms. This accomplishment is usually credited to Félix Dujardin, who worked a century later. While analyzing granules oozing out of a cut hydra, Trembley noted that they were held together by a "viscous material" in which "must be contained all the components that serve to carry out their movements of contracting, flexing, and so forth." He and his contemporaries, however, did not realize that the material might be the basic substance of all living tissue.

The astute investigator uncovered secrets of other aquatic organisms as well. He described for the first time the process of budding in the worm *Stylaria* and in the bryozoan *Lophopus,* a colonial invertebrate; he wrote about the anatomy of *Lophopus* in amazingly accurate and fine detail, and he was the one who pointed out that bryozoans are animals. Few people are aware that Trembley also observed cell division. Although the idea of a cell had not yet been conceptualized, he both described and sketched the multiplication of the single-cell alga *Synedra,* and he was the first to show that protozoans reproduce by division. The late John R. Baker of the University of Oxford, who published a definitive biography of Trembley in 1952, further credits the Swiss tutor with a number of discoveries on other animals, including colony formation and tube building in the microscopic aquatic animals known as rotifers.

Abraham Trembley's findings may be accepted as fact today, but early reports of his discoveries created a furor not only in the universities

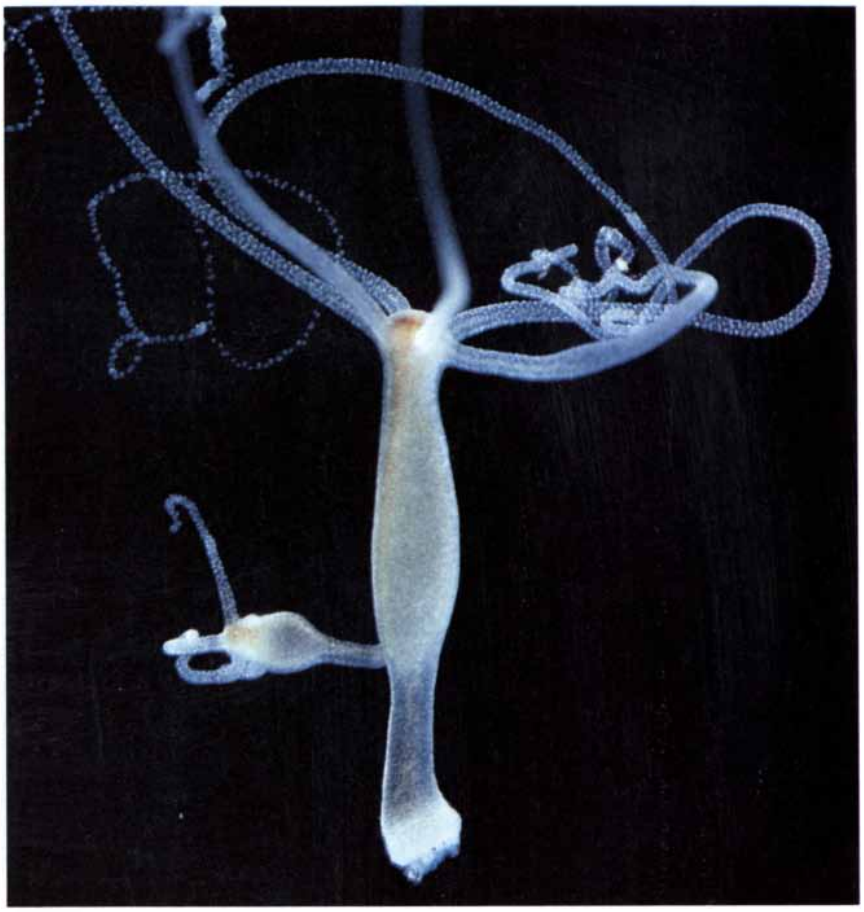
and scientific societies but also in the fashionable salons of the times. The initial reaction was disbelief, and religious questions were raised, among them: If cut pieces of a polyp could regenerate a whole organism, what then became of the animal's soul?

For many intellectuals negativity soon gave way to enthusiasm for the clues to nature that Trembley had uncovered. For instance, the French naturalist René-Antoine Ferchault de Réaumur, with whom Trembley corresponded for 17 years, reacted with mounting excitement as he verified Trembley's results. Indeed, Réaumur was so impressed that he encouraged his young friend to collect and publish the discoveries on hydras—something Trembley accomplished in 1744 with his beautifully illustrated book, *Mémoires, pour servir à l'histoire d'un genre de polypes d'eau douce, à bras en forme de cornes* (Memoirs concerning the natural history of a type of freshwater polyp with arms shaped like horns).

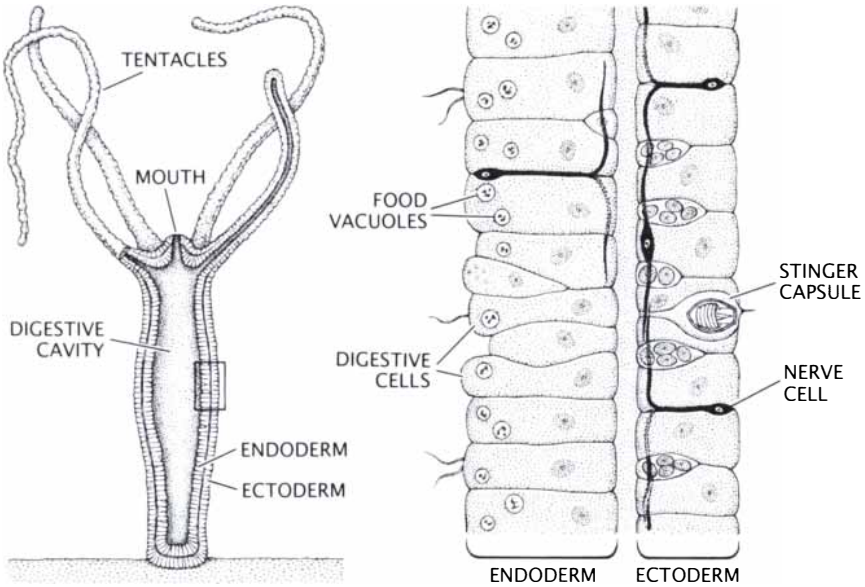
Réaumur also introduced Trembley's discoveries to the intellectual circles of Paris, the king of France and his court and the French Royal Academy of Sciences, which later offered Trembley the honor of becoming one of its *Correspondants*. In England Trembley was elected to the Royal Society of London in 1743 and was awarded its prestigious Copley Medal, considered then to be one of the highest accolades in science.

More profound than Trembley's popular acclaim was his immediate influence on serious students of natural history. Trembley's work—together with that of Réaumur, Bonnet and others—validated the importance of basing the study of living organisms on direct, careful observation rather than on preconceived ideas and theory. Trembley believed it was only by observation and experiment that he had been able to reveal phenomena, such as regeneration, that should have been discovered long before. "Nature must be explained by Nature," he insisted, "and not by our own views."

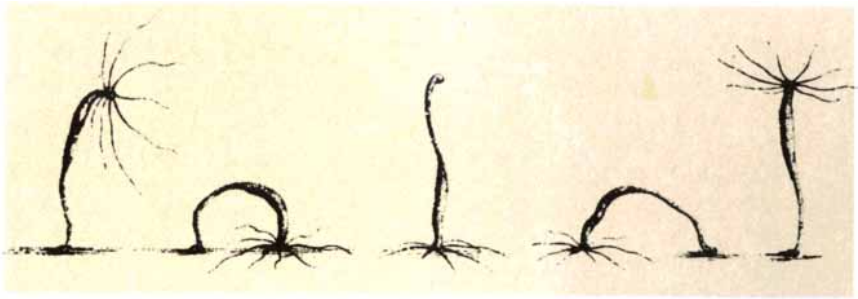
Trembley's successes also convinced many students of natural history to make the important transition from observation of God's minute creatures to active experimentation on them. More specifically, his work encouraged other scientists to devise studies that significantly advanced the understanding both of freshwater and marine invertebrates and of important biological phenomena. His experiments, for example, spurred



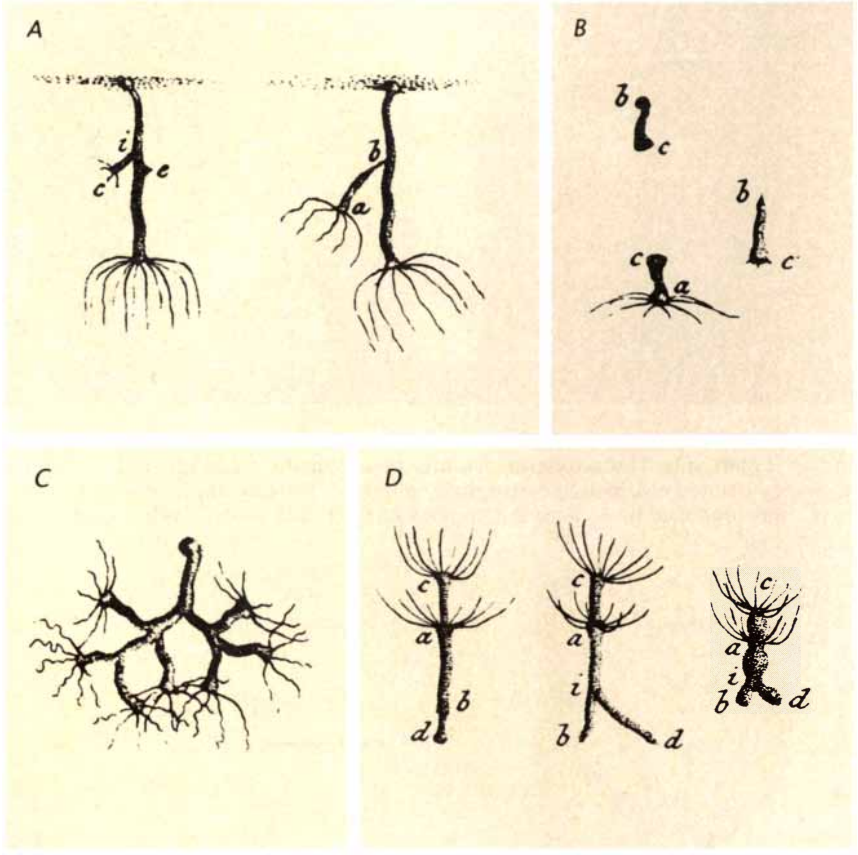
LIVING SPECIMEN of *Hydra oligactis*, which is about half an inch long, has a bud growing on its left side. The ectoderm, or outer "skin," of the animal is transparent. As Trembley pointed out, hydras derive their color from the food they store. The photograph was produced by Richard D. Campbell of the University of California at Irvine.



CROSS SECTION of a generic hydra shows its basic anatomy. The animal is attached to a surface by its base. The tentacled part, with the mouth at the center, is the head. Advances in microscopy since Trembley's day have shown that hydras have two layers of cells (*detail*). Within the cells of the endoderm, or inner layer, are food vacuoles that Trembley referred to as granules. Workers identified the stinger capsules (nematocysts) in the ectoderm nearly a century after Trembley made his discoveries on hydras.



SOMERSAULTING is one way a hydra travels. Seeing polyps "walk" in this way and in others helped to persuade Trembley that the creatures, which he also saw contract and extend, were animals. When he watched a hydra seize and eat prey, he was convinced. This engraving and those below were drawn by Lyonet and are from the *Mémoires*.



SEVERAL FUNDAMENTAL PROCESSES that are still under investigation were first discovered in the hydra by Trembley. He showed that polyps could reproduce without sex by budding (*A*). Once a protrusion, such as point *e* (*left*), emerges, it inevitably develops into a bud (*i–c*) and then a fully formed animal (*right, a–b*), which soon detaches from its parent. He further showed that a whole polyp can regenerate from a small piece (*B*). When he cut a specimen in two (*left*), the headless part began to regenerate a new head and tentacles within a day (*right*). Trembley also exploited the phenomenon of regeneration to make a seven-headed "monster" (*C*). He split the head of a polyp and then repeatedly divided the heads that regenerated. He called the result a Hydra, after a figure from mythology, and was thus the first to apply the word hydra to polyps; he did not refer to normal specimens that way, however. Trembley also demonstrated that two animals from the same species can be grafted together (*D*). In his first such experiment he cut the foot off a hydra (*left*), leaving *a–b*, and slipped the cut polyp over an intact specimen (*c–d*). The foot of *c–d* eventually tore through the outer polyp (*middle*) and seemed to fuse with it at point *i*; at the same time mouth *a* of the outer hydra seemed to fuse with the inner animal. By feeding mouth *c*, Trembley showed that the animals had fused and now had a single branched gut, *b–i–d*. The food caused both bodies to swell (*right*); if the animals had not merged, section *i–b* of the outer polyp would have stayed narrow.

several leading naturalists to conduct studies on regeneration. As a result, within 25 years after Trembley first cut a polyp in two, the phenomenon of regeneration was broadly recognized as a basic natural process. Some scholars believe the spreading influence of Trembley's work on hydras stimulated the development in 1752 of a precursor to today's dissecting microscope.

The discoveries made by Trembley are now part of every biologist's fundamental knowledge. Why then is the man generally accorded little recognition? One reason may be that he did not propose any theory to which his name can be linked. Such hostility to theory has made it difficult for historians to fit him into any philosophic or historic niche.

There are other reasons as well. Even in his own time Trembley's scientific prominence faded. He made few systematic contributions to science between the time he completed service with the Bentincks in 1747 and his death in Geneva in 1784. After leaving Holland he undertook a secret diplomatic assignment for the British government, traveled, taught, wrote several books (on education, politics, religion and moral philosophy) and, in his later years, concentrated his efforts on rearing the five children he fathered after marrying at the age of 46.

Even if Trembley had continued to devote himself to the study of invertebrates, his star might have fallen in the second part of his century because the European intellectual elite had turned to other subjects—such as electricity and the problem of irritability in living organisms. Late in the 19th century and in the beginning of the 20th century, embryology, evolution and genetics dominated research and theory in the life sciences. An anthropomorphic focus on vertebrates further dampened enthusiasm for Trembley's invertebrate subjects. Finally, as preeminence in biological research shifted across the Atlantic to a generally monolingual society, the fact that his masterwork on the hydra was not—until recently—translated from French into English tended to limit the acquaintance of biologists with the once renowned investigator.

Trembley's prominence in the collective memory of scientists may have faded, but a review of his *Mémoires* provides a quick reminder that he still has much to teach the modern scientist. Today's biologists

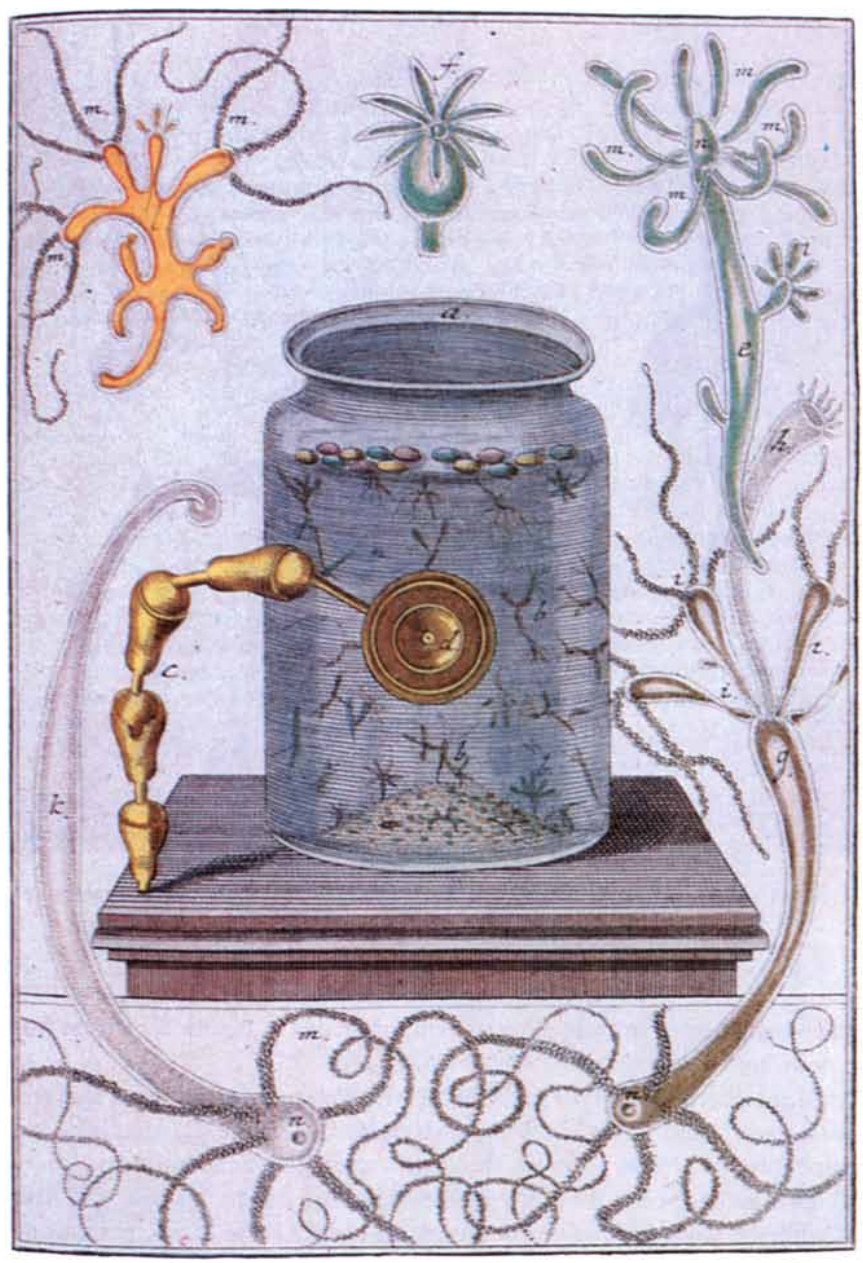
dipping into the book can gain insight into virtually every aspect of the biology of the hydra, including its structure, behavior, physiology, development and interaction with prey and predators. Moreover, many of the phenomena described in the book invite further study by contemporary developmental biologists.

Which of Trembley's qualities as a scientist might the aspiring biologist emulate? In addition to being an empiricist who insisted on postponing the development of theory until he had sufficient data, he was an observer quick to see the unusual and to report his findings with great accuracy and detail. He was an experimentalist who was not content until he could prove his findings in a number of ways. He was quantitative in his approach, backing up many of his experiments with numbers and repeating the experiments until he was convinced of their validity. He was an organismic biologist interested not in a single problem but in all aspects of an animal, and he was an operationalist who believed an experiment has no lasting value unless the methodology is described in a way that enables others to replicate it. It is not enough to say, he wrote, "that one has seen such and such a thing. This amounts to saying nothing unless at the same time the observer indicates how it was seen, and unless he puts his readers in a position to evaluate the manner in which the reported facts were observed."

Trembley had other noteworthy qualities as well. He worked not only in his study but also in the field, where he was able to discover a number of new species, and he investigated both the structure of organisms and the mechanisms behind the functions he observed. He was a technician par excellence, carrying out complex and delicate operations with hardly more than scissors and a boar's-hair probe as tools. He was, moreover, persistent. "One should not become disheartened by want of success," he wrote in the *Mémoires,* "but should try anew whatever has failed. It is even good to repeat successful experiments a number of times. All that is possible to see is not discovered, and often cannot be discovered, the first time."

We suspect that Trembley's admirable scientific objectivity stemmed in part from his piety. He believed all marvels were possible in God's magnificent universe. As a consequence he was undismayed by disconcerting findings that did not seem to fit accepted understandings. On December 11, 1742, he wrote to Bonnet: "Your worm with two tails is admirable, but it does not surprise me, because nothing surprises me."

What would Abraham Trembley think about contemporary biology if he were alive today? We suspect that this organismic biologist, who was "swept along, as it were, from one observation to another" to discover phototaxis, whole-animal regeneration, budding and grafting, might be somewhat ambivalent. He would probably marvel at the success of such fields as neurobiology and molecular biology, where organisms are exploited to answer specific fundamental questions. Yet he would undoubtedly be disturbed to discover that individual biologists increasingly study ever fewer phenomena. Nature is too vast, he might well insist, for us to neglect broad and detailed studies of the host of organisms that populate the planet. He might say: Let the organism speak.



TREMBLEY'S MICROSCOPE was no more than a single lens mounted on a multijointed arm. The drawing, made by Martin F. Ledermüller in about 1762, also shows Trembley's favorite receptacle for his hydras surrounded by (*clockwise from top left*) a hydra monster, a contracted and a relaxed green hydra and specimens that may be *Hydra oligactis.*

THE AMATEUR SCIENTIST

How to map electrically charged patches with parsley, sage, rosemary and thyme

by Jearl Walker

In December I wrote about the electrical sparking that can be seen (in a dark room, with dark-adapted eyes) as adhesive tape is peeled from a solid surface. The separation creates electrically charged patches that discharge to one another. What you see is a faint blue or blue-white glow that marks the moving line of separation between the tape and the surface.

After reading the article David K. Donald of the Hewlett-Packard Research and Development Laboratories in Palo Alto wrote to me about similar experiments he has carried out—and that indeed have been done by many people for more than 200 years—to identify the location and electrical sign of charged patches on a surface. In this century such experimentation figured prominently in the development of modern photocopying machines that depend on electrostatics to attract a "toner" powder that makes the copies. Indeed, much of Donald's work was done while he was with the Xerox Corporation.

You can repeat Donald's experiments in your kitchen (when the humidity is low enough). All you need is a smooth nonconducting surface, adhesive tape and an assortment of powders: flour, powdered spices or herbs, or the toner from a photocopying machine. A strip of the tape is affixed to the surface and then peeled off, leaving charged patches on the surface. If an appropriate combination of two of the powders is then quickly dusted over the surface, one type of powder collects in negatively charged patches and the other type collects in positively charged ones. If the powders are different colors, they provide a map of the charged surface. A few of Donald's results, made with a combination of ground cinnamon and toner from a Kodak photocopying machine, are shown below. In each example the tape has been peeled toward the right.

To prepare for an experiment, Donald pours a small amount of the powders into a plastic squirt bottle and adds "shaking chips"—small glass beads, metal nuts or other such objects—that help to break up clumps of powder. When the bottle is shaken vigorously, the toner particles become negatively charged and the cinnamon particles become positively charged. Then, in a typical experiment, he applies some kind of sticky tape to a plastic tool case. (The experiment must be done on a nonconducting surface such as plastic so that the charged patches are not immediately neutralized by conduction.) After he has shaken the bottle to make some of the powder airborne, Donald peels the tape and then squeezes the bottle to blow powder over the case.

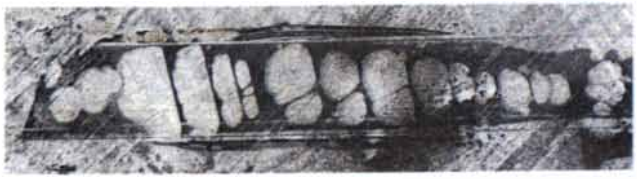
As the dust drifts over the surface, the electric fields from positively charged patches pull the toner dust out of the air and those from the negatively charged patches gather the cinnamon. The application takes about a second, during which the plastic loses little of its charge to moisture in the air or through conduction. When the dust has settled, the region from which the tape was peeled is colored brown by the cinnamon, indicating that the tape left the plastic negatively charged. The rest of the plastic surface is black (the color of the toner), presumably because when Donald wiped the case prior to the experiment, he left positively charged patches on it.

If you repeat the experiment, clip

Charge map made with cinnamon and toner

Spark paths

Complex spark paths



Petal-shaped patterns

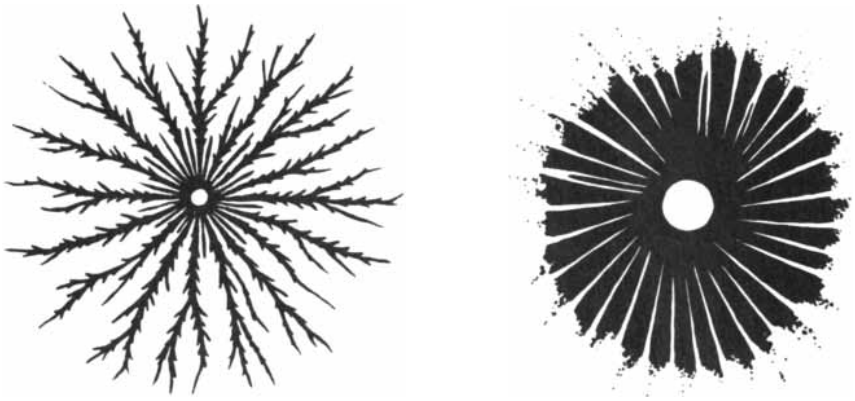
the nozzle of the bottle so that its opening is wider than normal. You might also clip the tube that extends into the bottle so that airborne dust is more easily blown out through the nozzle when you squeeze the bottle. Hold the nozzle from 10 to 20 centimeters above the surface to be dusted. Avoid releasing too much dust. If you do, tilt the plastic and tap it to knock off some of the dust, or blow gently across the surface.

Donald cautions that the experiment is guaranteed to make a mess, and indeed my kitchen and clothes are covered with multicolored dust. Be careful: the dust will ruin computers and floppy disks, and the toner will ruin clothing. To avoid a mess, you can do the experiment inside a large plastic soft-drink bottle. Put the dust in the bottle, peel tape from the outside surface of the bottle and then shake the bottle. The electric fields established by the charged patches on the outside surface will attract the powder to the inside surface. The pattern may, however, lack the fine detail achieved by the messier standard method.

Moreover, a major disadvantage of this approach is that the dust patterns cannot be preserved by Donald's usual technique, in which the powdery map is transferred to fresh layers of tape. Donald applies several strips of transparent sticky tape to the dusted surface, with the strips slightly overlapping one another. When he lifts the tape array gently, much of the dust remains stuck to it, and he then presses the array onto a sheet of paper. (Usually the paper is white, but sometimes, depending on the colors of the powders, he chooses an appropriately colored paper.) In transferring the powder to tape it is important to avoid sliding the strips of tape over the dusted surface. I stick each end of a strip to a finger of each hand, lower the tape to the dusted surface, press my thumbs down on the middle of the strip and then slide the thumbs outward toward the fingers.

The success of the experiments depends on the immobility of the charges on the surface from which the tape is peeled. Glass, a moderate conductor, functions poorly: by the time the dust settles, the charges have largely been dissipated by conduction. High humidity also ruins the experiments. Even if the room air is dry, the tape may be slightly "wet" if it has been in humid air in the days preceding an experiment.

Toner powders from other photocopying machines or from laser printers can be substituted for the Kodak powder, but in some cases the electrical polarity of the cinnamon and the toner powder may be reversed. (There is a simple test, which I shall describe below, that indicates which of two powders is negatively charged.) Instead of cinnamon and a toner you can use parsley, sage, thyme, cumin, various flours or a variety of other common kitchen staples as long as they are ground to a fine powder. The best results are obtained when the grains are tiny and quite uniform in size, so that the tape strips pick up all the grains and retain fine details in the map.



Lichtenberg figures formed by dust: an anode pattern (left) *and a cathode pattern* (right)

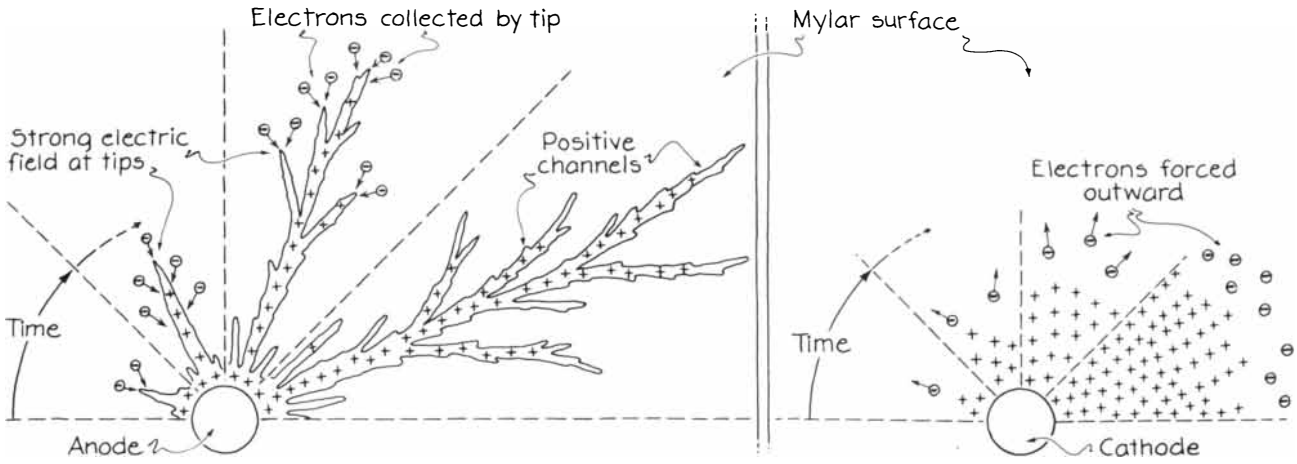
Donald enjoys working with unbleached wheat flour because it lacks the magnetic properties of some toners, which can smear a charge map to some extent. Several other kitchen powders do not work well. Mustard powder is too transparent; coffee and corn meal are too coarse even after grinding. You should also avoid any powder whose index of refraction matches that of the tape, because the dust is then invisible in the lifted map. Some powder combinations function better than others because of the way the powders interact when they are charged by shaking. Crushed paprika has a striking color but works only with toner; when it is shaken with flour, for example, the oppositely charged grains attract each other so strongly that they ignore the charges on the surface and settle uniformly over the test site.

When tape is peeled from plastic, small avalanches of electrons may jump along the surfaces without creating a true spark (which is a complete column along which the air is ionized). To promote sparking, Donald put a narrow strip of aluminum foil, the right-hand end of which was pointed, under the tape. He reasoned that when he peeled the tape and foil, the electric fields at the edges of the foil, and in particular at the pointed end, might be strong enough to ionize the air.

When Donald dusted the plastic, little of the powder was attracted to where the foil had been, indicating that the plastic was electrically neutral there. Throughout most of the region where the tape had peeled from the plastic the color was brown from the cinnamon, as in his previous trials. Where the edges of the foil had been, however, he found forked paths resembling lightning strokes, colored black by the toner. Sparks must have developed in the air just above the plastic, draining electrons from the plastic and leaving the positively charged paths. In some trials Donald found fan-shaped black patterns where the edges of the foil had been. Such a pattern is due to a corona: an ionization of the air that does not develop into a spark.

By repeating Donald's corona and spark experiments you can always tell which powder in a combination of powders is negative. It is the powder that collects to form either forked paths or fan-shaped patterns where ionization of the air has left positively charged regions. I tested this technique on a combination of two Day-Glo powders, Neon Red and Saturn Yellow. Several experimenters had found that Day-Glo powders, which are brilliant in color, define charged patches effectively. When I dusted my powders over plastic from which tape and foil had been peeled, the red powder collected along a forked path, indicating that the powder must have been negatively charged. (Five-pound packs of the powders can be bought from the Day-Glo Color Corporation, 4515 St. Clair Avenue, Cleveland, Ohio 44103.)

Donald produces a quite different



How different charges create different Lichtenberg figures

distribution of charge when he peels sticky tape from a film of cellulose triacetate. Part of the charge map that he lifts from the acetate is black from toner, but there are also pale brown—almost clear—petal-like regions. The left side of a petal is narrow and curved; the right side is wider and straight. (Remember, the peeling is from left to right.)

Donald explains that during the peeling the acetate becomes positively charged, the tape negatively charged. When the charge difference is large enough, electrons begin to flow from the tape to the acetate, almost neutralizing it. The discharge begins in a narrow region—which will be the left side of a petal when the acetate is later dusted. As the discharging extends across the width of the tape, the area that is almost neutralized widens. When the charge difference between the tape and the acetate gets to be small enough, the discharge stops abruptly, forming the right side of the petal. The continued peeling then rebuilds the charge difference until discharging is reestablished and another petal is formed.

On some surfaces sticky tape peels in a stick-and-slip manner, giving rise on the charge map to a series of striations that run across the width of the strip from which the tape was peeled. Interesting charged patches can also be created when tape is peeled from tape, as when a length of tape is pulled from a dispenser roll. After pulling off some tape, dust it in the usual way and then lay another strip over it for preservation. (You must do the dusting quickly, because the tape is partially conducting.)

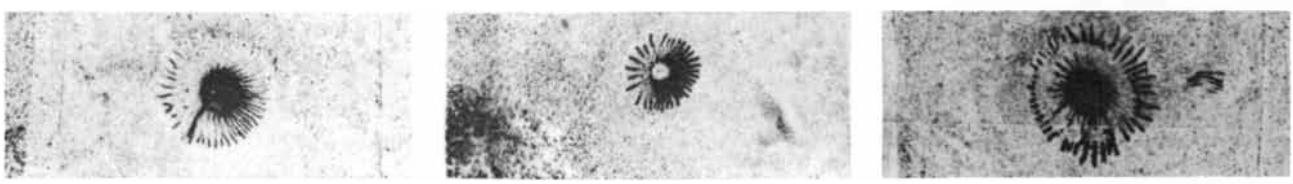
As I mentioned above, the technique for dusting samples that have undergone discharge and sparking goes way back: it was discovered in 1777 by Georg Christoph Lichtenberg of the University of Göttingen. He noticed that when dust drifted over a cake of resin that had been sparked, dust grains aggregated to form beautiful patterns, which now bear his name. Soon afterward someone recognized that a mixture of two powders can reveal the polarity of the charges on a surface that has been sparked. When sulfur and minium (red lead) are sifted through the mesh of a muslin bag, the sulfur colors the positive regions yellow and the minium colors the negative regions red.

In this century Lichtenberg figures have helped to demonstrate how discharging and sparking proceed. In many experiments a narrow electrode is placed above a wide, flat electrode covered with a thin insulating material, and the two electrodes are connected to a device that can produce a sudden discharge between them. Then the insulating layer is dusted to reveal Lichtenberg figures.

The shape of a figure depends on the nature of the discharge. If the narrow electrode is an anode (that is, if it is higher in voltage than the other electrode), the figure, called an anode pattern, consists of many forked, branched lines radiating from a point directly under the anode. If the narrow electrode is a cathode (lower in voltage than the other electrode), the resulting cathode pattern is a circular patch consisting of many lines, which are often too narrow to resolve individually.

With Donald's guidance I set out to make some Lichtenberg figures in my university library. During the low-humidity days of winter the library is notorious for the sparks that result when one walks over the carpeted floor and then reaches for a metal door or bookshelf; the spark is often strong enough to be felt and even heard. I decided this nuisance could finally be put to some use. Is my finger an anode or a cathode? I could tell by arranging to have the spark create a Lichtenberg figure.

With strips of sticky tape I attached a small square of Mylar to the side of a large metal bookshelf. Then I walked about the floor, shuffling my feet and also swinging my arms so that my body became charged by the brushing of clothing against my skin as well as by my movement over the carpet. Then I returned to the patch



Lichtenberg figures made by a hand-held pinhead **(left),** ***pinpoint*** **(middle)** ***and scissors point*** **(right)**

of plastic film and brought my finger up to it, causing a mild discharge. When I quickly squirted Xerox toner and cumin onto the Mylar, I found a black pattern about a centimeter wide. It was complex but appeared to have forked lines radiating from where I had touched the film, indicating that I had acted as an anode. I lifted the pattern with sticky tape and filed it in my notebook.

In repetitions of the experiment I held either a key, a straight pin or the point of a scissors blade up to the Mylar, thinking that the sharp end would provide a stronger electric field and a more vigorous discharge than my blunt finger. Indeed, audible and visible sparks sometimes formed in spite of the layer of plastic film. In each case the dusted Mylar revealed an anode pattern: fine, forked lines radiating from where the point had touched. Apparently, then, as I walked about the library my body had lost electrons and become positively charged. Back in my laboratory I was able to produce cathode patterns on squares of Mylar with electrostatic charging devices that are common to a physics classroom.

The anode and cathode patterns differ because of the way charge flows over the Mylar during the discharge. When a narrow anode is positioned above the film, electrons from the film and the air just above it flow to the point directly under the anode and then up to the anode in a series of avalanches or sparks. Positively charged channels of sluggish or immobile positive ions develop on the film's surface and in the air just above it, snaking outward from the point under the electrode. As the channels lengthen, the strong electric fields at their tips collect even more electrons, which then pass on to the anode. After the discharge the pattern of crooked, positively charged channels remains on the Mylar. The initial voltage difference between the anode and the cathode under the film determines the width of the pattern: larger voltage differences produce wider patterns.

If instead a narrow cathode is positioned above the Mylar, the discharge consists of a series of avalanches or sparks that send electrons from the cathode down to the film, where they are driven outward radially. As electrons from the film and the air just above it join in the outward flow, the Mylar under the cathode becomes positively charged and begins to mask the cathode's electric field from the departing electrons. Depending on the actual distribution of charges, the peripheral electrons then undergo forces that are not radial, and they spread outward in many directions. No channels form. When the discharge stops, the positively charged region of the Mylar under the cathode is approximately circular, with a diameter that depends on the initial voltage difference between the cathode and the anode.

The library experiments gave rise to two perplexing patterns. One involved the straight pin. When the head of the pin was held toward the Mylar, the normal anode figure developed. When the pointed end was held toward the film, however, the anode pattern had a clear center. I suspect that the point may have pierced the film, enabling electrons from the bookcase to neutralize the center of the pattern. The other puzzle was that a sharp point often left two patterns, one within the other, with a clear zone between them. Both patterns were anode figures. I think an initial discharge produced the larger pattern; a bit later, as my unsteady hand moved the point closer to the Mylar, pushing the plastic film against the bookcase, a smaller second discharge produced the narrower pattern. The electron collection in the second discharge may have obliterated part of the first pattern.

You may want to challenge my interpretations of these strange patterns. You might also enjoy searching for evidence of extra discharging in the Lichtenberg figures. Sometimes clouds of electrons on the perimeter of a pattern are discharged just as the voltage difference between the electrodes disappears. For example, consider the usual arrangement for making a cathode pattern. When the voltage difference drops toward the end of the discharge, the electrons outside the pattern might sometimes travel into positive regions within the pattern, leaving positive trails on the Mylar surface. Such discharging could be only slight or it could be an actual spark.

There are a host of experiments to be done with electrostatic charging. Charged patches are often left when plastic food wrap is peeled from the roll or some other surface. Laundry dried in a machine without an antistatic material often exhibits sparking. Can you produce a Lichtenberg figure with the help of a cat that you have charged electrically by rubbing its fur? I shall be glad to hear about your experiments on this timeworn and dusty bit of physics.

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COMPUTER RECREATIONS

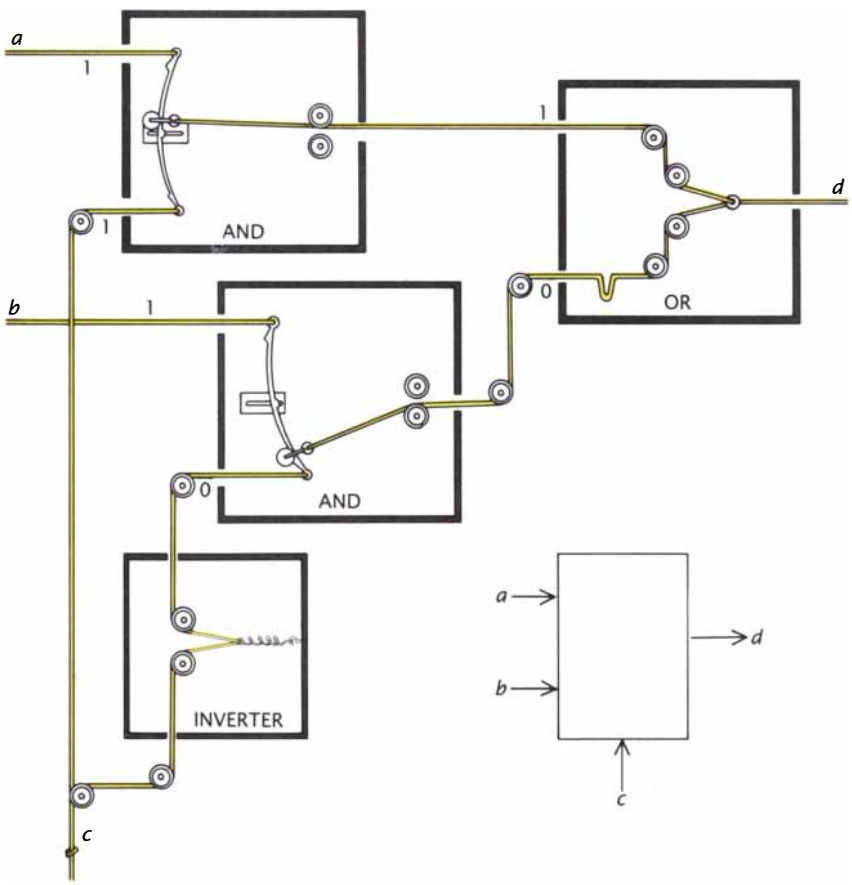
An ancient rope-and-pulley computer is unearthed in the jungle of Apraphul

by A. K. Dewdney

On the island of Apraphul off the northwest coast of New Guinea archaeologists have discovered the rotting remnants of an ingenious arrangement of ropes and pulleys thought to be the first working digital computer ever constructed. Chief investigator Robert L. Ripley of Charles Fort College in New York dates the construction to approximately A.D. 850.

The Apraphulians were excellent sailors. Their ships were wonderfully built and equipped with the most elaborate rigging imaginable. Were the Apraphulians led to the digital computer by their mastery of rope or was it the other way around? Experts continue to debate the topic hotly.

The ancient rope-and-pulley computer has recently been partially reconstructed by Ripley and his team at the Tropical Museum of Marine Antiquities in nearby Sumatra. Scouring a site that extends through several kilometers of dense jungle east of the Pulleg Mountains, the group found faint traces of buried jute fibers and noted the exact position of badly corroded brass pulleys and associated hardware. The reconstruction has given me an ideal opportunity to introduce readers to the principles of digital computing without resorting to tiny and mysterious electronic components. Here are gates, flip-flops and circuits made entirely of rope and pulleys. It is all visible and perfectly easy to understand.



***An Apraphulian multiplexer: rope* c *determines whether signals from* a *or* b *reach* d**

The Apraphulians used a binary system just as we do, but the numbers 0 and 1 were represented by the positions of ropes instead of by electric voltages. Imagine a black box with a hole drilled in one side. The reader holds a taut rope that passes through the hole. This position of the rope represents the digit 0. If the reader now pulls on the rope, a creak and squeal inside the box is heard as a foot or so of rope comes out. The new position of the rope represents the digit 1.

One can represent numbers with such boxes. Any number from 0 through 7, for instance, can be represented by three boxes [*see top illustration on opposite page*]. By employing more boxes, larger numbers can be represented. Ten boxes suffice to represent all numbers from 0 through 1,023.

My example of the black box is not arbitrary. The Apraphulians apparently loved to enclose their mechanisms in black wood boxes, small and large. It may be that the construction of computers was the prerogative of a special technological priesthood. The sight of great assemblages of black boxes may have kept the masses trembling in awe.

One of the key devices used by the Apraphulians converted a 0 into a 1 and a 1 into a 0. (It is occasionally convenient to speak of 0 and 1 instead of "in" and "out.") Akin to what modern computer engineers call an inverter, this interesting mechanism consisted of a box with a hole drilled in its front and another in its back [*see bottom illustration on opposite page*]. When someone (or something) pulled the input rope at the front of the box, an equal amount of output rope would be played out of the hole in the back. On peering into the box, the reason is obvious: the ropes entering the box from front and back pass over two fixed pulleys toward one side of the box, where they attach to a single spring.

As some readers may have surmised already, the digits 0 and 1

were not encoded so much by "out" and "in" as they were by the direction in which the rope moved. The point is best illustrated by a box that has no mechanism in it whatever. A piece of rope enters a single hole in the front of the box and leaves by a single hole in the back. If one pulls the rope from the 0 position to the 1 position at the front of the box, the rope moves from "in" to "out." The direction of movement is toward the puller. The rope simultaneously moves from "out" to "in" at the back of the box, but since the direction of movement is still toward the puller, the rope at the back of the box also moves from 0 to 1.

Two additional mechanisms almost complete the ancient Apraphulian repertoire of computing components. The first mechanism had two input ropes entering a box. If either rope was in the 1 position, the single output rope would also be in the 1 position. The Apraphulians managed this trick by absurdly simple means [*see top of illustration on next page*]. Each rope entering the front of the box passed over a pair of pulleys that brought it close to the other rope. The two ropes, passing toward the rear of the box, were then tied to a single ring linked to the output rope. If either or both of the input ropes were pulled, the ring would be pulled directly. Because the output of the box was 1 if one input *or* the other was 1, today's engineers would call this an OR gate.

The ancient Apraphulians fabricated what we would call an AND gate from three pulleys and a curved rod [*see bottom of illustration on next page*]. One of the pulleys was free to roll along the rod, its axle being connected directly to an output rope. The other two pulleys were paired, serving chiefly to position the output rope at the exit hole. With both input ropes in the 0 position, the rod coincided with the arc of a circle centered on the paired exit pulleys. If one of the input ropes was pulled into the 1 position, one end of the rod was pulled away from the center of its resting circle. The pulley attached to the output rope would then roll "downhill" toward the end of the rod that had not been pulled; the position of the output rope would be substantially the same as before since that end of the rod still coincided with the resting circle. (A peg in the middle of the rod kept it from swinging to either side of the box when just one of the input ropes was pulled.)

Only when both input ropes were pulled would the output rope move into the 1 position. In this case the entire rod would have been pulled back into a new position; whichever end the rolling pulley occupied would be equally far from the exit pulleys. The name AND gate is derived from the fact that the output of this device is 1 if and only if one input rope *and* the other are in position 1.

With these components one can build all the control circuits of a digital computer. These include circuits that compute arithmetic functions, interpret program code and direct the flow of information among the parts of the computer.

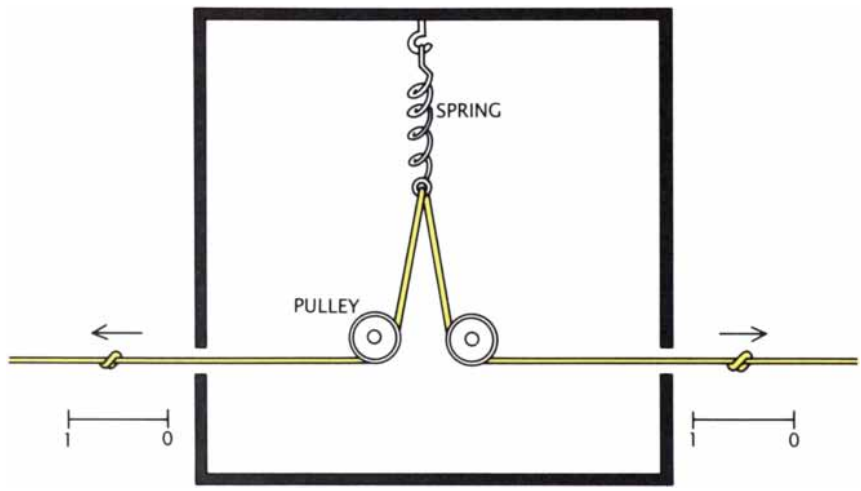
Did the Apraphulians construct their computer along such lines? The evidence is too fragmentary to reach a definitive conclusion, but archaeocomputologists working with Ripley maintain they have discovered a simple multiplexer within the half-buried complex. In electronic computers a multiplexer is essentially an electrical switch that directs the passage of many signals through a single wire. For example, the simplest multiplexer would have two input wires we might label *a* and *b*. At any given moment each wire could carry a 0 or 1 signal. Which of the two signals, *a* or *b*, will be allowed to pass through the device and out a single output wire *d?* The answer to that question is the business of a control wire, *c;* if it carries a 1 signal, the signal from wire *a* will be transmitted along the output wire. If the control wire carries a 0, on the other hand, the signal in wire *b* will be transmitted [*see illustration on opposite page*].

This reconstructed double-input Apraphulian multiplexer consists of two AND gates, an OR gate and an inverter. The whole thing is so simple that one dares to believe computer recreationists might build their own Apraphulian multiplexer at home. Hardware stores might suffer a puzzling run on rope and pulleys. In any event, one can follow operations of the multiplexer by referring to the illustration. Ropes *a* and *b* enter the multiplexer from the top left, each going to its own AND gate. Rope *c* is split. One branch runs directly to the other input port of the AND gate to which rope *a* goes. The second branch of rope *c* passes through an inverter and then runs to the AND gate to which rope *b* goes. If rope *c* is pulled to a value of 1 and held, any sequence of 0's and 1's sent along rope *a* will be faithfully transmitted through the upper AND gate and on to the OR gate. At the same time any signal sent along rope *b* will be stopped at the lower AND gate. If rope *c* is relaxed to its 0 position, the inverter creates a 1 at the lower AND gate. In this case any signal sent along rope *b* will now be transmitted through the lower AND gate and signals on rope *a* will be ignored.

The OR gate merely ties the two

BOX 1	BOX 2	BOX 3	NUMBER
IN	IN	IN	0
IN	IN	OUT	1
IN	OUT	IN	2
IN	OUT	OUT	3
OUT	IN	IN	4
OUT	IN	OUT	5
OUT	OUT	IN	6
OUT	OUT	OUT	7

How Apraphulians represented numbers



The Apraphulian inverter

output signals together, so to speak. If the signal from rope *a* is currently being transmitted, one can easily visualize exactly what happens directly from the diagram: if rope *a* is relaxed to the 0 position, the pulley in the AND box rolls to the end of the rod. A 0 is thus transmitted along the output rope and into the OR box. The other input rope to this box is already in the 0 position (slack). The natural tension on the output rope *d* immediately pulls it into the new position, namely 0. If one pulls on rope *a* again, the pull is transmitted along the path that has just been described, with the result that rope *d* is retracted.

The matter of slack ropes compels me to take up the question of tension in the Apraphulian computer. Sometimes, as in the OR gate of the example, a rope will become slack. There is naturally a danger that such ropes will slip right off their pulleys. Ripley tells me that in such cases the Apraphulians used a specially modified inverter with an extremely weak spring to remedy the problem. Wherever a rope was likely to develop slack, a "weak inverter" was installed to maintain the minimum tension associated with the signal 0.

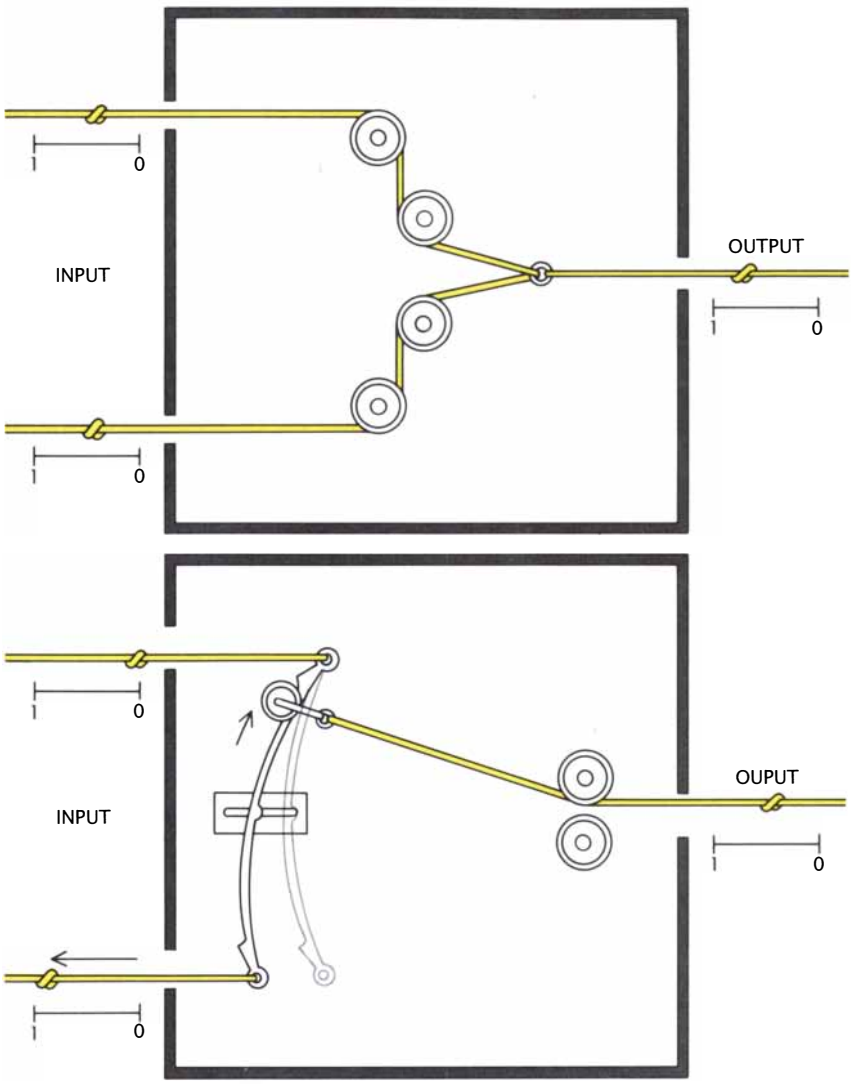
No general-purpose computer is complete without a memory. The memory of the Apraphulian computer consisted of hundreds of special storage elements we would call flip-flops. Here again the remarkable simplicity of the Apraphulian mind is immediately evident. In line with modern terminology, the two ropes entering the mechanical flip-flop are labeled set and reset [*see top illustration on opposite page*]. The two ropes were connected over a series of three pulleys in such a way that when the set rope was pulled away from the box into the 1 position, the reset rope would be pulled toward the box into the 0 position. The common rope was connected to a sliding bar at the back of the flip-flop box. The output rope, physically a continuation of the set rope, had a large bead attached to it that engaged a slot in the sliding bar. As the set rope was pulled, the bead rode over the end of the bar, popping into the slot when the set rope reached the end of its travel.

As a consequence the output rope was held in position until the enormous rope computer changed things by pulling on the reset rope. That had the effect of pulling the sliding bar away from the bead, releasing it and playing the output rope into the 0 position. In this case the flip-flop would henceforth "remember" 0. How were such memory elements used in the Apraphulian computer?

Ripley and his team were puzzled to discover in the midst of the vast Apraphulian computer complex a large overgrown field nearly a kilometer wide. Buried just below the surface of the field were several thousand rotting flip-flop boxes arranged in rows of eight. Ripley, with the aid of the archaeocomputologists, eventually surmised that the field represented the Apraphulian computer's main memory. Each row of eight boxes would have constituted a single, eight-bit "word" in the same sense that the three boxes of my earlier example would have constituted a three-bit word. In that vein, imagine a row of three flip-flops that had been set to the values 1, 0 and 1. They would have stored the number 5.

The content of this particular memory word would have been accessed by the rope-and-pulley computer as follows. Each flip-flop in the row would send an output rope to an associated AND box. The other input to each AND box would come from a special rope used to retrieve the contents of the word in question. When the ropes were pulled, the outputs of the AND boxes would be identical with the outputs of the flip-flops. The AND box ropes would lead to a large assemblage of OR boxes and thence into a special array of flip-flops we would call a register. A single tug on the rope associated with the word under examination would place the same binary pattern of rope positions in the register.

The computer's main logic unit undoubtedly would have directed the flow of information not just from memory to registers but between registers as well. In particular, by



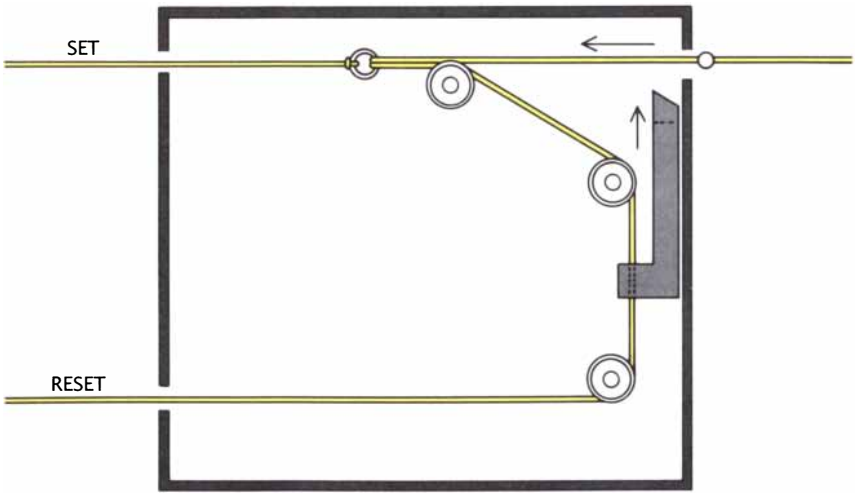
***The Apraphulian OR gate* (top) *and AND gate* (bottom)**

the use of multiplexers and demultiplexers (which perform the opposite function of multiplexers), the computer would have sent patterns from register to register. At a specific register that we would call the arithmetic register, patterns would have been combined according to the rules of addition and multiplication.

The Apraphulian computer is believed to have been programmable. If it was, part of its vast memory would have been used to store the program. Program instructions would also have been merely patterns of 0's and 1's retrieved by the same mechanism outlined above. Those patterns would in due course have been sent to an instruction register for interpretation by the computer's logic unit.

It is a pity I can do little more in these pages than to hint at the marvelous complexity of the Apraphulian machine. It must have been an amazing sight when in operation. Because of the enormous lengths of rope involved, no human being would have had the strength to pull the input levers into the appropriate positions. The presence of elephant bones in the Apraphulian complex makes the source of input power immediately clear. At the output end large springs maintained appropriate tensions in the system. Perhaps flags on the ultimate output ropes enabled members of the technological priesthood to read the outcome of whatever computation was in progress.

The Apraphulian rope-and-pulley computer makes for an interesting contrast with the nanocomputer introduced in the January column. The rope machine, of course, inhabits a distant past whereas the nanometer-scale machine dwells in a hazy future. The Apraphulian computer is relatively massive in scale, covering thousands of acres; the nanocomputer is incredibly tiny, occupying an area one-thousandth the size of a human cell nucleus. The mere concept of either machine serves as a springboard into a speculative realm where recreation blends with science. Think, for example, of the ongoing dream of artificially intelligent machines. We find it easier to accept the possibility of an electronic computer that thinks since our own thoughts are to a great extent electronically mediated. Because any modern computer (and its program) is conceptually translatable into Apraphulian form, any artificially intelligent device ever realized now or in the future will have its rope-and-pulley counterpart. Can we imagine HAL 9000, the paranoid computer in the movie *2001: A Space Odyssey,* being so constructed? Are we willing to admit that an enormous building full of ropes and pulleys could be just as smart as we are?



The Apraphulian flip-flop served as a memory element

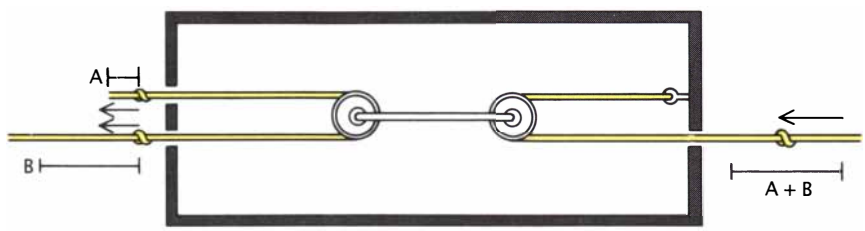
We leave the island of Apraphul with just one backward glance at its misty past: how might the vast digital computer have evolved? From analog ones, of course. The illustration below shows an analog adding machine made from two ropes and two pulleys. The two ends of one rope enter the front of a box through two holes. The rope passes over a single pulley that is linked with another pulley by an axial connector. One end of the second rope is attached to the back of the box. The rope passes over the second pulley and then through a hole in the back of the box. Readers might find some diversion in discovering for themselves how the machine adds two numbers; if the two input ropes are pulled a distance a and b respectively, the output rope travels a distance $a + b$.

So much is clear. But how did the Apraphulians manage analog multiplication? I shall try to publish the simplest design sent to me. In this context, I must ask all those who have written to me and received no reply to be patient. I am still able to read mail but the large volume prevents me from sending replies to all correspondence.

Most programmers (tyros or otherwise) attempting the special effects described in the December column settled on worms as the effect of choice. Sydney N. Afriat of Ottawa, who was last heard from in connection with the Tower of Hanoi problem in the November 1984 column, notes that the worms are particularly exciting to watch when the program is run in compiled form.

Warner Clements of Beverly Hills, Calif., disliked the wraparound dismemberment of his worms. Rather than allowing the creatures to crawl off one edge and to reappear at the opposite edge, Clements' program alters the direction of motion by +.25 or −.25. The choice depends on whether or not the variable called *change* is greater than .5.

Robert D. Scott, Jr., of Madison, Va., may be typical of a certain unfortunate class of readers running a version of the BASIC language that has enough differences from the version I described to make WORMS uncrawlable. Such differences, although fatal, are usually quite slight and easily fixed—once they are detected.



An Apraphulian adding machine

BOOKS

A stone text, the golden wall, the retinal carpet, a Saab heaven

by Philip Morrison

LAETOLI: A PLIOCENE SITE IN NORTHERN TANZANIA, edited by M. D. Leakey and J. M. Harris. Oxford University Press ($150).

Hardly another page in all the weighty Book of Sediments bears so graphic a text as that found at Laetoli. It is pressed into a six-inch, level layer of cemented gray volcanic ash. That stratum lies within a 500-foot-thick succession of volcanic beds, visible wherever a small river has meandered on its way down to a wide salt lake on the Serengeti. Here and there over some 30 square miles of the upland savanna a little stretch of that particular long-lasting layer, harder than the material above it, is exposed by erosion. Where that has happened "prints are visible on the surface."

The first prints were found in 1976. By now just nine exposures of the Footprint Tuff have been minutely searched; nearly 10,000 impressions have been counted over a total exposed area of less than an acre. Nine-tenths of them are small oval marks left by the African hare and the tiny deerlike dik dik, both animals abundant at this place today, in modern although kindred species. "An elderly Musukuma tracker" helped to identify the genera of the creatures that left the tracks, although he tried to fit individuals into living species. Trails were also left by hyena and ostrich, giraffe and rhino; you can see one or two pawprints of a really big cat.

The little horse of that epoch is encountered in three trackways; at one place the crossing pathways of an adult and a younger animal suggest a mare and her foal. The sequence of the old prints, hoof and side toe marked, fits the pattern of the single-foot gait, "like a fast walk instead of a slow run," during which one foot is always on the ground. It is favored for surefootedness by equids "for instance when it suddenly starts snowing." These prints have been compared with those of the Iceland pony, specially bred for single-foot travel. By scaling from the modern pony, the size and speed of the Laetoli horses can be estimated: the mare stood three feet high at the withers, a good foot less than today's pony; she crossed the slippery ash-covered terrain—a slip is marked in her hoofprints—at some four miles per hour.

The beds at Laetoli are well dated; large flakes of mica with a good potassium content can be sorted from the ash at many levels and their radiogenic argon production measured. The Footprint Tuff itself is consistently found to be about 3.5 million years old. The geologist's interpretation of the fabric of that tuff is striking. The lower fraction of the tuff consists of 14 layers of ashfall. Those layers conceal local irregularities such as footprints without change in thickness; the material must have been undisturbed ever since it was deposited. Clear raindrop imprints are seen widely at several interfaces; the showers were enough to dampen the ash but not to erode it. Above those layers lie a few thicker ones, which show that heavier rainfall redeposited and mixed the layers of new-fallen ash. Footprints are found in many of the layers.

At the base of the tuff grass roots are visible, but no grass blades are seen in the tuff itself; the grass was kept short, probably by grazing. There were few trees nearby on this open land: the pollen found is grassy, and the birds are ground feeders, not forest dwellers. This ash was laid down at the close of the dry season, just as the first new rains came, each layer probably deposited by a new eruption. The annual wet season arrived as the upper layers fell. The prints in the lower part are those of dryland savanna creatures, hares, guinea fowl, rhinos; in the upper layers are the tracks of those animals that migrate, as they still do, when the rains come, chiefly the hoofed and horned herds and the baboons.

How can coarse ash, particles the texture of sand, record footprints so well? Just the right amount of moisture is needed; it is hard to see how that could have been managed for each of a dozen printed layers. The answer is that this was no commonplace volcano. Its clouds consisted of a carbonatite ash, rich both in sodium and in calcium carbonate. The first rainfall enabled the soluble soda ash to cement the surface layer. The very volcano is still visible, 15 or 20 miles to the southeast, its much eroded cone protruding from the flank of the grand caldera of the younger Ngorongoro. Its long-cold lava is of matching age, and its ash has the unusual carbonate-rich composition, a hint of reworked sea-floor material.

This archaeologically favored region, known as the East African Rift Valley, is a place where our own kind have long been at home. The layers preserve our ancestral bones and prints. Three trails of hominid tracks are there at one locality, where fortune exposed a single indentation of a heel. A few inches of darker material were then removed for a distance of some 100 feet to disclose those trails, shown here in a dramatic color photograph. (Someday a museum at the spot will house the wonders; for the time being they have been carefully covered up again with layers of sand and plastic sheet.) Two specialists agree: these are the prints of virtually human feet, whose age alone serves to part them from our own species. The prints show no features intermediate between apewalk and fully upright bipedal human stride; that transition must be older. While various beds have yielded portions of jaws and teeth from two dozen individual hominids, no worked stone at all is found. Everything fits the pattern of the gracile australopithecines. They are identical with individuals whose crushed bones in limestone caverns not far from Johannesburg show them somewhat later to have been regular prey to the big cats.

Indeed, that must have been so at Laetoli. Finds of outsize teeth and jaws point to truly lionlike felines (along with sabertooths), then at the pinnacle of the faunal pyramid. Apparently the savanna ecology was already fully formed in Laetoli days when across the slippery new ashfall a slight four-foot eight-inch tall hominid led a smaller one (by the hand?); their two trails are parallel at a nearly fixed distance, and the smaller prints

show a quickstep maneuver to catch up. The leader had in fact walked in footprints left behind by a third individual, larger still, who had gone first across the ash. All were at daily risk from the hunting carnivores; these were nimble walkers, clever game animals, not yet Promethean. They had neither fire nor weapons. Or did those small brains already hold some idea of pit traps or of sharpened sticks?

The burden of this technical monograph with its 33 expert contributors from three continents is not new. The work was mainly completed by the early 1980's, much of it even published. More than half of the bulky text is not devoted to traces of behavior in all those footprints (and in intricate buried castings of termite nests, and of the brood cells of solitary bees). Instead it is the familiar technical paleontology of careful description and identification of skeletal fragments of all kinds, bone by bone and tooth cusp after tooth cusp. Recall that this site first came under the scrutiny of Louis and Mary Leakey 50 years ago for its fossil bones. They were digging in Olduvai Gorge when a Masai told them of many old bones on the surface 20 or 30 miles south at Laetoli, "the place of red lilies," and offered samples in evidence.

This report is worth the general reader's attention because the richness of specialists' detail makes it overwhelmingly persuasive. It is a nearly full account from the human past unrivaled in poignance. These finds are as startling as when 50 years ago a few big molars of our distant forebears showed up in the dusty wood drawers where old-fashioned Chinese pharmacies kept their best-quality dragon's bone.

DARKNESS AT NIGHT: A RIDDLE OF THE UNIVERSE, by Edward Harrison. Harvard University Press ($25).

The night is dark because the sun is hidden behind the bulge of the earth, we reply. The response is true, but provincial. Any space traveler sees an even blacker sky than ours; in it the sun is a small, fierce disk for one who orbits nearby, or a mere pinpoint if the journey is a distant one. Why is the sky not more brightly illuminated by the countless stars?

Around that disarmingly simple query the author has woven a graceful history of basic cosmologic ideas from Pythagoras on, without ever turning away from the central topics implied by the question. A little closer look is enough to show how the

riddle attracts—and resists. Suppose space is transparent, unending and filled with stars, concordant with the sample given us by the sun and its neighbors. As we look outward our endless line of sight must sooner or later strike some distant star. If that is so, the sky would become a golden wall, ablaze in every direction like the disk of the sun itself; no dark voids at all dim our eventual direct view of remote stars. Something of our appealingly simple premise is wrong. Just what?

A novel solution was presented tongue in cheek by an Edwardian scientist-engineer, Edward Fournier d'Albe, an original who "flits through the pages...like a ghost." He was an accomplished man who in 1925 successfully transmitted television images from London and worked lifelong for the development of science in Ireland. He had a tidy answer: all far-off stars are simply ranked in straight rows out to infinity but so arranged that they are hidden one by one neatly behind the nearby constellations! He offered other models more seriously. One of his proposals was that most stars are dark; those obscure the distant glow. It takes a trillion dark stars for every sun; we can exclude so massy a universe.

Perhaps space is misted over? Less concentrated absorbers, say gas or dust, fail as well. We know now that any absorbing matter will itself heat up, to emit in turn—again, a bright sky. Absorption was the proposal of two early theorizers. Jean-Philippe Loys de Chéseaux, an astronomer born near Lausanne, was the first to analyze the issue quantitatively, in an appendix to his treatise on the famous comet of 1744 and its six-branched tail. Chéseaux was followed two generations later by Wilhelm Olbers, a physician and gifted amateur astronomer of Bremen. (In recent years the riddle has been called by Olbers' name, without clear reason.)

Perhaps the distant spaces are void even of ether, so that light cannot arrive from the far distance? Simon Newcomb, a redoubtable astronomer, put something like that forward a century ago. Yet surely such entrapped light will only circle round and round, and again the local sky will brighten intolerably; the line of sight follows the path of light itself. That same conclusion excludes the more modern invocations of curved finite spaces, ruling out a variety of arguers right up to the present.

Two geometric escape routes exist.

The simplest is that of the Stoics; they saw our universe of stars as merely an island of light in the dark and infinite void. That lonely view was taken by Otto von Guericke of Magdeburg, famous for his trial of the horses tugging against the vacuum. Minds even more productive than von Guericke's have followed that path: Johannes Kepler, William Herschel and, it seems, the young Harlow Shapley. A subtler trendy variant conjures up an example of what we now call a fractal: the starry universe is infinitely filled, nowhere void, yet tends to emptiness because its architecture is hierarchical—trees, copses, woods, forests... No finite set of levels, such as the superclusters we really see, will do.

Some explanations implicate the red shift; after all, the universe is not the static system of Newton and young Einstein. The emissions of systematically receding stars will be reddened to invisibility. That does not work either, at least in a cosmos that expands but is full of enduring stars. The effect is in the right direction, plausible but too weak; most of the starlight would be only a little affected by the expansion of the universe. Here we touch more difficult issues: in a steady-state cosmology that posits the continuous creation of matter, reddening can indeed dim the golden wall of the distant stars. For the strongly evolving big-bang universes of today's consensus, it is the red shift that has diluted the furnace world of the past, when light owed nothing to stars. Our sky is now uniformly filled with millimeter waves, a glowing wall no eye can see. But that radiation was never starlight.

The direct answer to the old riddle was anticipated by Edgar Allen Poe, in a metaphysical essay written in the last year of his short life. (*Eureka: A Prose Poem* got good reviews but it sold slowly; his publisher paid him $14 for the little book.) "Were the succession of stars endless...we could comprehend the *voids*...our telescopes find...by supposing the distance of the invisible background so immense that no ray from it has yet been able to reach us at all." It is time that dims the golden wall. That most robust of bearded Victorian worthies, Lord Kelvin himself, worked it all out in his own "Baltimore Lectures" a century ago. In a uniformly starry, transparent, static universe matched to our own experience of the near-solar sample, the golden wall is so far away that light would need a million million solar

lifetimes to travel here. The past of the stars is simply not deep enough.

The long table of solutions to the riddle ends with Edward Harrison's own. He augments the idea of a too shallow past by presenting the essential completing fact that the energy in all the mass we might reasonably pack into accessible space is hopelessly insufficient to support such a lengthy process. (A sequence of transient stars flashing cunningly on and off to fool us is on a par with Fournier d'Albe's hidden constellations.) Cosmologist Harrison is not complacent. He concedes that after 25 years of intermittent pondering he still does not "know all the answers." There are dissenters even now, serious if few, who postulate somehow the recapture and recycling of diffused energy in a sophisticated version of a proposal of William D. MacMillan's that is 60 years old. The list of answers is not yet closed; the riddle is still mused upon.

Have you ever pulled out a single yarn end to unravel an entire piece of knitted cloth? This small volume does something like that to the well-tailored fabric of our physical cosmology; it is an expository pleasure and an introduction to the issues, made easy for the general scientific reader to grasp.

EYE, BRAIN, AND VISION, by David H. Hubel. Scientific American Library, distributed by W. H. Freeman and Company ($32.95).

"You can imagine what a surprise it must have been to observe that shining a flashlight directly into the eye of an animal evoked such feeble responses." It was Stephen Kuffler at Johns Hopkins in the early 1950's who first broke out of that curious old trap set for the neurophysiologist. His electrode picked up sharply amplified nerve discharges from a random cell in the retinal ganglion, a transparent netted layer of cells just in front of the rods and cones in your eye or in a cat's. To produce the effect Kuffler did not depend on broad illumination. Instead he directed a small spot of bright light at his subject. Plainly, less light was more.

Kuffler found that once the spot size grows above a modest part of the visual field, the cell response declines to a slow, irregular firing no different from the firing in full darkness. Tiny spots evoke only a small response; as the spot is enlarged, response increases up to a clear maximum and then falls. The point-by-point stimulus of the retina that forms an optical image as do dots on film has been transformed by the retinal circuitry into specific, complex, receptive fields. The cell sampled here responded to a bright patch of definite size, provided there was a darkened surround. If the cell was exposed to a bigger bright spot or a smaller one, its firing was inhibited. Indeed, there were two principal kinds of field in the ganglion; the other field was the obverse of the first—it required a dark center and a definite, brighter surround.

An important conclusion presents itself: the inhibitory response is as central to such a scheme as the excitatory response. The synaptic connections that bind neurons even at this outermost threshold of the brain, three intricate layers of them within a thickness of a quarter of a millimeter, achieve a telling synthesis, the alphabet of visual perception. The 125 million rods and cones feed only a million cells in the retinal ganglion; from that compression meaning emerges. No one before Kuffler had guessed that "the optic nerve would virtually ignore anything so boring as diffuse-light levels."

David Hubel, now a Nobel laureate who has his own celebrated laboratory at the Harvard Medical School, was a young research worker with Kuffler then and for years thereafter. This introductory book, brilliantly illustrated and as clarifying as it is candid, steers through the narrow strait between superficiality and excess detail to make an exciting summary for neurobiological innocents willing to follow arguments from microanatomy, neurophysiological experiment and clinical variety.

Once meaning was apparent, the visual signal could be pursued up the entire optic tract. These days it is pretty hard to avoid the obvious and helpful metaphor: wiring links the crowded circuit boards of the brain. The three cell layers that form the retinal board are close-packed; a few inches of thick cable, the optic nerve, couple their output to the lateral geniculate bodies, six layers of 1.5 million cells. The layers seem to repeat more or less the receptive fields of the retinal ganglion. Their output radiates in a broad fan of delicate neural wiring to the primary visual cortex in the rear of the brain. It is there that Hubel and Torsten Wiesel and their colleagues demonstrated elaborate receptive fields, fields not only responsive to spots of dark and light but also reactive to movement and sensitive to the orientation and even

the length of straight lines of light in the retinal image.

By now there are remarkable confirmations and extensions of the mapping of the primary visual cortex, apart from the signals found by the electrode probes. One photograph here shows a frozen section of the striate cortex of a macaque monkey. Into one eye of the anesthetized animal a target-shaped pattern was projected for 45 minutes after a radioactive tracer of cell metabolism was injected. The active cells took up and held the tracer, and the radiation imprinted the cell locations on a photographic plate. There is the target pattern, visible but smoothly distorted, its magnification varying from one end of the cortex to the other.

The system can be described in terms of what Hubel calls modules. Each module consists of a few hundred small detectors, much interconnected. Each module represents a chunk of cortex, a couple of cubic millimeters in volume, that maps a small area of one retina. Each area includes the full range of receptors sensitive to lines in any orientation. They are smoothly ordered along one axis of the chunk. Across that axis the two eyes report alternately. Of course, the entire model is highly idealized; vision varies over the field, and much overlap is essential.

Progress, indeed, and some sense of unity: the same theme is encountered again, this time excited by color. Within the cortex there have been detected what are called blobs, small groups of cells that respond to color (unless the color is presented in spots that are too large). Blobs are blind to orientation and to white light. They are color-coded in a complex way that recalls the center-surround opposition Kuffler found in the ganglion. Hubel's chapter on color vision passes the acid test of that much discussed domain; the phenomena of brown and purple are made as understandable as the rainbow colors. The tentative model, joint work with Margaret S. Livingstone, is close to the ideas of Edwin Land on color-field comparison at borders; it is tailored to the neurological findings, of course. If color vision is just one means by which shapes manifest themselves, it is no wonder we are not yet near understanding the perception of visual form. The transformation from the syntax of hard-wired nature to the familiar vocabulary of nurture remains tantalizingly beyond these experiments so far.

The computers of our time have

enormous numbers of layered and intricate components, rich cross-connections, inbuilt circuitry, stored experience. The author does not use these patent analogies much; his interest is focused on processes he can probe. A cell may be a member of 100 constellations, each consisting of 1,000 cells, out of whose overlapping receptive fields our concepts arise. Such ideas are still woolly, Hubel concedes. All the same a generally parallel architecture of many feedback connections among distinct but interacting functions is apparent. Some rich collaboration of skillfully programmed algorithms might turn out to be formally equivalent; that is not what this exploration directly reports. Final answers are not at hand, but the path has been opened wide and the journey so far found exhilarating.

WORKING KNOWLEDGE: SKILL AND COMMUNITY IN A SMALL SHOP, by Douglas Harper. The University of Chicago Press ($29.95).

Willie's shop, simple although not small, is a length of Quonset hut lying parallel to the paved road it adjoins, out in the hardscrabble farmlands tucked between the St. Lawrence River and the reserve of the Adirondack Park. The empty fields lie snowy and stubble-covered around it. The hut's dooryard is a crowded Saab heaven, where doze a couple of dozen old cars, a cache of parts for that esteemed product of Göteborg, accompanied by a random sample of less esoteric automotive ruin. For 10 years the ethnographer-author and Willie felt out time after time how to talk and work with each other, until 300 pages of transcript were there to be added to Douglas Harper's lengthy field notes and his sequences of photographs.

Now the ingredients have been made into a case study, as warm and lively as it is reflective, that records an important example of "material and folk culture.... I want to explain the way Willie has explained to me...to show a small world that most people would not look at very closely." Harper is a campus wordsmith, closer to grand ideas and far from the material. To approach the viewpoint there in the small shop he employed a powerful method (ascribed to the anthropologist John Collier). Called "photo elicitation," it seeks to organize the interviews around the photographic sequences. Willie would respond to the photographs. He is an articulate and thoughtful man, sometimes on sure ground, sometimes quite tentative and alert. Therefore he often demystifies "what...seems like an intuitive method" of repair, but in fact resembles, apart from calculation, the process of the design engineer.

Harper learned a good deal, just as many others learned who formed part of the shop's circulating group of customers: farmers, the occasional over-the-road trucker and exurbanites such as Harper himself with ailing and indispensable Saabs.

Willie was first taught by his father, a blacksmith who made the transition to auto mechanic as engines replaced horses. His work is not simply craftsmanship; that is not to say it is without craft. It is too improvisatory, imaginative, irregular and full of novelty to fall into the same category as the work of a journeyman who executes with skill the demands of a single trade. The base of Willie's working knowledge—this he shares with the craftsman—is the deep understanding of materials. In a setting where often he must design, invent and modify if he is to succeed, Willie handles a variety of materials: ferrous and nonferrous metals, plastic, wood, refractories.

Fixing is a narrower art than making; Willie is both constrained and proud to do both. Harper relates this style to prestandardized handwork, which was the rule before the artisans' trades were fully formed. It seems also a modern way, found not only on the isolated twig ends of the tree of industry but also wherever a product is made anew, in model shops, mixing rooms and tool cribs; it is an occupation for old hands, crew chiefs and serious young technicians, from Nagoya to Norfolk and Novosibirsk.

The touchstone is a degree of understanding. Those who approach repair as a matter of exchanging some broken part for the right replacement will never be mechanics. They know and see components but not the purposes and problems of design. Among the photograph sequences here several make plain what it is a mechanic can do. One brief page (with a drawing) shows what befell the white metal die-cast door handles that became through some small mistake part of the early Saab 99. The engineers were perhaps misled by matters of cost. The handles were made to be squeezed open, but the plastic ball bearings that bore the hand pressure on the lever would stick, break and fall out after "dirt and stuff" had worked on them. The metal was too weak to hold the pivot shaft for long against the force of a hard pull. The photographs show Willie filing and fitting a new stronger, smaller lever to trip the latch; there is no ball bearing. "The new ones have a different design...."

The book is Veblenian, explicitly so in one sharp passage. It is the instinct of workmanship, said Thorstein Veblen, that is fundamental to human action, to constructive human behavior. Such a view goes beyond analysis to judgment. The last third of the book examines the social context of that shop in the Quonset. First of all comes the stubborn independence of its owner, and the degree to which out there in open country he does his best to avoid relationships (such as those with institutions) that he cannot conduct face-to-face. Next is Veblenian indeed, the impulse to teach: Willie's grown son is a mechanic of high repute, one schoolgirl daughter is already a resource in the shop.

Harper learned much, for "the shop becomes a school, and to get work done you must often become a student." It is no wonder that a community of visitors centers there. Willie has too much work; he allots his own time. He serves the farmers in need right out in their fields during cultivation or harvest. Others may wait interminably. Those who come back share in a certain social reciprocity: they listen, they wait, they lend an occasional hand. Plenty of people in self-interest or carelessness offend the implied rules and drift off; some are slowly brought back in. This is not at all an ideal world, but it is a real one.

Every day alienation grows; every day what they call de-skilling widens. The North Country itself will not change fast, although Willie, who sees this book as a lasting record of his kind of work, expects that such work will be gone soon enough. The dairy farmers begin to trade their equipment in sooner and the automobiles get more complex. Willie's story offers wider hope; technology does not demand, as even Doug Harper thinks, that we human beings remain captives of our own creations. It is not the complexity of machines that presents a hopeless imbalance. We can master any machine, except perhaps our most powerful weapons. What we must learn is how to build social institutions that reflect the spirit of the small shops.

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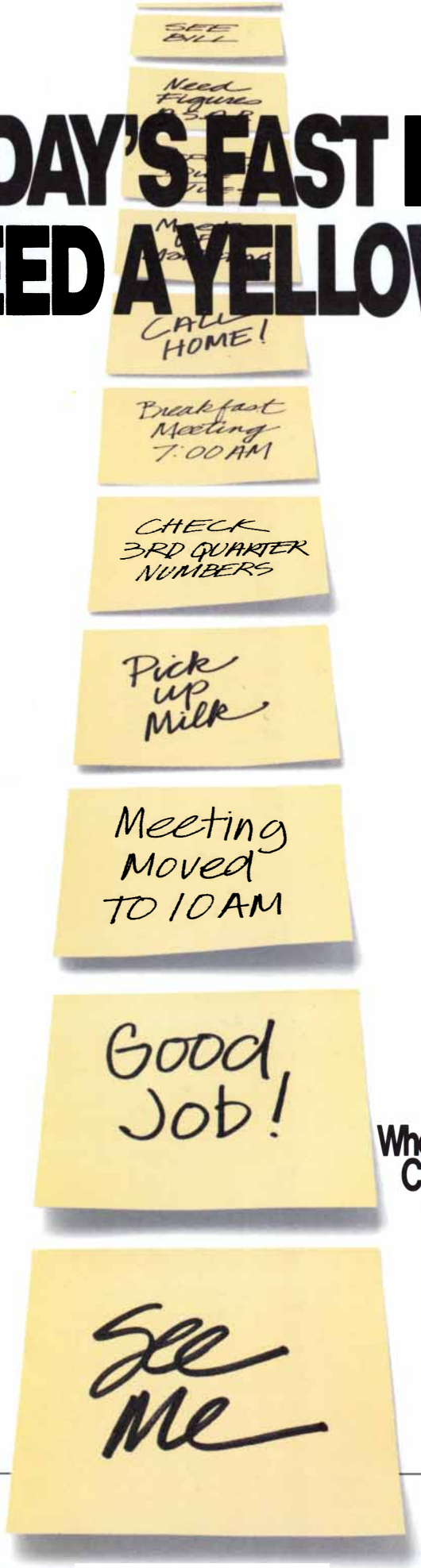

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