SCIENTIFIC AMERICAN

SEPTEMBER 1989
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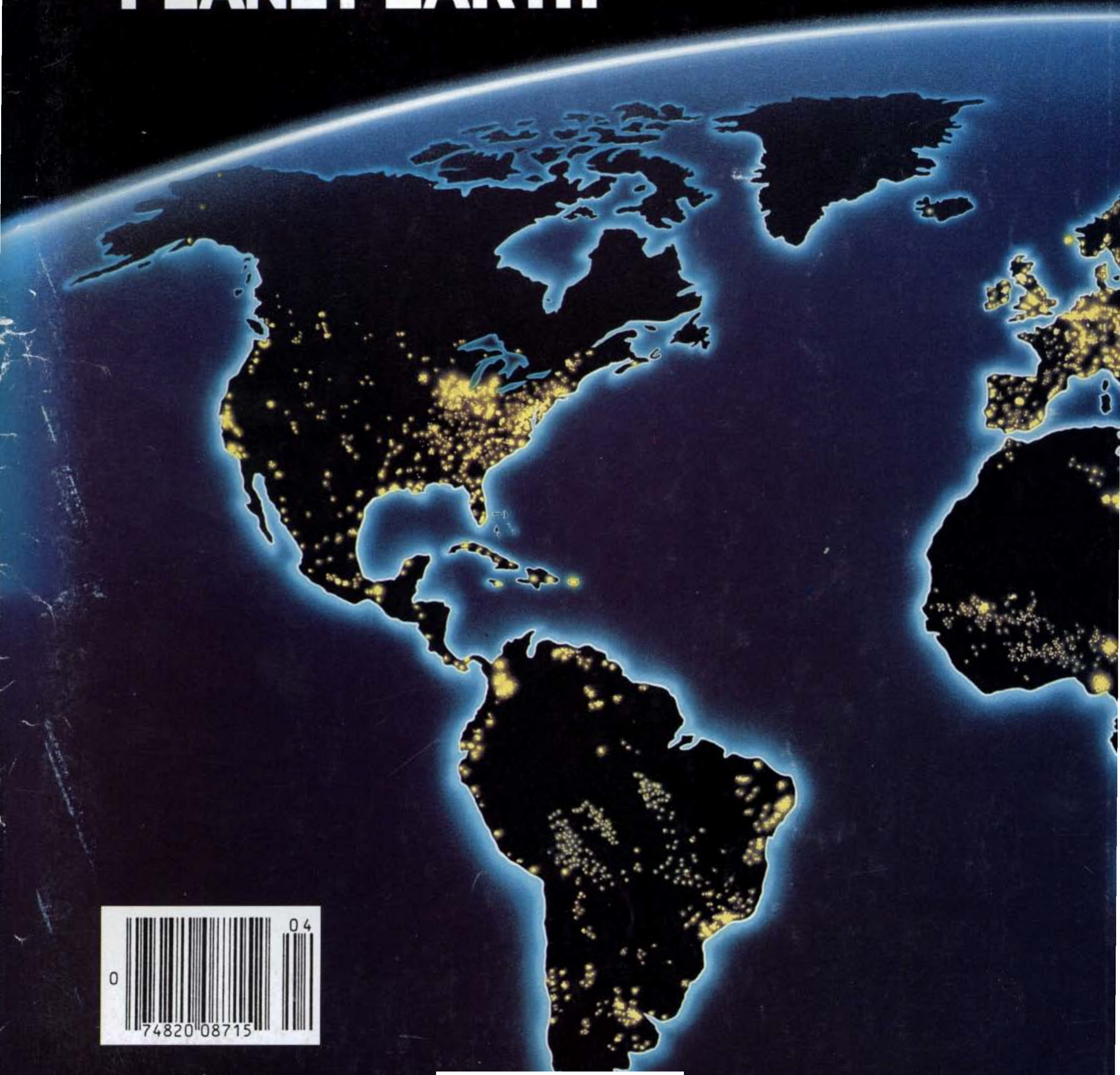
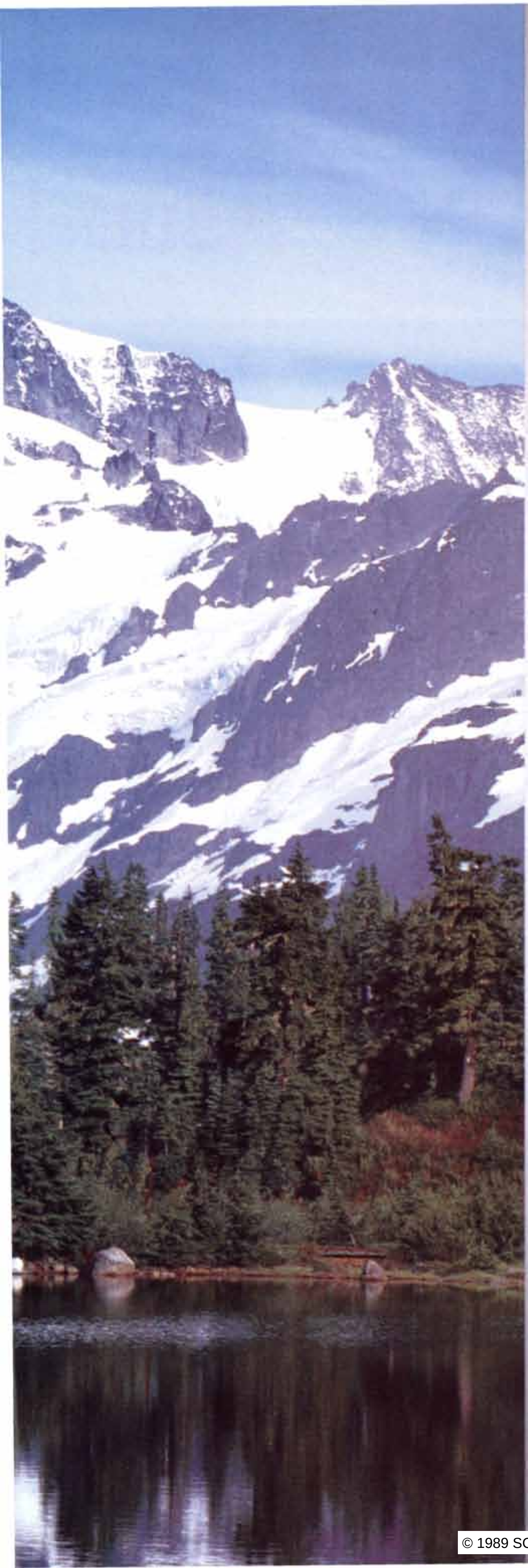
SPECIAL ISSUE

MANAGING PLANET EARTH

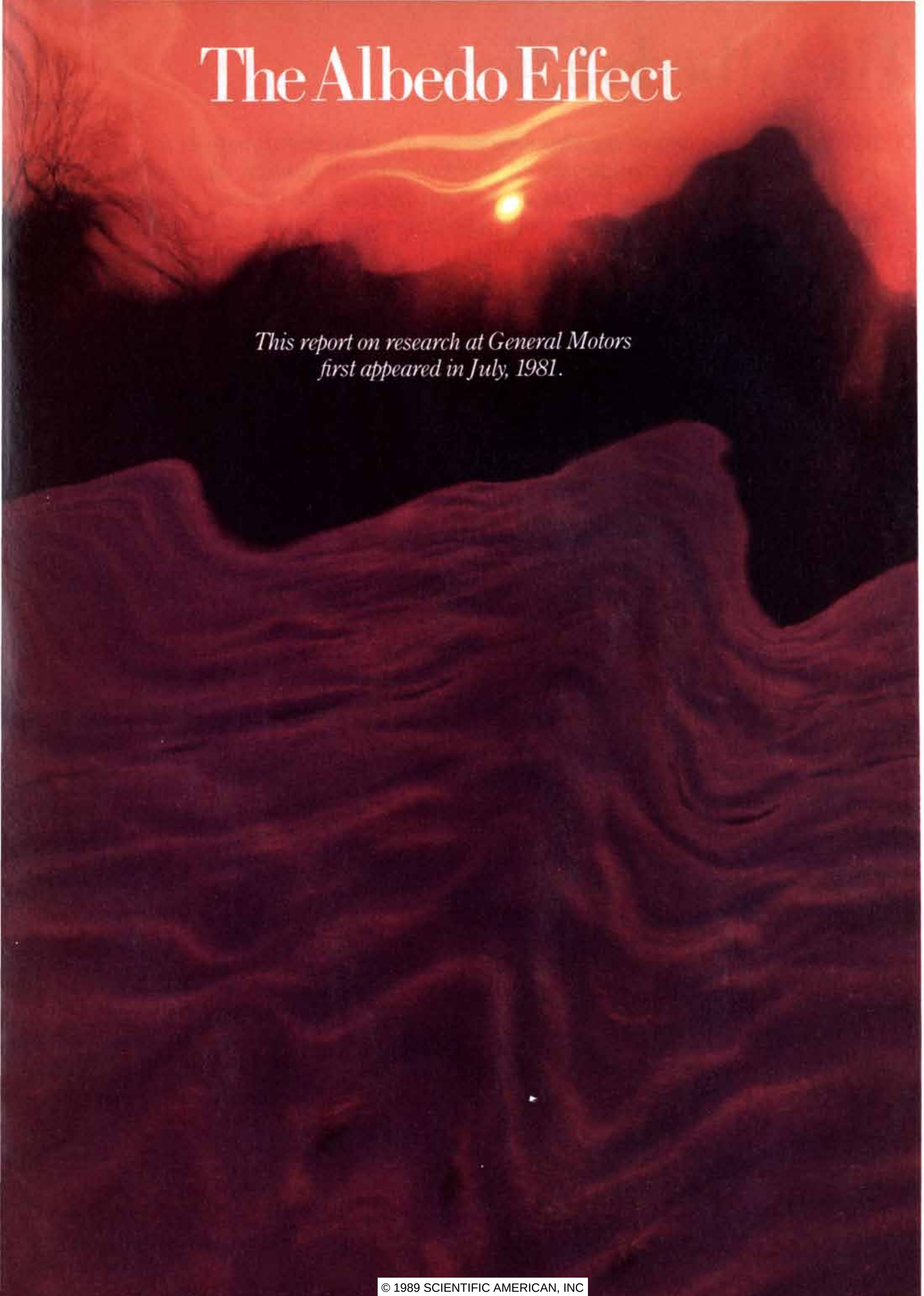


THE COVER PAINTING depicts points of light that reflect the impact of human beings on the earth, as seen at night by satellite. The major sources of light are urban areas (especially in the Northern Hemisphere), slash-and-burn agriculture (in South America), grassland burning (in Africa) and natural-gas flares (in Siberia and the Persian Gulf). Floodlights, operated by fishing fleets to attract squid, illuminate the Sea of Japan; city lights trace the path of the Trans-Siberian Railroad; and lights along the Nile River contrast with the virtually dark Sahara. Although these and other features are only approximations (fires vary seasonally, for example), they effectively portray patterns of human activity around the world. George V. Kelvin executed the painting with data provided by Woodruff Sullivan of the University of Washington. Sullivan has compiled a mosaic image, "The Earth at Night," from satellite photographs made by the Defense Meteorological Satellite Program of the U.S. Air Force.



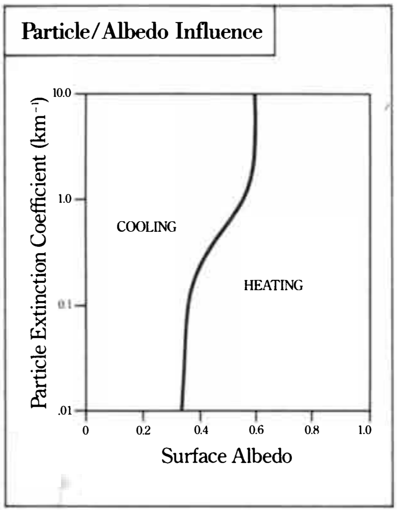
The Albedo Effect

This report on research at General Motors first appeared in July, 1981.



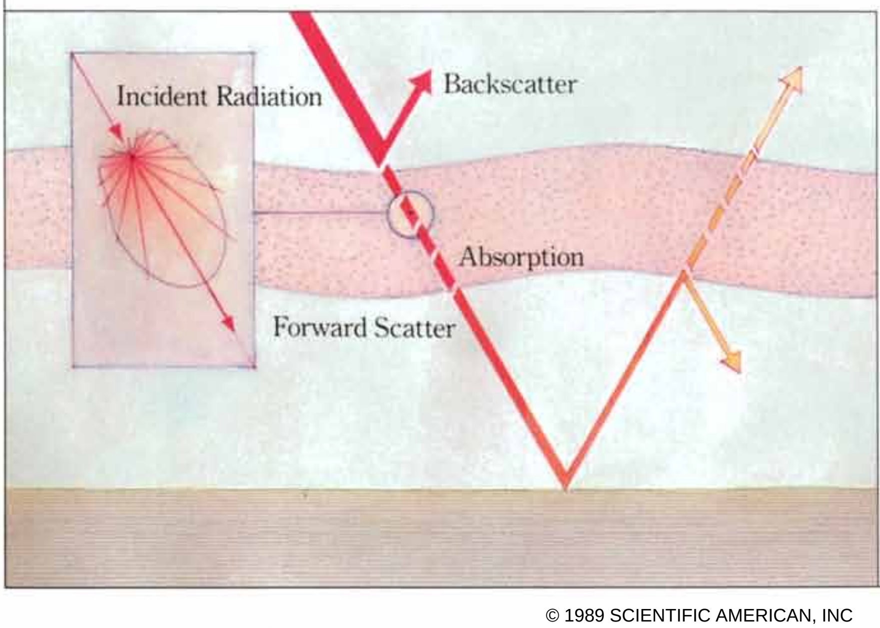
The Albedo Effect

Mathematical models of the atmosphere are the chief scientific tools for predicting long-term climate and identifying possible climatic changes that may result from man's activities. Recent advances at the General Motors Research Laboratories have revealed new information about the contribution of airborne particles to the delicate thermal balance of the earth's atmosphere.



Regions of heating and cooling determined by particle characteristics and surface albedo.

Radiation scattering exhibited by a layer of particles. The inset shows the distribution of scattering by a single particle of mean size.



DEVOID of its atmosphere, the bare earth would reach an average temperature of only −1°C. Atmospheric interaction with solar and terrestrial radiation raises the average surface temperature to fifteen degrees Celsius, making life as we know it possible. Small fluctuations in overall temperature can have large-scale effects. It is believed that a drop of a few degrees Celsius lasting for a period as short as four years could trigger an ice age. Fundamental studies conducted at the General Motors Research Laboratories explore the effect of various atmospheric factors, natural and man-made, on the earth's thermal balance.

New knowledge of the influence of airborne particles on the earth's thermal balance has been revealed by investigations carried out by Dr. Ruth Reck. Dr. Reck's work at General Motors integrated for the first time the complex factor of particles into radiative-convective atmospheric models. Her findings help determine under what conditions particles have a cooling influence, and under what conditions they have a heating influence.

Airborne particles have many sources: volcanic issue, wind-raised dust and sea salt, ash, soot, direct and indirect products of combustion and industrial processing, the products of the decay of plant and animal life, the liquid droplets and ice crystals that make up clouds. Particles alter the radiation flow in the atmosphere by the processes of scattering and absorption. Particles differ by size and composition, factors which determine optical properties.

Prior to Dr. Reck's work, models for calculating the vertical temperature profile included layers of clouds and the significant gases—O_2, O_3, H_2O and CO_2—but neglected the particle factor. To establish the thermal effect of particles, later models assumed a uniform vertical temperature change.

Dr. Reck's contribution was to add the particle factor to a one-dimensional model developed at the Geophysical Fluid Dynamics Laboratory at Princeton University. This model divides the atmosphere into nine layers. An initial temperature distribution is assumed, and the model is used to compute the net radiative energy flow into or out of each layer. A particle population is input for each

This research is one example of the breadth of GM's commitment to a healthful environment. Dr. Reck has since examined how albedo has varied historically with climate. She has also studied the role of volcanic aerosols, tested the sensitivity of climate models to albedo changes, and initiated new research into the greenhouse effect.

layer. Calculated radiation imbalances result in a temperature change for each layer within the model, subject to the condition that change in temperature with altitude not exceed the adiabatic lapse rate. The new temperatures are used to compute a new radiation balance. This process is repeated until there are no further changes in temperature.

The particles of interest, known as Mie-scattering aerosols, are comparable in size to the wavelength of the incident radiation. Dr. Reck models the interaction of these particles with the radiation field in terms of two parameters: the single scattering albedo of the particle, which describes backscatter, and an anisotropic scattering factor, which measures the degree of forward scatter. From these two quantities and the size distribution and abundance of the particles, the transmission, absorption and backscatter of each layer in the model can be calculated.

DR. RECK discovered that whether particles have a heating or cooling influence depends upon the surface albedo, or reflective power, of the earth directly beneath them. Snow (0.6) is more reflective than sand (0.3); water is less reflective than either (0.07). Her results indicate that when surface albedo is small, the net effect of particles is to "shield" the earth from incoming solar radiation, producing a cooling influence. When surface albedo is large, a trapping effect prevails, in which the portion of solar radiation that reaches the earth's surface is "trapped" between the surface and the particles, producing a net heating influence. The competition between these two effects, shielding and trapping, determines the overall thermal influence of particles.

Dr. Reck calculated that for the latitudes between the equator and 35°N, where average surface albedo is low, the current background level of atmospheric particles decreases solar radiation reaching the earth by ~1%, thus producing a net cooling effect. Her findings indicate that heating takes place at latitudes north of 55°N, where average surface albedo is high. Calculations with the model indicate a correlation between the increase in particle abundance due to volcanic activity in 1970 and a subsequent ice build-up in 1971.

"Previous models did not adequately take into account the role played by particles in the earth's thermal balance," says Dr. Reck. "The geosystem is continually changing. It is important for us to understand the elements that affect this evolution, so that we may know how man's activities influence the atmosphere."

General Motors

MARK OF EXCELLENCE

THE WOMAN BEHIND THE WORK

Dr. Ruth A. Reck is a Staff Research Scientist in the Environmental Science Department at the General Motors Research Laboratories.

Dr. Reck received her B.A., *magna cum laude*, in chemistry and mathematics from Mankato State University, and holds a Ph.D. in physical chemistry from the University of Minnesota. Prior to joining General Motors in 1965, she was a Research Associate in the Applied Mathematics Department of Brown University.

Since 1985, Ruth has been a member of the U.S./Canada International Joint Commission Science Advisory Board, chairing, among other groups, the Atmospheric Indicators Task Force and the Atmospheric Deposition Section. She also serves on the National Science Foundation Review Board, Division of Polar Programs.

In 1988, Dr. Reck was honored by the Institute of Technology, University of Minnesota with its Outstanding Achievement Award for her work as an environmental scientist, scholar, and communicator.

SCIENTIFIC AMERICAN

September 1989 Volume 261 Number 3

DEPARTMENTS

THE ILLUSTRATIONS

Cover painting by George V. Kelvin

Page	Source
46	Steve McCurry, Magnum Photos, Inc.
48–54	George Retseck
59	Richard O. Bierregaard, Jr., Photo Researchers, Inc.
60–62	Hank Iken
63	Chester C. Langway, Jr., SUNY at Buffalo (*top*), Hank Iken (*bottom*)
66	Bruno Barbey, Magnum Photos, Inc.
68	Hank Iken
71	Gary Braasch
72–74	Hank Iken
75	Claude Lorius, Laboratory of Glaciology and Geophysics of the Environment
76–77	Jesse Simmons
78	V. Ramanathan, University of Chicago
81	Thase Daniel, Bruce Coleman Inc.
82	Hank Iken
84	Gabor Kiss
86	Ray Pfortner, Peter Arnold, Inc. (*top*), Jeff Foott, Bruce Coleman Inc. (*bottom*)
88	George Retseck
90	Ted Spiegel
94	United Nations
109–110	Gary Braasch
111–112	Patricia J. Wynne
114	*Landsat* images courtesy of Earth Observation Satellite Company, Lanham, Md.
116	Michael J. Balick, Peter Arnold, Inc. (*top left*), Michael J. Balick, New York Botanical Garden (*top right*), Mark Moffett (*bottom*)
118	Sebastiano Salgado, Jr., Magnum Photos, Inc.
120–124	Ian Worpole
125	Robert Caputo
126	Hill and Knowlton
129	*Landsat* images courtesy of Earth Observation Satellite Company, Lanham, Md.
130	Gabor Kiss
131	J. C. Tucker, National Aeronautics and Space Administration
132	Gabor Kiss
133	J. K. Aase, U.S. Department of Agriculture
134	World Bank (*bottom*)
137	Currey and Clark, St. Cloud, Minn.
138–139	Gabor Kiss
140	Paul Logsdon
141	Joe Lertola
142	Gabor Kiss
143	Chris J. Calwell, Natural Resources Defense Council
145	S. Varnedoe
146	Edward Bell (*bottom*)
146–147	Hank Iken (*top*)
148	Wellman, Inc.
149	George Bodenburgh, General Motors Corp.
150	Joe Lertola
151	Mark Sherman, Bruce Coleman Inc.
154	Co Rentmeester, The Image Bank
156	Johnny Johnson
157	Raghu Rai, Magnum Photos, Inc.
158–163	Ian Worpole
164	International Development Research Center, Ottawa
166–167	Warner Collection of the Gulf States Paper Corporation, Tuscaloosa, Ala.
168	George Retseck
169	Joe Lertola; data © by The New York Times Company
170	Joe Lertola
172	Joe Lertola (*top*), Scott Willis, *San Jose Mercury News*/Copley News Service (*bottom*)
174	Laurie Burnham
175	*Soviet Life*
176–177	Jearl Walker
178–179	Michael Goodman
180–181	Andrew Christie
182	Greg Turk, University of North Carolina at Chapel Hill
183	Andrew Christie

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SCIENTIFIC AMERICAN

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LETTERS

To the Editors:

"Lessons of *Sunraycer*," by Howard G. Wilson, Paul B. MacCready and Chester R. Kyle [SCIENTIFIC AMERICAN, March], not only is intriguing but also is scientifically accurate and devoid of hyperbole. The last two features are usually not characteristic of articles on electric vehicles addressed to the layperson.

A sentence on page 93 raises the possibility that electric cars as currently designed could have the batteries charged at "a large and expensive battery charger at a servicing location." This would be the equivalent of an "electric filling station," filling the batteries with electricity instead of a tank with gasoline. Some basic calculations indicate the remote probability of ever being able to pull into an electric service station, say "fill 'er up" and drive off 10 minutes later with a recharged battery set.

All data to date on technically successful electric automobiles indicate that about 30 kilowatt-hours must be stored in the battery for the vehicle to be driven an acceptable amount in daily use. Let us assume that the lessons of *Sunraycer* lead to improved designs, so that only 15 kilowatt-hours are required to "refuel" a battery in, say, six minutes. The charging rate would have to be 15,000 watt-hours in 0.1 hour (six minutes), or 150,000 watts. That is the amount of power that about 10 ordinary private homes would draw with their appliances going full blast—before the 100-ampere fuses or circuit breakers tripped, that is.

If we assume a battery voltage of 150 volts (rather hazardous, but I take this figure to make calculations simpler), then the charging current would have to be 1,000 amperes. Thus, the connector from the "battery service station" to the batteries would have to be a cable set approximately an inch and a half in diameter, and the connector to the car would weigh about 10 pounds and require a "gas tank cover" about six inches in diameter. There are many other problems associated with this concept of quick recharging, but we'll skip them.

The possibility that, instead of being recharged in the car, a dead battery could be quickly exchanged for a fresh one presents economic, technical and liability problems. For example, who is responsible for a faulty battery that may manifest itself after one has driven only 10 miles since the battery exchange? There are answers, but they are not simple.

VICTOR WOUK

U.S. Representative to the International Electrotechnical Committee on Electric and Hybrid Vehicles
New York City

Author's response:

The point we were making was that a modern electronic inverter, configured to return to the battery the rather considerable power that results when the motor is operated as a generator and used to brake the car, is actually a powerful battery charger. Most electric vehicles built to date have not had such on-board chargers and, therefore, have required "large and expensive" battery chargers at their servicing locations. Since the normal recharging time for electric vehicles is several hours, the power demand need not be high, and large cables and connectors are not required.

If an electric vehicle could obtain a fast "fill up" at the electric service station, the present concerns about vehicle range would become less important. At the moment, batteries suitable for electric-vehicle application could be recharged to half full in about 30 minutes, but new battery developments may significantly shorten that time. In either case, Dr. Wouk's comments would become most relevant. A very high power source would be required, and the recharging cable and connector would be massive. Perhaps the solution to the latter problem will come at some future time with the achievement of room-temperature superconductivity.

HOWARD G. WILSON

To the Editors:

It is very seldom that articles in *Scientific American* contribute to my understanding of Robert Service's poetry. Nevertheless, until I read "Absinthe," by Wilfred Niels Arnold [SCIENTIFIC AMERICAN, June], I had always imagined that when "... the stranger watered the green stuff in his glass, and the drops fell one by one ..." he was drinking such cheap booze that even its color was off. Further, it had never been clear to me why "They say that the stranger was crazed with 'hooch' ... " when he had only had the one drink before he shot Dan McGrew, but it is understandable if the stranger suffered from absinthism.

MICHAEL CLOVER

Los Alamos, New Mexico

To the Editors:

"Free-Electron Lasers," by Henry P. Freund and Robert K. Parker [SCIENTIFIC AMERICAN, April], fails to mention the seminal and elegantly successful radio-frequency linac free-electron laser R&D program at the Los Alamos National Laboratory. At this complete facility, designed specifically as an FEL, many firsts have been achieved, including records for output power, beam quality, tunability, energy recovery and quantitative measurements of the power amplification of the light beam itself (as opposed to the relatively easy-to-measure power decrease of the driving electron beam).

Research aimed at overall system requirements has resulted in integrated machines optimally directed toward specific objectives, including high-duty-factor and continuous-wave application. A particularly important development is a new photoemitter electron gun that provides an electron beam of unprecedented brightness (high intensity with simultaneous high quality). This now fully engineered injector is the enabling technology for a third-generation, compact FEL now being built as a prototype; this FEL will produce light at wavelengths of about .2 micron and longer, using a family of advanced wigglers, to meet the research requirements of universities, hospitals and other institutions. Other programs in progress include detailed design of a far-ultraviolet FEL intended to be a national research facility. The technology of the Los Alamos FEL is being taught to the Boeing Company as part of Los Alamos's technology-transfer program.

R. A. JAMESON

Accelerator Technology Division
Los Alamos National Laboratory
Los Alamos, New Mexico

Editor's note: The references to the Los Alamos FEL work were eliminated through editorial inadvertence. For a complete summary of the experimental record, see "A Review of Free-Electron Lasers," by C. W. Roberson and P. Sprangle, in Physics of Fluids B, *Vol. 1, pages 3–42; January, 1989.*

In 1917 Boeing built its first airplane, 200

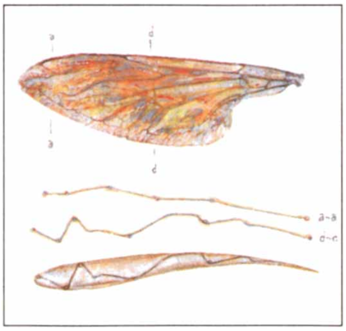
If you are an engineer or scientist, we'd like you to consider Boeing as a place to pursue your career. That's what this advertisement is all about. It's based on the belief that a good way to learn about a company is to meet the people who work there. To that end, we'd like to introduce Dr. John McMasters, a research aerodynamicist and one of some 20,000 engineers at Boeing. In his workaday world, he helps design Boeing jetliners. In his spare time, he's a self-proclaimed paleoaerodynamicist.

Ask Dr. John McMasters to define the proper field of study for an airplane designer and he'll say, "Everything that flies. All the time, professionally and avocationally."

That includes jetliners, certainly. And also insects, seeds, birds, bats, a certain reptile that executes aerial maneuvers of surprising grace and precision, hang gliders and boomerangs. Plus things that once flew, but don't now, such as pterosaurs.

Especially pterosaurs, in fact. They dominated flight for 120 million years and, reptiles or jets, all flying things encounter the same basic problems.

Sit back and ask McMasters to elaborate. It's a fascinating story.



The irregular surface and tubular structure of insect wings are an elegant solution to a very difficult flight problem.

You'll learn that 20 years ago, as a graduate student, he embarked on what he now describes as a ridiculously complex enterprise: the study of general locomotion.

"It was not the least bit modest," he says. "I envisioned a grand theory of optimal locomotion embracing the entire range of natural and man-made devices traveling through the air, on land, and in or on water."

His unified theory remains elusive, but the search has been hugely rewarding.

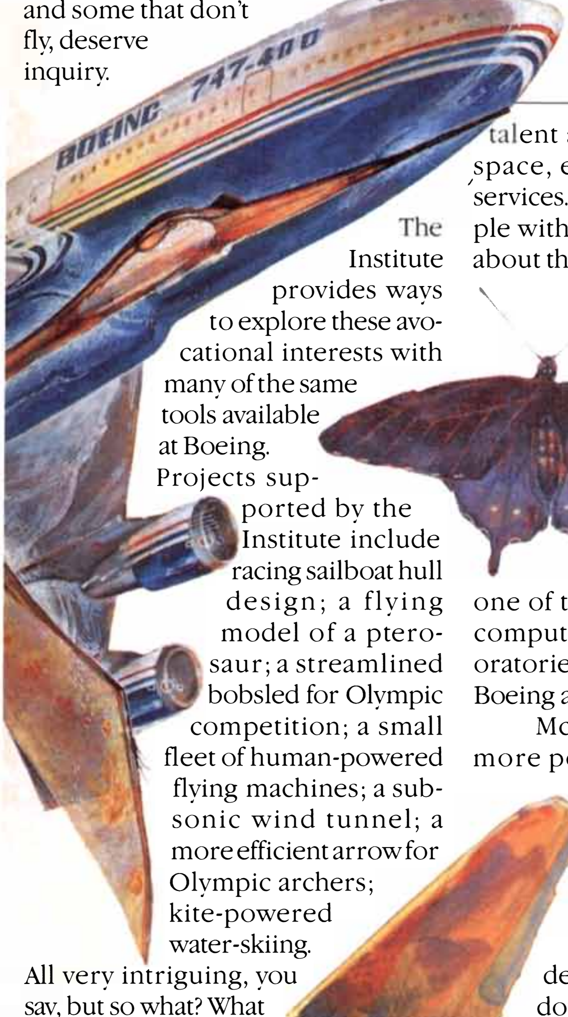
McMasters' investigations have included jumbo jets, bat wing architecture, the wing geometry of soaring birds, the

…million years after reptiles learned to fly.

complexities of flapping flight, and similarities between hang gliders and flying reptiles.

Along the way, he helped found the Flight Research Institute (FRI). Members, including many Boeing people, agree that all flying things, and some that don't fly, deserve inquiry.

The pinion feathers at the wing tips of large land-soaring birds are a natural model for winglets on the newest Boeing 747 jetliner.



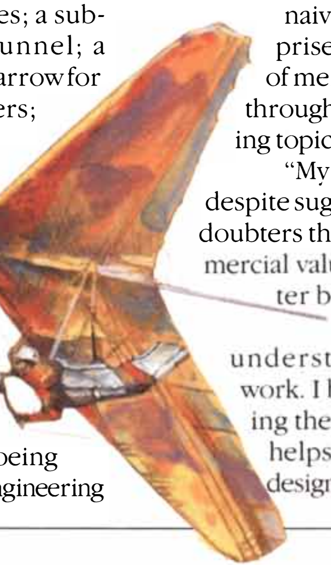
The Institute provides ways to explore these avocational interests with many of the same tools available at Boeing. Projects supported by the Institute include racing sailboat hull design; a flying model of a pterosaur; a streamlined bobsled for Olympic competition; a small fleet of human-powered flying machines; a subsonic wind tunnel; a more efficient arrow for Olympic archers; kite-powered water-skiing.

All very intriguing, you say, but so what? What difference does it make?

There are at least two answers. McMasters points out that Boeing needs the best scientific and engineering talent available in aviation, aerospace, electronics and computer services. The company looks for people with ideas and a lively curiosity about the world and its possibilities.

Boeing supports inventive minds in many ways, contributing to higher education, helping employees pursue advanced degrees, creating courses and institutes if necessary, including one of the world's most advanced computational fluid dynamics laboratories—one of the tools used by Boeing aerodynamicists.

McMasters' second answer is more personal: "What began as a naive but serious enterprise has become a sort of merry drunkard's walk through a range of fascinating topics.



"My inquiries continue, despite suggestions from some doubters that there's little commercial value in designing better butterflies, and thus no merit at all in understanding how they work. I believe understanding the principles of flight helps make one a better designer of devices that do have commercial value.

"Equally important, I believe it's periodically valuable to stand back from the details of a career to see a whole picture—to see one's work in full perspective.

"The effort can be immensely refreshing. And humbling."

If the idea of a career at Boeing interests you, send your curriculum vitae to Corporate Engineering, The Boeing Company, P.O. Box 3707-R86, Seattle, WA 98124.

If you have questions about the opportunities for scientific and engineering professionals, include a note specifying your area of interest, and a knowledgeable Boeing engineering representative will respond. We are an equal opportunity employer.

Dr. McMasters is a research aerodynamicist at Boeing Commercial Airplanes Division. He has taught at Purdue University and Arizona State University and has written 65 technical papers, reports and articles. He is preparing a book on the Biological Origins of the Aeroplane. McMasters is a graduate of the University of Colorado and Purdue.

BOEING

50 AND 100 YEARS AGO

SCIENTIFIC AMERICAN

SEPTEMBER, 1939: "Dr. A. E. Dunstan, British petroleum technologist, did not stretch facts beyond possibilities when he visualized the petroleum home of the future. Dr. Dunstan's dream house will have a roof of petroleum-base tile and walls of synthetic glass or hollow brick, while doors, partitions, windows and even furniture will be fashioned of some form or another of petroleum-extracted plastics. The people in these petroleum-created homes will even wear clothes whose origin will lie in petroleum."

"Any atom or molecule will emit light if it be struck a hard atomic blow, and all light originates from atoms that have thus been stimulated by heat or electricity. Since any material object—a star, a drop of blood, a speck of putty—is composed of atoms, any material object can be induced to emit light by heating it until it becomes an incandescent vapor. The light that is thus emitted carries inevitably in itself many secrets concerning the atoms from which it originated. It is the function of the spectroscope to analyze this light and thus lay bare these secrets for the eye of science to read."

"Early theories of the earth's magnetism were based on the assumption that the earth is a huge, permanently magnetized body. Such theories would no doubt be very successful if it were not for one serious obstacle. The interior of the earth is very hot, being at least several thousand degrees centigrade, and all permanently magnetized bodies lose their magnetism when they become hot. The only alternative, then, is to say that the earth is a huge electromagnet, not a permanent magnet, and that the magnetism is caused by enormous electric currents. One can conceive of the earth as a large ball of molten metal with a thick crust of solid material floating on top. It is in the molten metal that the electric currents flow."

"A mechanical secretary that takes dictation, writes letters that talk, answers the phone, records business deals and conferences, reads the boss to sleep and acts as watchman has been introduced. The machine, briefly, is a voice recording and reproducing unit as light and compact as a portable typewriter. It records 7,800 words (10 average-sized letters) on a collar of cellophanelike material that costs five cents and is so thin that three of them can be folded into an envelope and mailed for a three-cent stamp."

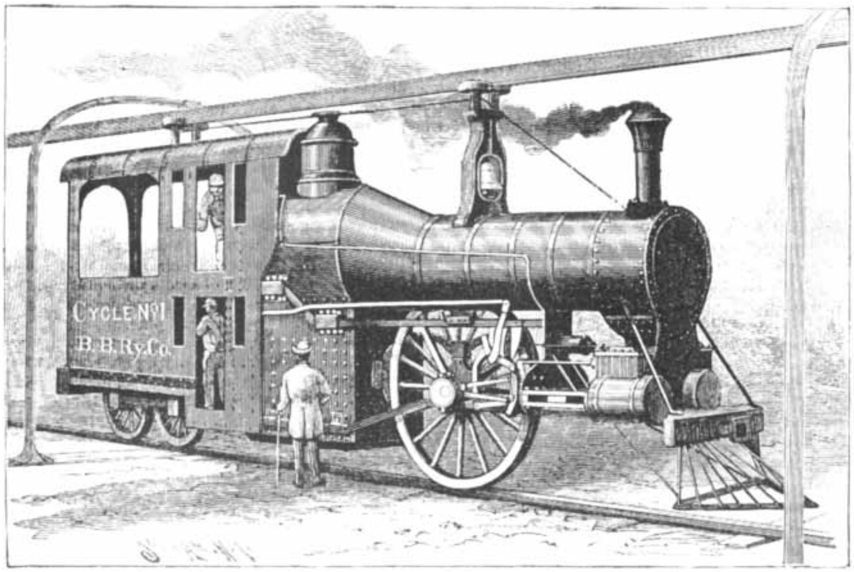
SCIENTIFIC AMERICAN

SEPTEMBER, 1889: "One of the latest novelties in the application of electricity consists of an electric reading lamp, which is being fitted to the carriages on the main line of the South-eastern Railway. The apparatus is situated immediately over the passenger's head; the light is obtained by the introduction of a penny at the top of the box and lasts for half an hour."

"At a recent meeting of the French Academy M. Lippmann presented a note by M. G. Gueroult, in which it is suggested that by the combined use of a phonograph and an apparatus for instantaneous photography and reproduction of the pictures obtained, it would be possible to reproduce at any future time not only the speech of a person but also a vivid picture of the person's gestures and facial expression. A person speaking or singing into the phonograph would be photographed by an automatic apparatus geared with the barrel of the phonograph. The pictures would be instantaneous, and taken at the rate of, say, ten pictures per second. They would then be developed and arranged in a special lantern for reproduction on a screen isochronously with the phonograph."

"In the spring a pier was built at Ocean Grove, on the Atlantic coast of New Jersey, having eight gates, each of which swings on a steel rod, so that the lower part of each gate is submerged about two feet at low tide and seven feet at high tide. At the top of each gate is attached a rod serving as an angle bar for the piston rod of a force pump, the force of each wave sufficing to effect a stroke of the piston, and the pump being used to elevate water from the ocean to tanks that are forty feet high. It is said that one day recently, when the surf was by no means high, 40,000 gallons of water were thus raised. The water is used for sprinkling the streets."

"The Boynton bicycle engine, suggesting a very radical change in railway construction, arrived in New York last week from Portland, Me., where it was built. It weighs twenty-two tons, and came on a truck attached to the rear of a regular train. The engine and train are to be kept on their single track by upper wooden guiding beams supported fifteen feet above the track by a bridge-like skeleton frame arching above the roadway. This form of construction is designed to reduce the weight of the cars, both passenger and freight, relative to the load carried, and to save power lost in rounding curves, it being intended to so balance the train that there will be but little strain on the top guiding rail."



The Boynton bicycle locomotive

You've waited years to buy a new car. Don't blow it now.

They haven't invented the disposable car yet, although they've come pretty close.

Until they do, the car you buy today is the one you're going to live with for quite a while.

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Look at it this way.

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shows that 95 percent have gone on to college.

And there's BIPED Corporation's Office Technologies program, which we also assist. It's helping disabled persons gain employment in information processing.

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We hope that you will join us in making a streetwise decision.

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SCIENCE AND THE CITIZEN

Greening the Summit

The environment arrives on the international political agenda

Even before it convened, July's summit conference in Paris of the Group of Seven major industrial democracies had been dubbed the "green summit." It met expectations. For the first time in the history of such gatherings, the final communique cited the "urgent need to safeguard the environment" as one of three main global economic challenges, together with sustained growth and integration of developing countries into the world economy. No less than 19 resolutions on environmental matters followed, ranging from expressions of concern about future climatic change to condemnation of indiscriminate ocean dumping. Green, it seems, is this year's color for the well-dressed statesperson.

"A healthy international competition for leadership on global environmental issues has emerged," observes J. Gustave Speth of the World Resources Institute in Washington, D.C., with evident satisfaction. West Germany spearheaded the move to give the environment a major role; only Japan, which does not have a strong environmentalist movement, seemed chary of boarding the bandwagon.

Although the summit communique seeks more research, it also calls for "decisive action" to protect the environment despite persisting uncertainties—a touchstone for environmentalists. The communique is careful, however, to acknowledge the need for assessment of the costs, benefits and resource implications, a drum beaten by the Global Climate Coalition, an organization of U.S. industries. The summit statement makes one specific commitment: to phase out chlorofluorocarbons by the end of the century, a measure that goes beyond the existing Montreal protocol. The communique also calls for controls on ozone-depleting chemicals not now covered by the protocol.

The Group of Seven leaders "strongly advocate common efforts to limit emissions of carbon dioxide" and other gases that climatologists fear could contribute to global warming. The favored mechanism for such controls is via a "framework or umbrella convention," which, the communique says, is

"urgently required." Such a convention, envisaged as a broad statement of principles and objectives, would be a first step toward specific protocols, to be negotiated later "as scientific evidence requires and permits."

Environmentalists had hoped for a bolder statement from Paris, one committed to a timetable. The many uncertainties surrounding global climatic change, however, together with the potentially huge cost of efforts to limit it, mean policy formulation has been contentious. In the U.S. the Office of Management and Budget, concerned about budget impacts, drew criticism earlier this year for altering the congressional testimony of a NASA scientist, James E. Hansen, who believes that greenhouse warming has already been detected. The changes appeared to be designed to weaken his conclusion, which many scientists doubt.

A convention is thought desirable because "unilateral action taken by one or more countries might create the perception that you're solving the problem," as William K. Reilly, administrator of the Environmental Protection Agency, put it recently. The Intergovernmental Panel on Climate Change is already laying plans for an agreement modeled along the lines of the Vienna convention on substances that deplete the ozone layer, the formal understanding that is implemented by the Montreal protocol. The panel is scheduled to complete an interim report in the fall of next year; a convention could follow. One early conclusion of panel members is that special efforts should be made to ensure that developing countries, which could quickly become large emitters of carbon dioxide, are full participants in the assessments.

Nevertheless, officials do not exclude voluntary efforts by members of the Group of Seven to limit greenhouse-gas emissions. Environmentalist groups that want rapid action point out that the Group of Seven produces 41 percent of global carbon dioxide emissions from fossil fuels; without leadership from the worst offenders, they say, the rest of the world is unlikely to follow. Moreover, they argue, some measures to reduce emissions, such as improving energy efficiencies, would bring economic benefits.

The rhetoric of the Paris summit communique is sufficiently stirring so that governments may now be put under some pressure to decide exactly what kinds of actions they might be prepared to take. But the Paris declaration marks the beginning of a history, not the end of one. *—Tim Beardsley*

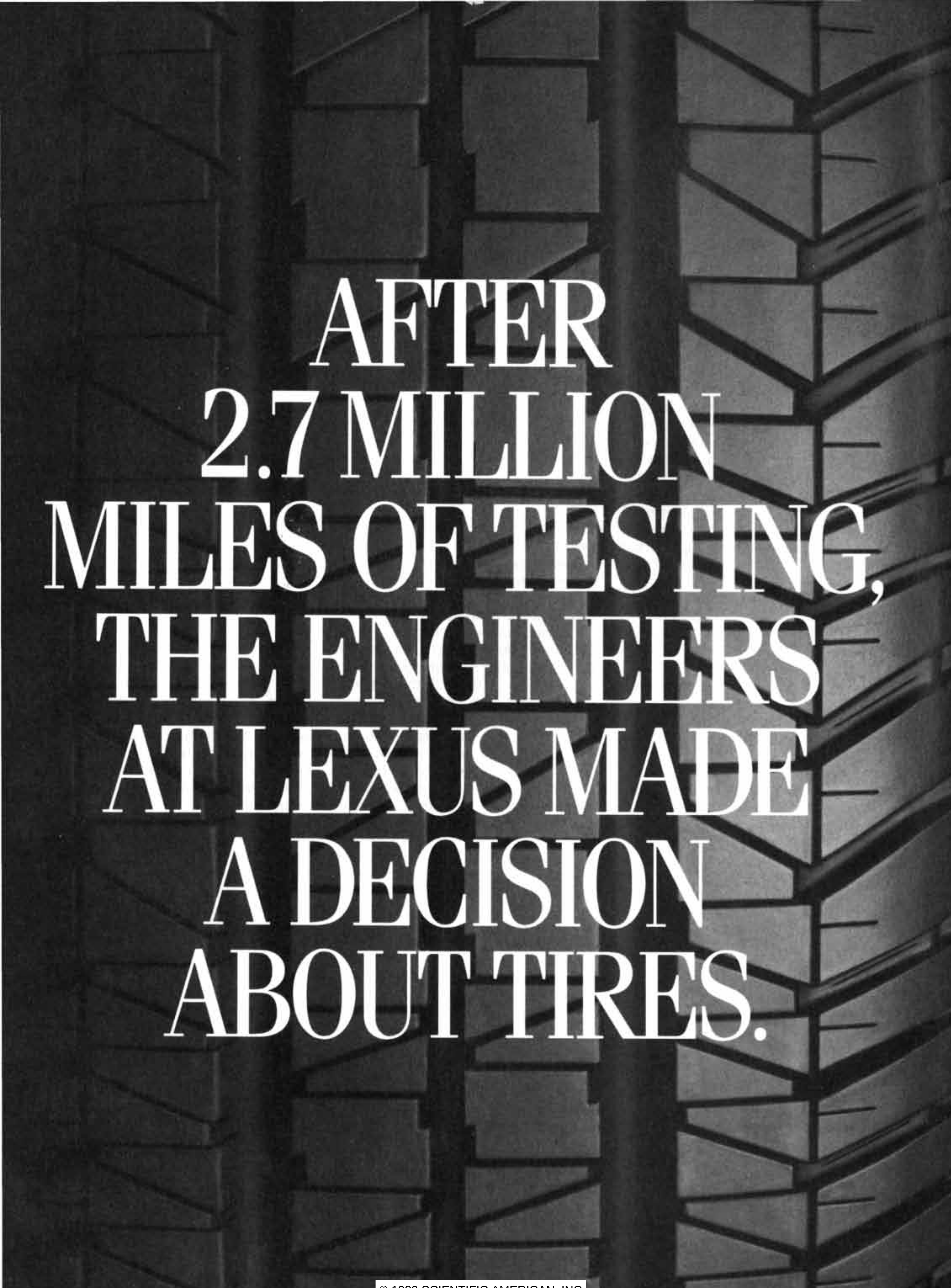
Intellectual Exports

Congress ponders limiting foreign access to research

On Capitol Hill a major justification for public support of university research is the argument that the results should enhance U.S. industrial competitiveness. Well then, some members of Congress want to know, why are universities selling American know-how to foreign companies?

The question is being put officially and heatedly. At a distinctly unfriendly hearing held earlier this summer, members of New York Congressman Ted Weiss's subcommittee on human resources and intergovernmental relations grilled the president of the Massachusetts Institute of Technology, Paul E. Gray, about M.I.T.'s industrial liaison program. Membership in the program costs 287 industrial corporations some $35,000 apiece each year. The fee entitles members to meet faculty experts, attend seminars and receive research reports months before publication. Weiss complained that M.I.T. faculty who receive extensive federal research support have held most of their liaison-program meetings with foreign companies, many of them Japanese. He was particularly incensed that the liaison program maintains an office in downtown Tokyo.

M.I.T. insists that Weiss's fears are unjustified. A spokeswoman says that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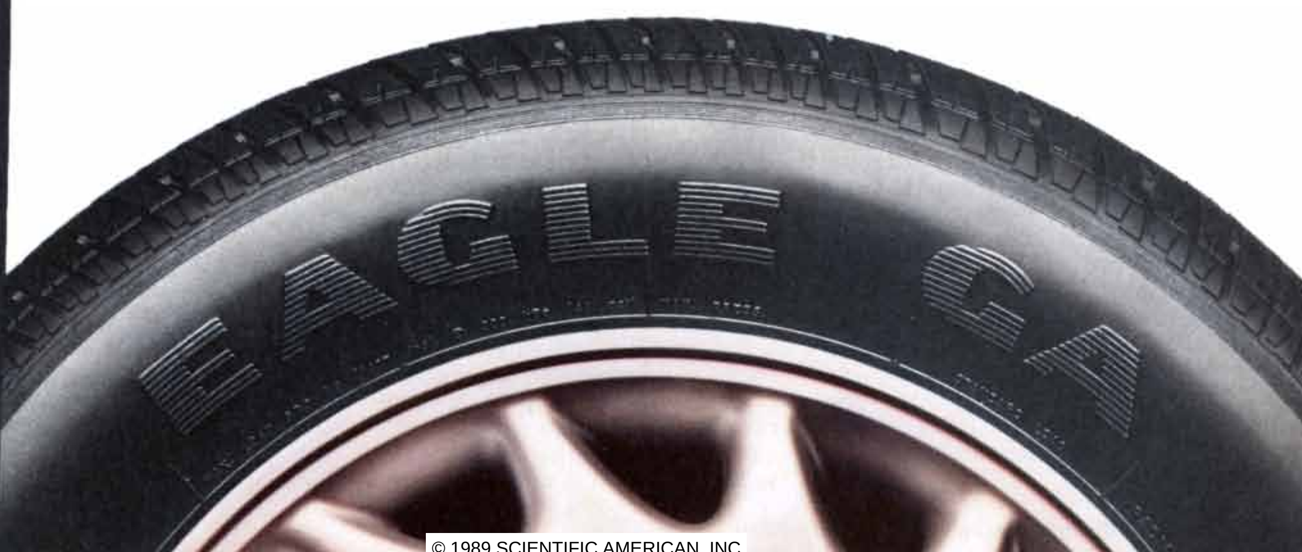

EAGLE GA

the university's technology-transfer activities as a whole actually benefit U.S. companies far more than others; the domestic companies depend on informal contacts with M.I.T. experts rather than on the liaison program. Gray told Weiss at the hearing that the program "does not provide exclusive access, privileged access or private access to results," since the research it covers is published in due course. "It does," he conceded, "provide facilitated access."

Richard J. Samuels, an M.I.T. professor who runs a program aimed at increasing U.S. awareness of Japanese research, argues that the best way to redress imbalances in technology transfer is to train U.S. students to "participate in science globally." U.S. institutions should, he says, try harder to ensure that their researchers have "a professional network that includes Japanese colleagues." Samuels's program will send 43 M.I.T. students trained in Japanese into Japanese research laboratories this year. Shutting foreigners out of universities "spirals off into reciprocal mutual destruction," Samuels maintains.

From the university standpoint such xenophobia is also bad business. Richard M. Cyert, president of Carnegie-Mellon University, says that "in the past we have tended to turn aside Japanese firms because in some of our areas we were trying to enable America to catch up." Cyert adds that the "extremely discouraging" lack of interest by U.S. companies has led him to a change of heart; he now welcomes approaches from Japanese companies. The California Institute of Technology and Stanford University similarly welcome foreign inquiries.

Whatever the perceived level of domestic interest, universities are likely to battle adamantly any attempt by a protectionist Congress to roll back what administrators and researchers regard as vital academic freedoms. Carol R. Scheman of the Association of American Universities protests that to limit access to basic research would be to make universities agents of foreign policy.

A congressional aide says, however, that several liaison programs like M.I.T.'s are under scrutiny; draft legislation "to ensure that federally sponsored research benefits primarily American companies" is a possibility. Political butterflies about competitiveness mean such a law could gather support. Whether U.S. corporations would drink from an exclusive research trough remains an open question. *—T.M.B.*

Chilling Out

Shades of Langmuir: a panel suspects cold fusion isn't so

As prospects for cold fusion cool, some elders of the physics tribe are recalling a talk given in 1953 by the late Irving Langmuir, the physicist and Nobel laureate who was associate director of the General Electric Company's research laboratories in Schenectady, N.Y.

Langmuir, speaking on "the science of things that aren't so," listed several features of such work:

1. The maximum effect is produced by a causative agent of barely detectable intensity.
2. The effect is of a magnitude that remains close to the limit of detectability.
3. The investigators claim great accuracy of measurement.
4. Fantastic theories are presented that contradict experience.
5. Criticisms are met by ad hoc explanations presented on the spur of the moment.
6. The ratio of supporters to critics rises to somewhere near 50 percent and then falls gradually to oblivion.

The spirit of Langmuir's remarks seems to suffuse an interim report on cold fusion issued in July by a 22-member panel established by the Energy Research Advisory Board.

The unusual heat effects that some investigators have reported when heavy water is electrolyzed with a palladium cathode are for the most part small, the panel observes, and the measurements are difficult. None of the results the panel saw were "sufficiently free of ambiguities and calibration problems to make us confident that the steady production of excess heat has been observed." The panel concluded that "experiments reported to date do not present convincing evidence that useful sources of energy will result from the phenomena attributed to cold fusion."

Although panel members visited several laboratories where anomalous heat effects have been claimed, the visitors were never able to see an experiment actually producing excess heat; instead a variety of excuses were offered, according to John R. Huizenga of the University of Rochester, one of the panel's co-chairmen.

The panel's report notes some unresolved issues. In particular, "bursts" of heat reported by some laboratories are currently "not understood," and some experiments are reported to have detected unusually high levels of tritium—a possible fusion by-product. The panel recommends that the Department of Energy fund "at a modest level" cooperative experiments aimed at resolving such contradictory claims, adding that "no special programs . . . are justified at the present time."

That is bad news for the University of Utah, where the original claim of power generation by cold fusion was first announced by Utah's B. Stanley Pons and his collaborator, Martin Fleischmann of the University of Southampton in the U.K. The University of Utah had petitioned Congress for funds to support a cold-fusion research center.

Might cold fusion, as some workers maintain, occur at very low levels—levels too low to produce measurable heat? The panel said the evidence—emission of neutrons at a low rate—is "not persuasive." Again, it urged collaborative experiments.

"The fact that so much of the evidence is contradictory makes it hard to come up with a final conclusion," Huizenga observes. It seems possible, however, that the panel's final report, to be presented in the fall, will be the epitaph of cold-fusion power.

As for Langmuir, the legendary experimentalist may be turning in his grave. G.E. is the one major corporation to have signed a collaboration agreement with the University of Utah. So far, a company spokesman says, it has seen no evidence for energy from cold fusion. *—T.M.B.*

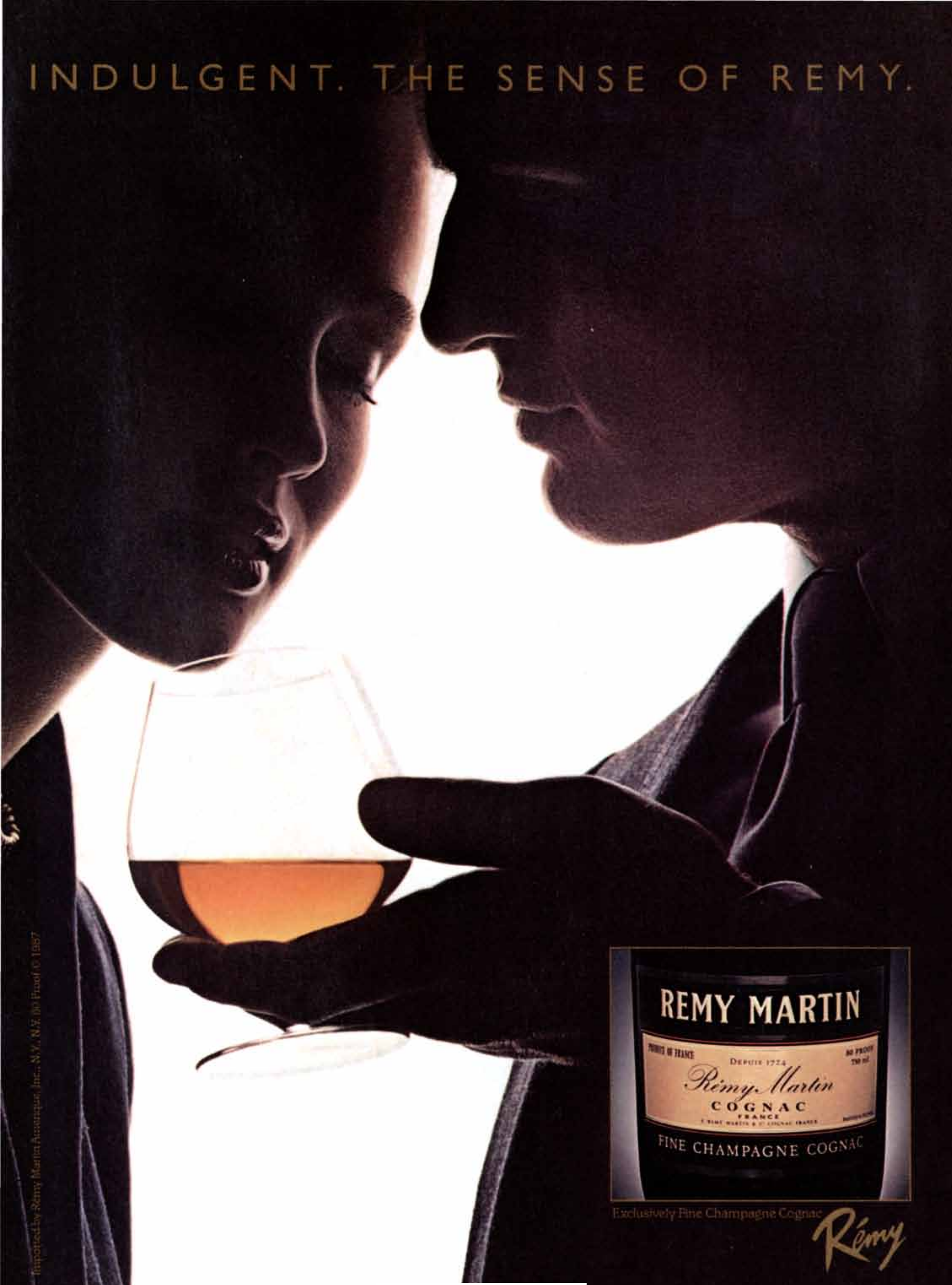
PHYSICAL SCIENCES

Hot Spot

Computers re-create weather of an ancient supercontinent

Continents come and continents go. Some 300 million years before the present, the earth's landmasses fused into a single vast island called Pangaea. The supercontinent lasted for about 100 million years before breaking up.

What was the weather like in Pangaea? The question is important because the formation of Pangaea during the Paleozoic era marked a major turning point in the evolution of life, during which reptiles emerged as a dominant species. Many paleontologists have assumed that the Pangaean climate was "equable," fairly warm throughout the year. That picture does not withstand computer simula-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tion. According to recent reports by two groups of climatologists, much of the supercontinent was a desert whose temperatures fluctuated wildly over the course of a year.

Thomas J. Crowley of the Applied Research Corporation, William T. Hyde of Texas A&M University and David A. Short of NASA's Goddard Space Flight Center have performed simulations focusing on Pangaea's temperature. They report in *Geology* that in the supercontinent's interior—and particularly in the vast southern region called Gondwanaland—the maximum annual range of temperatures was some 20 percent greater than on any modern continent. Summers were as much as 10 degrees Celsius (18 degrees Fahrenheit) warmer than they are anywhere today; in winter, temperatures in the same region frequently dropped well below freezing.

In explaining the results, Crowley compares a continent to a piece of sheet metal, which heats up quickly when exposed to heat and cools just as quickly when the heat source is removed. As the landmass becomes larger and its interior is farther removed from the buffering effects of the ocean, the fluctuations in temperature become greater. Gondwanaland alone, Crowley remarks, was about 40 percent larger than the entire Eurasian landmass.

The temperature calculations of Crowley and his colleagues agree with an earlier report in the *Journal of Geophysical Research* by John E. Kutzbach and Robert G. Gallimore of the University of Wisconsin at Madison. The Wisconsin team also found that the interior of Pangaea would have been quite arid—and perhaps utterly without water. "All the moisture from the coasts gets wrung out as you go inland," Kutzbach explains.

The transformation by continental fusion of vast regions of land into deserts, where summers were blistering and winters frigid, might have contributed to the widespread extinction of land-based species during the late Paleozoic, Crowley says. The climate studies also suggest why reptiles, which adapt readily to hot, dry climates, replaced amphibians as the dominant vertebrate species during this period. —*John Horgan*

The Impact Giveth...

Did cosmic collisions help create life as well as destroying it?

For almost a decade scientists have debated whether the collision of extraterrestrial objects with the earth triggered the widespread extinction of species observed at several points in the fossil record. The most dramatic mass extinction—and the one spurring the most debate—occurred 65 million years ago at the cusp of the Cretaceous and Tertiary periods; nearly half of all species, including the last of the dinosaurs, vanished then. A report in *Nature* by Meixun Zhao and Jeffrey L. Bada of the Scripps Institution of Oceanography at the University of California, San Diego, provides new evidence that an extraterrestrial object triggered the mass extinction.

To date, the most compelling piece of evidence supporting the impact theory has been a thin layer of clay laid down at the Cretaceous-Tertiary (K-T) boundary. The clay is rich in iridium, an element that occurs rarely in the earth's crust but commonly in meteorites; the layer also contains quartz crystals that seem to have been striated by an enormous shock. Critics of the impact theory have maintained, however, that volcanic eruptions might have spewed iridium-rich matter up from the earth's mantle; vulcanism, they say, could also account for the shocked quartz.

Hoping to settle the issue of vulcanism versus impact, Zhao and Bada decided to search K-T boundary sediments for unusual organic compounds that, like iridium, are generally found only in the remnants of meteorites. No organic compounds can survive the tremendous heat of vulcanism, so that cause could be totally ruled out. The heat generated by a very large object slamming into the earth could also have destroyed organic compounds contained in the object, but Zhao and Bada hoped that detectable traces might have survived the cataclysm.

They analyzed samples of K-T sediments taken from a site in Denmark called the Stevns Klint. Sure enough, they found two amino acids—aminoisobutyric acid (AIB) and isovaline—that are virtually unknown in nature but have been detected in carbonaceous chondrites, a class of meteorites also known to contain iridium. Oddly, the AIB and isovaline occurred not inside the iridium-rich clay itself but in the carbonate sediments immediately above and below it. The workers think they can explain this puzzle: the AIB and isovaline may have diffused out of the clay, to which they bind poorly, and lodged in the carbonate sediments, to which they have a greater chemical affinity.

Another, more surprising finding was that AIB and isovaline were present in unusually copious amounts. The ratio of the amino acids to the iridium at the Stevns Klint site was some five times greater than had been observed in the remnants of carbonaceous chondrites. This finding suggests the object that struck at the K-T boundary was exceptionally rich in amino acids—a previously unidentified type of meteorite or, perhaps, a comet, according to Zhao and Bada.

Temperatures in the interior of southern Pangaea fluctuated wildly from season to season

ANNUAL TEMPERATURE RANGES (in degrees Celsius) in Pangaea some 255 million years ago were calculated in a computerized climate model developed by Thomas J. Crowley, William T. Hyde and David A. Short. The ranges are based not on absolute daily highs and lows but on monthly averages.

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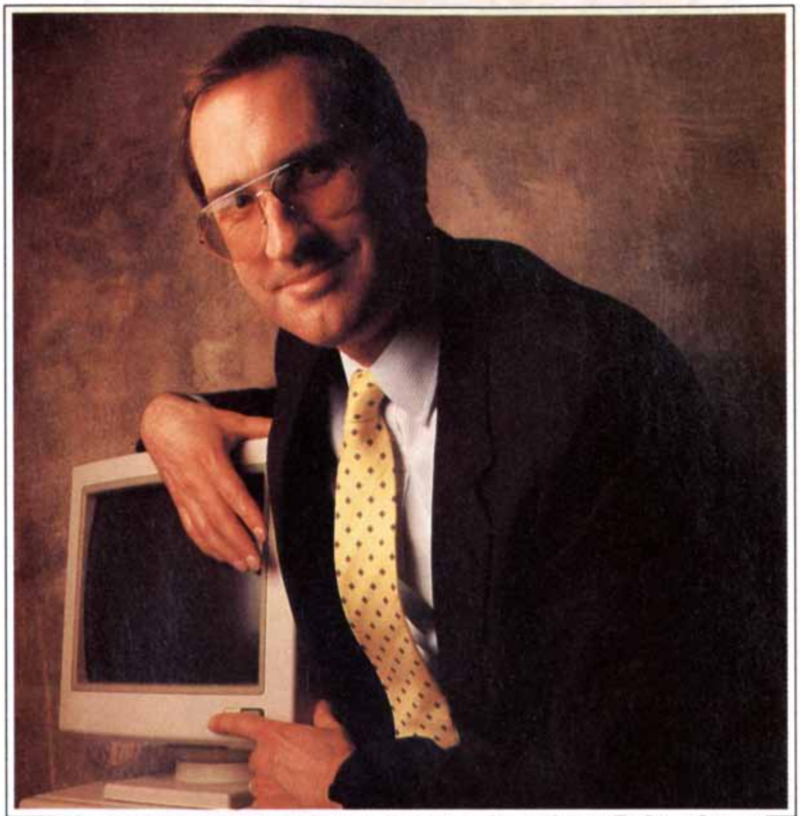

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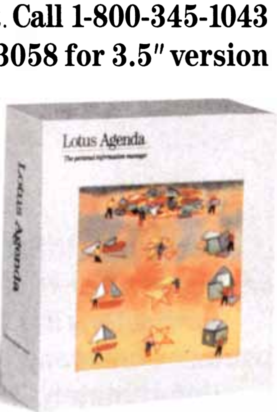

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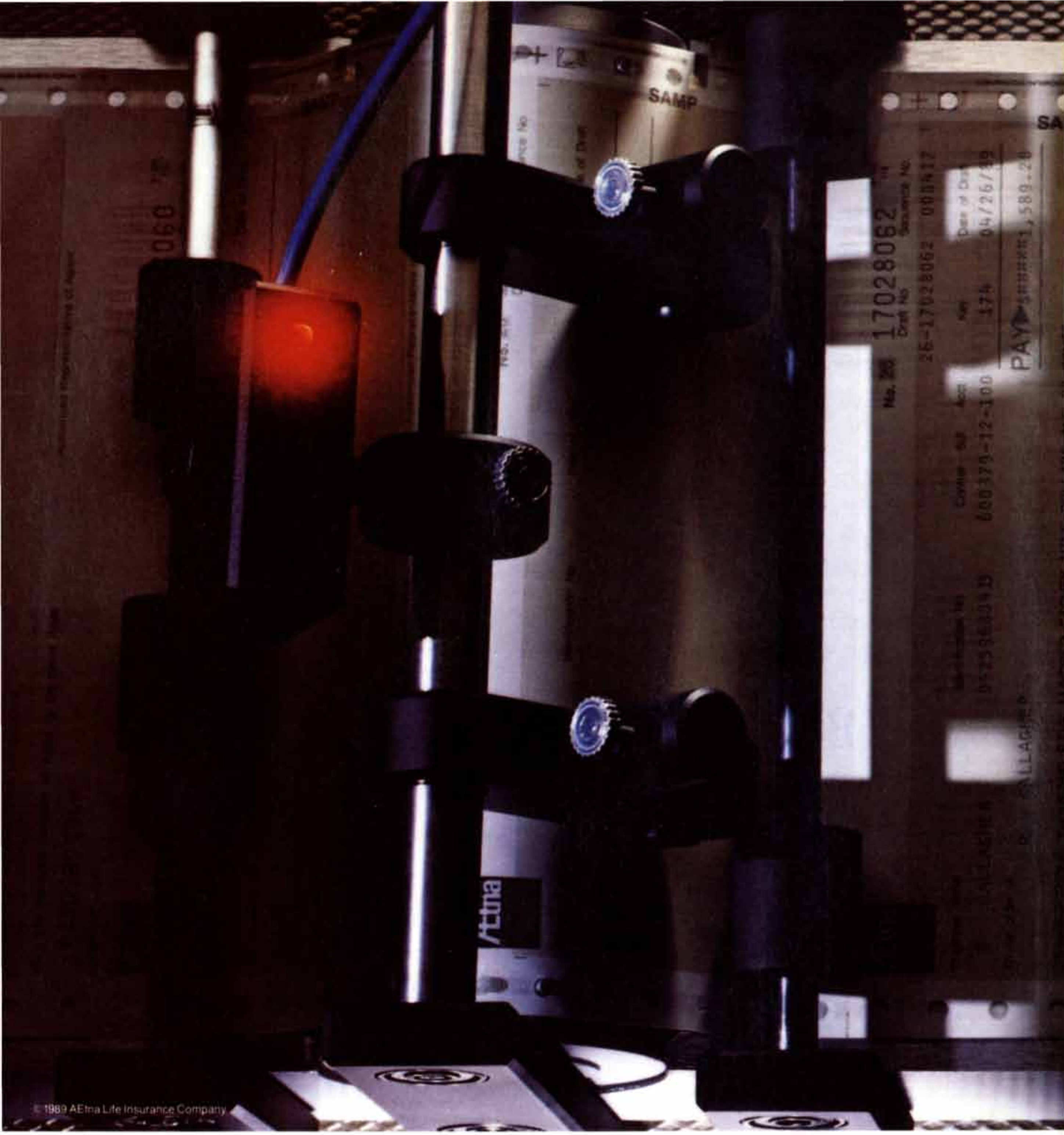

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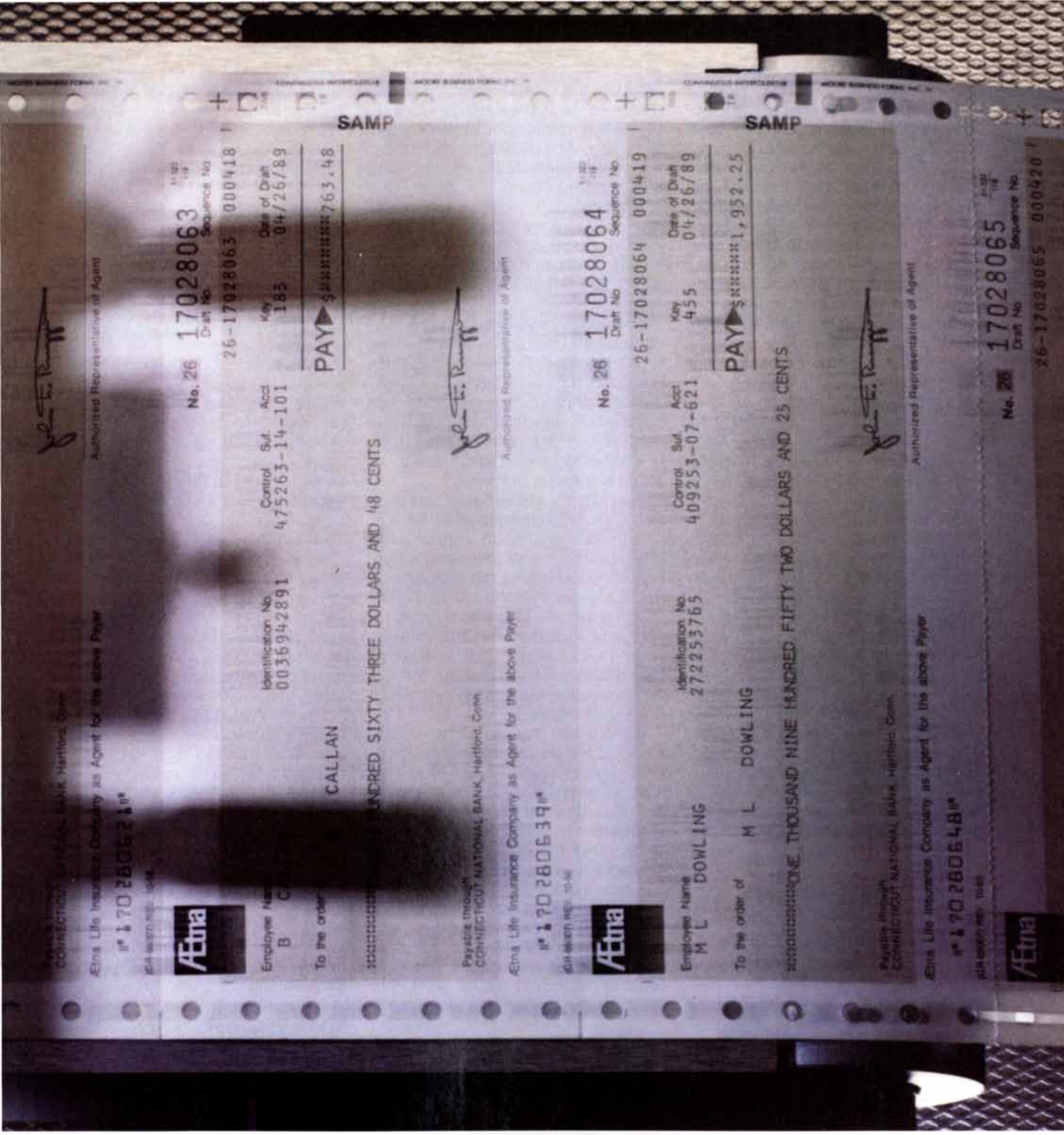

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Although there is no direct evidence that comets contain amino acids, observations of Halley's comet in 1986 revealed organic precursors.

The abundance of AIB and isovaline also implies that complex organic molecules—and amino acids in particular—can survive a large impact event far more readily than had been thought. Zhao and Bada hope to test this hypothesis in laboratory experiments. They also plan to examine K-T sediments from other sites for signs of AIB and isovaline. "We want to prove this is a global and not just a local phenomenon," Zhao says.

If confirmed, the findings of Zhao and Bada would give new weight to an old idea: that cosmic collisions brought life as well as death to the earth's surface. Billions of years ago, when life began, impacts occurred much more frequently: the earth's atmosphere was thinner and the amount of debris in the solar system was greater than during later periods. Nevertheless, most scientists have assumed that the chemical seeds of life somehow arose from the earth's primordial soup and that impacts, at best, contributed only a few raw materials to the process. Now it appears that impacts could have been a major source not only of simple organic molecules but also of full-fledged amino acids, one step away from proteins. Commenting on this notion, Carl Sagan of Cornell University intones: "The impact giveth, and it taketh away." —*J.H.*

Brown Dwarfs Here...

Brown dwarfs there... maybe. But are they everywhere?

Over the years astronomers have spotted many of the theoretical curiosities known as brown dwarfs: stars supposedly too light to undergo thermonuclear burning. Unfortunately, some of them have vanished under closer scrutiny; others have hung on in a kind of limbo, neither confirmed nor wholly rejected. Now a group headed by William J. Forrest of the University of Rochester claims to have found the best evidence yet that brown dwarfs exist, possibly in vast numbers.

The finding grew out of a simple assumption by Forrest: a brown dwarf should be at its brightest just after it has formed, while the heat generated by gravitational contraction is at a maximum. After that, the dwarf grows ever dimmer and harder to detect.

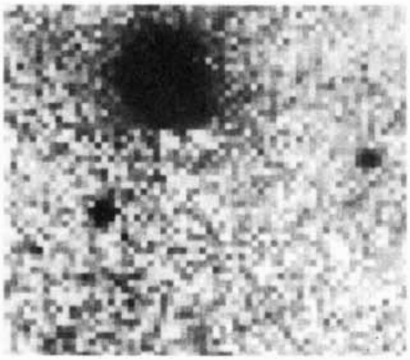
With this in mind, Forrest decided to search for brown dwarfs in the Taurus-Auriga complex, a section of the Milky Way about 450 light-years away. The complex is a stellar nursery; stars there are only about a million years old, on average. (The sun, by comparison, is more than four billion years old.) If Taurus-Auriga contained brown dwarfs that young, Forrest reasoned, they should be bright enough to detect.

The strategy apparently worked. Using an infrared camera mounted on NASA's Infrared Telescope in Hawaii, Forrest's team detected nine objects that had the putative characteristics of brown dwarfs: low luminosity and reddish hue. But were these actually dim objects in Taurus-Auriga or brighter ones far beyond it?

One way to answer that question would be to determine whether the objects had moved in concert with other Taurus-Auriga stars over a long period. On checking photographs of the region made in the 1950's, Burton F. Jones of the Lick Observatory in California identified six of the objects observed by Forrest's group; of these, four demonstrated the same "proper motion" as the other stars in the Taurus-Auriga complex.

These four objects, Forrest says, are solid candidates for brown dwarfhood. Just to be sure, he plans to analyze the objects' spectrums to establish that they match the spectrums predicted for brown dwarfs and not some other object: an ordinary star obscured by dust, perhaps.

Forrest's finding may have cosmic implications. If brown dwarfs are as abundant in the entire Milky Way—and in other galaxies—as they seem to be in the Taurus-Auriga region, they could account for a major portion of the "missing mass" that astrophysicists have been searching for lo these many years. —*J.H.*



TWO BROWN DWARF candidates gleam dimly near an ordinary star in the Taurus-Auriga complex in an infrared photograph by William J. Forrest.

BIOLOGICAL SCIENCES

In the Beginning

Evidence grows that RNA was the first self-made molecule

Molecular biologists concerned with the origin of life have always had their own version of the chicken-and-the-egg problem: Which came first, nucleic acids or proteins? Which, in other words, was the original self-replicating molecule? Proteins have many structural and catalytic talents, but they lack the genetic information for their own assembly; that information is held in the nucleic acids DNA and RNA. Single-strand nucleic acid molecules do act as templates for copying themselves, but they cannot finish the job without the protein enzymes, called polymerases, that link nucleotide bases into chains. The latest discoveries about the catalytic powers of some nucleic acids support the idea that the first self-replicating molecule was RNA—or something much like it.

In 1981 Thomas R. Cech and his colleagues at the University of Colorado at Boulder took an important step down this evidentiary trail: for the first time, they saw pieces of RNA snip themselves out of longer chains and splice together the severed ends of the sequences that had bordered them [see "RNA as an Enzyme," by Thomas R. Cech; SCIENTIFIC AMERICAN, November, 1986]. Such enzymelike behavior opened up new possibilities. Because this catalytic RNA, or ribozyme, could splice bits of genes, perhaps other ribozymes could act as polymerases and link nucleotides during gene replication.

Several classes of ribozymes have been discovered since then, and yet none has been able to act as a polymerase. The ribozymes normally act on themselves, cutting or splicing at specific sites along an "internal template." As Cech and others have shown, ribozymes act on other RNA molecules only in the laboratory and then only if those molecules share the ribozymes' template sequences.

Moreover, ribozymes are much pickier about the nucleotide bases they will splice together than polymerases are. For example, in the case of the ribozyme isolated from the protozoan *Tetrahymena thermophila* by Cech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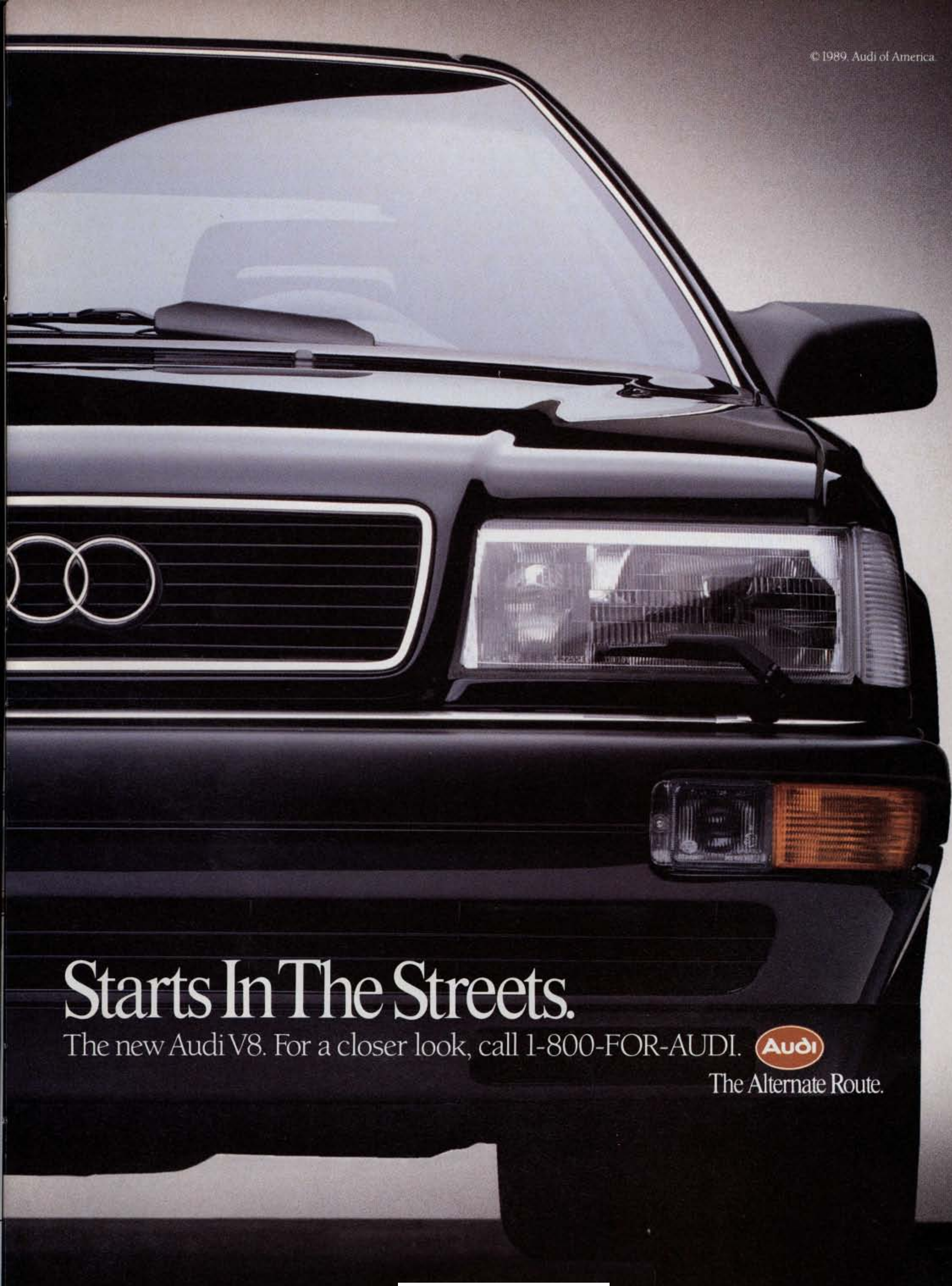
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and his colleagues, a strand to be spliced must terminate with the base uridine, and its corresponding base on the internal template must be the base guanosine; the two bases interact weakly to form what molecular biologists call a "wobble" base pair. These restrictions appeared to make ribozymes too selective to function as general polymerases.

An artificial ribozyme recently created by Jennifer A. Doudna and Jack W. Szostak of the Massachusetts General Hospital in Boston has overcome both of these limitations. Working with the *Tetrahymena* ribozyme, they were able to distinguish its catalytic center from the nearby internal template. They then modified the molecule so that these sections were separated, which freed the ribozyme to act on various external RNA templates.

Doudna and Szostak also reasoned that the ribozyme's base-pair selectivity resulted from an affinity for the distinctive geometry of wobble base pairs. They hoped to fool the ribozyme by making other base pairs look like wobble pairs. This sleight of hand, for reasons not yet fully understood, turned out to require the addition of spermidine, a small positively charged organic molecule. With spermidine in the reaction mixture, the modified ribozyme was able to splice RNA strands without restrictions.

No one is claiming that Doudna and Szostak's modified ribozyme is anything like the original self-replicating molecule of life. The modified ribozyme can stitch together preassembled strands of RNA along an external template, but it does not work well at adding individual bases to a growing chain. Nonetheless, by showing that ribozymes are capable of more of the necessary behaviors, Doudna and Szostak have significantly strengthened the case for RNA. *—John Rennie*

Short-Answer Question

A defective receptor may cause pygmies to be short

Why are pygmies short? One might assume that their reduced stature is due to a lack of growth hormone, the pituitary hormone that stimulates growth in adolescence. That speculation would be false, however, since pygmies are known to have normal levels of growth hormone. Recent work by Gerhard Baumann of Northwestern University Medical School and his co-workers points to a different culprit: the cellular receptor whose interaction with growth hormone gives rise to the hormone's effects.

Baumann, with Melissa A. Shaw and Thomas J. Merimee, analyzed blood samples from 20 pygmies of various ages living in the Ituri Forest region of Zaire. Seven white Americans and five black Africans of normal height served as control subjects. The heights of the adult pygmies in the study's sample ranged from 132 to 146 centimeters (4 feet 4 inches to 4 feet 9 inches).

The 32 blood samples were analyzed for the activity of high-affinity growth hormone binding protein. This binding protein, discovered by Baumann's group in 1986, is known to have the same amino acid sequence as the extracellular part of the growth-hormone receptor. (The receptor is a transmembrane protein, having a portion inside the cell, a portion extending through the surface membrane and a portion outside the cell.) Indeed, the binding protein may arise by the splitting off of the extracellular part of the receptor. Once in the blood, it forms complexes (of unknown function) with growth hormone.

Baumann and his co-workers found that the pygmies in their sample had only about 50 percent as much binding protein as the controls. Because the binding protein is a portion of the growth-hormone receptor, low levels of binding protein might reflect a correspondingly low level of growth-hormone receptors, which might in turn be responsible for the pygmies' diminished stature.

The full answer, however, is likely to be more complex than simply a reduction in receptor number. Even a 50 percent reduction in the total number of receptors should be easily overcome by injections of exogenous growth hormone. Yet pygmies are known to be resistant even to large doses of growth hormone. Pygmies may have defects in the function of growth-hormone receptors as well as in the total number and also abnormalities unrelated to the receptors, Baumann said recently.

Furthermore, it has not been proved that the binding protein does in fact arise directly from the receptor molecule by cleavage. It may be synthesized and released along a separate secretory pathway. Further work is now under way to explain the function of the binding protein and to tease out its relations with growth hormone and the growth-hormone receptor. Such work, Baumann says, could ultimately have significant clinical implications for those afflicted by forms of dwarfism resulting from defects in the receptor for growth hormone. *—John Benditt*

Jeepers, Creepers

Mantis shrimp's peepers rely on 10 (!) types of photoreceptor

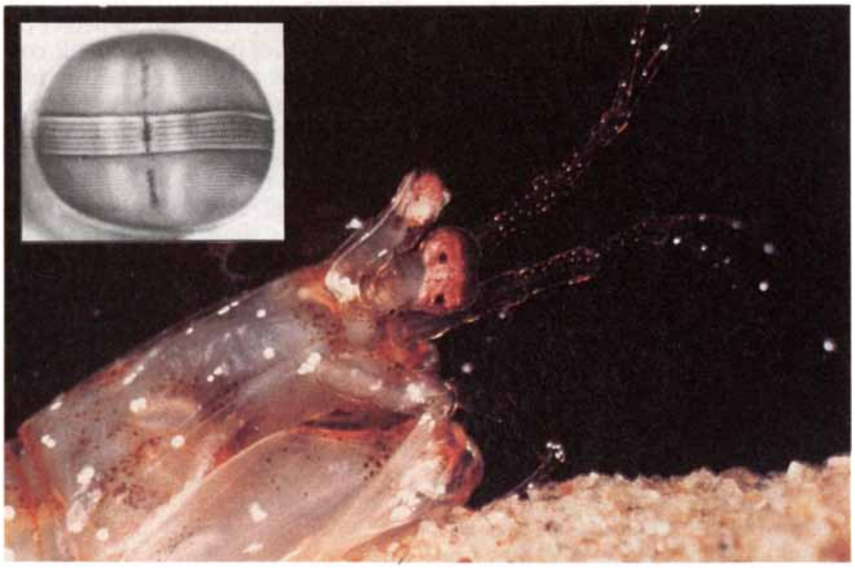
The human eye perceives color through a system based on three visual pigments. Although it is efficient, the arrangement is not the only one possible. Certain flies and fishes, for example, rely on five pigments; until recently, they were thought to hold the record. According to a report in *Nature,* however, the eyes of certain species of mantis shrimp contain 10 visual pigments and perhaps more—a new record.

The eye of the mantis shrimp consists of a large number of visual elements called ommatidia. Most of the ommatidia, like those in a fly's eye, form a simple hexagonal lattice on a hemispheric surface. In the mantis-shrimp eye, however, a horizontal band of six parallel rows of ommatidia divides the surface.

The ommatidia in the regions above and below the horizontal band probably all contain the same visual pigment and are all sensitive to the same wavelength of light. The largest number of pigments, as described in *Nature,* reside in four of the six horizontal bands. (The other two bands, which are apparently designed to detect the polarization of the incoming light, contain just one pigment each.) The four bands are each made up of two tiers of photoreceptors: each ommatidium in these bands is split into two parts, and the photoreceptor cells in each part contain a different pigment which responds to a different range of wavelengths. Two of the bands contain colored filters, so that only the wavelengths of light to which the pigment is highly sensitive can pass through. That may keep the photoreceptor cells from responding even to very strong signals in other wavelengths. Separate filters cover cells in the inner and outer tiers. In addition, the outer tier of photoreceptor cells acts as a filter for the inner tier.

Why would a shrimp need to distinguish colors so well? The authors of the report, Thomas W. Cronin of the University of Maryland and N. Justin Marshall of the University of Sussex, suggest that color discrimination could be important in recognizing other shrimp. For example, the mantis shrimp is equipped with armlike ap-

Only three millimeters wide, the mantis-shrimp eye contains a record number of visual pigments



MANTIS-SHRIMP EYE* (inset) *consists of visual elements called ommatidia laid out in a hexagonal lattice. The eye contains at least 10 types of visual pigments, most of which are found in four of the six bands of ommatidia bisecting the eye. The three black spots, called pseudopupils, represent regions where the ommatidia are directly facing the camera and are absorbing more light.

pendages that are used in combat with other shrimp. Inside the "elbow" of each appendage the shrimp bears distinctively colored markings. When two shrimp are about to fight, they show each other the insides of their elbows. Being able to distinguish colors well could keep a shrimp from taking on the wrong opponent. *—Ari W. Epstein*

TECHNOLOGY

No Slick Fix

Oil-spill research is suddenly back in favor

The three oil spills that fouled U.S. waters during one June weekend have combined with the *Exxon Valdez* spill in March to throw a stark light on how far support for research into cleanup techniques has declined. "Oil pollution has received a low ranking compared with other threats," observes Richard S. Golob of World Information Systems, publisher of *Oil Spill Intelligence Report.* "It has been regarded as a problem that has been solved." Golob points, for example, to the Environmental Protection Agency's decision to close down its spill-cleanup test facility in New Jersey earlier this year. The research budget of the Coast Guard, which developed the oil-skimming weir in the early 1980's, fell from $6 million in 1980 to $300,000 this year. The American Petroleum Institute spent $600,000 a year on cleanup research in the early 1980's but a mere $100,000 a year between 1985 and 1988.

That trend might be about to go into fast reverse. In the wake of the Alaska spill, API has proposed that the oil industry create a new organization, the Petroleum Industry Response Organization, that would be given $250 million in its first five years to establish five U.S. regional spill-response centers. The budget would include from $30 to $35 million for research.

"Prevention must continue to be the first line of defense," says Stuart Horn of Mobil Oil Corporation, who worked on the API plan. One way to reduce the frequency of accidents would be to use double-hulled tankers, an expensive option now under study by the National Research Council.

The emphasis must remain on prevention, Horn explains, because containment methods are often ineffective in the open ocean. Booms, or floating fences, cannot contain a spill when waves are more than a few feet high or when currents exceed .7 knot. Skimming devices are also ineffective in a strong swell or when the oil is viscous or has weathered to a "mousse," a water-oil emulsion. Dispersants, in contrast, which break oil up into small globules that are more easily consumed by microorganisms, need good wave action. The National Research Council has blessed the use of modern dispersants, although regulatory authorities are still reluctant to sanction them. API's assessment suggests such chemicals still need improvement.

New concepts that deserve study, according to API, include absorbent powders, chemical coatings to make shorelines repel oil, and chemicals to thicken and immobilize oil. It has been proposed that tankers carry gels that in an accident would be mixed with the cargo to halt spreading. Yet the time and energy needed to mix cargo and gel seem likely to limit the idea's application. The National Institute of Standards and Technology is even investigating burning off major spills.

Biology offers another solution. Alfred W. Lindsey of the Environmental Protection Agency reported to Congress that experiments in Alaska in which oil-eating bacteria were sprayed onto polluted beaches achieved some initial success. API targets such "bioremediation" for the biggest single research effort. It remains to be seen whether bioremediation can in fact improve on nature's own rates of biodegradation.

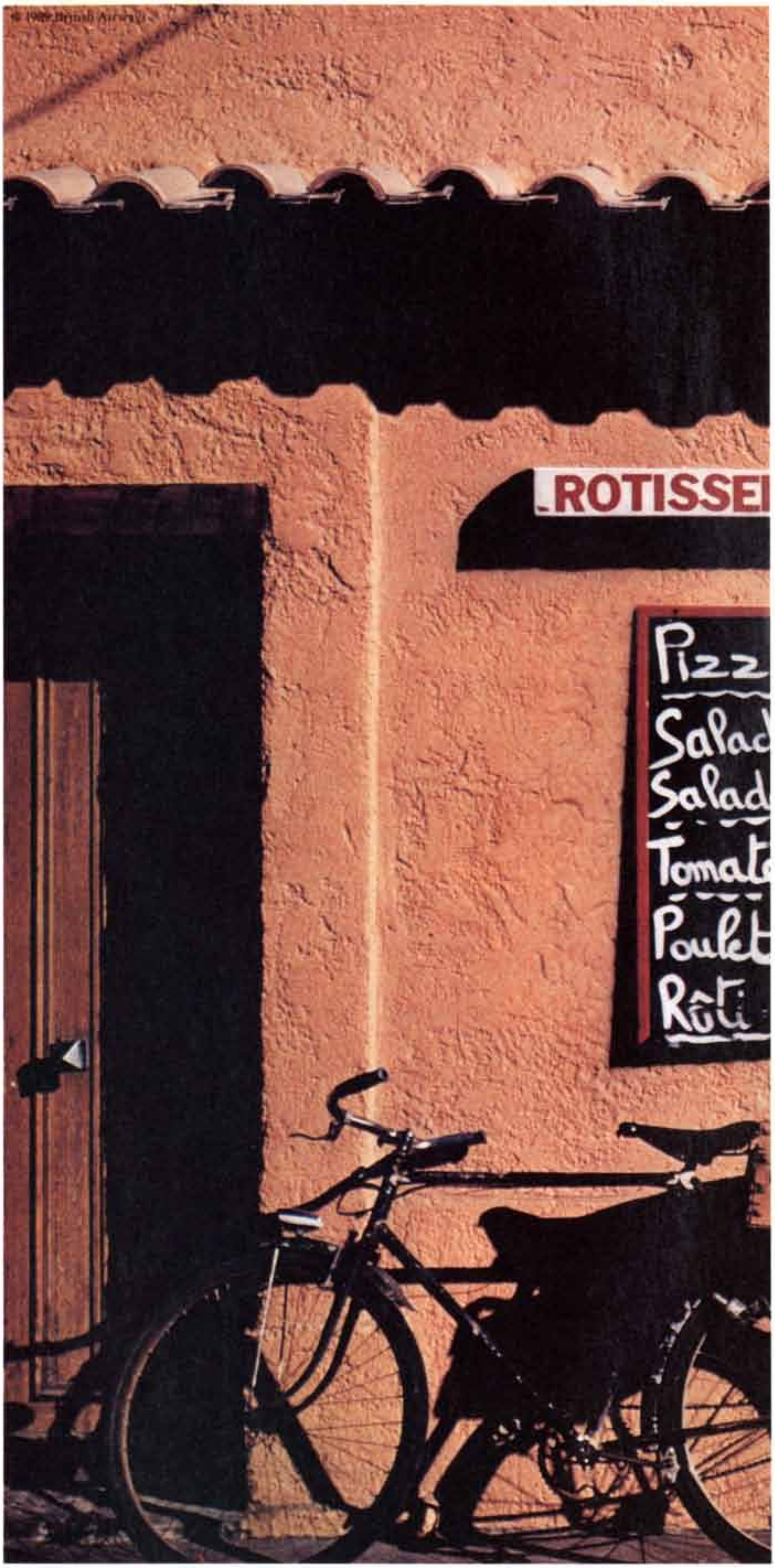
Golub concludes that the major lesson of the spring oil spills is the importance of speed. The fumbled response in Alaska, he notes, almost certainly contributed to the damage from the *Exxon Valdez,* since the sea was calm at the time. The regional response centers proposed by the oil industry could have a bigger effect on future spill response than any improvement in technology. *—T.M.B.*

MEDICINE

Different Strokes...

Premature infants gain from being handled

Could the isolation of the high-technology cocoon surrounding a premature infant subtly stress the young life it protects? Preemies maintain a tenuous vitality; compared with infants who come to full term in the womb, they grow at a feeble pace. Recent research on both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preemies and rat pups supports earlier observations that lack of tactile stimulation—in preemies, stroking, in rats, licking—seems to slow their growth. Yet most of the 240,000 preemies born each year in the U.S. are kept in incubators that discourage touching.

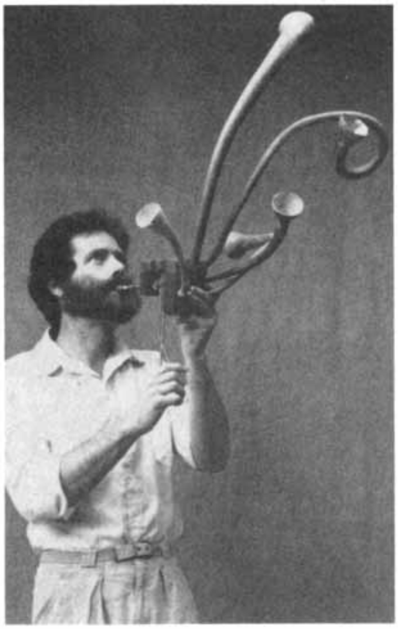
The findings emerge from the work of Tiffany M. Field of the University of Miami Medical School and Saul M. Schanberg of Duke University Medical Center. They have identified physiological changes that could explain the apparently faster growth of preemies who are stroked. Several times a day the investigators stroked and handled 20 preemies according to a standard routine. Those infants gained weight 21 percent faster than a control group that was not stroked, even though there was no difference in the amount of food they consumed. Schanberg says the robust difference indicates that the stroked preemies were growing "in a more happy way." The stroked preemies also had higher levels of neurotransmitters and hormones (norepinephrine, epinephrine and dopamine) in their urine—levels closer to those in full-term infants.

Faster weight gain reduces the amount of incubator time: one study suggests the savings in hospital costs could amount to $3,000 per infant. Moreover, stroked preemies may experience fewer complications later.

Why does touching seem to benefit preemies? Experiments with rat pups provide clues. Rat pups deprived of maternal licking experience biochemical changes, such as loss of sensitivity to growth hormone, that cause them to stop growing; Schanberg believes the changes represent a survival strategy that helps lost pups to conserve energy. He and his colleagues Jorge V. Bartolome and Cynthia M. Kuhn have shown that injecting the natural opiatelike chemical beta-endorphin into the brain of a rat pup mimics the effects of maternal deprivation, suggesting it may be a central chemical switch that precipitates the changes. Exactly how it works is not yet clear. "We have separate pieces of the puzzle," Schanberg says, "but they don't fit together yet." —*T.M.B.*

Beyond the piano: musicians explore the acoustics of kelp and clay and ostrich eggs

Musicians who find violins humdrum, and trumpets mundane, need not buy a synthesizer to generate offbeat sounds. They can turn instead to such acoustic alternatives as the Glass Harmonica: glass bowls that rotate on a spit and whine eerily when rubbed with moistened fingers. Or the Fountain Chime, a seven-foot-high string of clay bells encased in a clear acrylic tube; a handful of steel pellets poured down the tube produces a tintinnabulary explosion. Or the Ostrich-Egg Ocarina. These are a few of the instruments featured in *Experimental Musical Instruments*, a bimonthly newsletter dedicated to the "design, construction and enjoyment of new sound sources." Bart Hopkin, a teacher, musician and long-time maker of fanciful instruments, started the journal four years ago and now has more than 500 subscribers. The newsletter highlights some instruments—the French horn with a trombone slide, for example, and the Pikasso Guitar, which looks like several guitars wrestling—that are variations on familiar themes. Others—such as the Dachsophon, a strip of wood that, when clamped to a table and sawed with a bow, sighs and snorts like a nursing piglet—elude categorization. In the photograph (by Janet Gillies), Hopkin plays the Seaweed Horn, which he fashioned from bull kelp culled from the California shore. The curious can contact *Experimental Musical Instruments* at P.O. Box 784, Nicasio, CA 94946. —*J.H.*



Too Much Pressure?

Are deep-water divers risking their bones and brains?

A few years ago C. E. "Whitey" Grubbs, a manager at Global Divers & Contractors, Inc., and a grandfather of the underwater welding industry, got fed up with trying to teach divers to weld, and so he decided to teach welders to dive. "Everybody thought I was crazy," he admits. That summer he trained 42 welders for the Chicago Bridge & Iron Company and took them out to repair oil derricks in the Gulf of Mexico. "I only lost two." Lost? "One got terrible headaches during decompression, although the EEG's didn't show a single thing wrong." The other one fell off the derrick he was welding; his tether broke the fall, but Grubbs says the scare was enough to put him off diving for good.

Such testimonials abound in commercial diving. Yet some of the risks of diving may be missing from those accounts. For years medical investigators have been trying to determine whether or not repeated exposure to changes in pressure causes cumulative damage to organs and tissues. Richard E. Moon, who studies diving-related injuries in the department of anesthesia at Duke University Medical Center, summarizes the current state of knowledge: "The jury's still out."

People who dive for profit make up a small percentage of the millions of divers in the U.S. But any diver can fall prey to the two most common diving problems: gas embolism and decompression sickness, or the "bends." Gas embolism occurs when gas in the lungs expands during ascent; a diver can prevent it by exhaling as he or she comes to the surface. The bends occur when nitrogen that has dissolved in the blood under high pressure returns to the gaseous phase during the diver's ascent. The bubbles of gas can cause pain, paralysis, seizures and even loss of consciousness.

A diver can avoid such acute effects by surfacing slowly or by entering a pressurized diving "bell" that is brought to the surface and then slowly decompressed. Gradual decompression enables a diver to exhale the gas accumulating in the blood. The U.S. Navy decompression tables are a

common reference for decompression times in this country; a one-hour dive at 100 feet, for example, would require about 40 minutes of decompression.

Yet the tables are not foolproof. "Half or more of the scuba divers who get the bends were operating within the specifications of the USN tables," Moon says. "Clearly, following the Navy tables does not inoculate you against decompression sickness." Several groups are trying to discover what accounts for individual variations in tolerance of decompression. Moon and his colleagues have preliminary data correlating severe cases of the bends with a congenital heart anomaly that enables some blood to bypass the lungs, thereby denying gas in the blood its route of egress.

The commercial divers who maintain and repair the oil rigs on the continental shelf are the ones who routinely go deepest for the longest periods. Those divers are paid by the hour and may receive supplementary "depth incentives"; they can make as many as 140 dives a year at depths of up to 1,000 feet. It pays contractors to have their divers decompress as quickly as physiologically possible.

For time-consuming jobs in very deep water, it does not make sense to decompress at all. Enter "saturation" diving. On board ship or barge, saturation divers are confined to a chamber that is pressurized to match the pressure of the depth at which they will be working; a similarly pressurized diving bell taxis them to work and back. A typical saturation dive lasts 20 days, during which divers have no physical contact with the terrestrial world.

"It's a very charged area in occupational medicine," says Keith W. Van Meter, who treats diving injuries in the hyperbaric unit of Jo Ellen Smith Medical Center in New Orleans. Investigators agree that decompression sickness can lead to osteonecrosis, or death of bone tissue, if gas bubbles block the flow of blood to the bone. Indeed, there is evidence that such bubbles can form and block bone capillaries even when a diver does not get the bends. But "these effects are subtle and could be caused by other things," including chronic alcoholism, says J. Morgan Wells, director of diving at the National Oceanic and Atmospheric Administration.

There is also some evidence that diving can lead to neurological deficits, again in the absence of acute symptoms. Ian M. Calder and A. C. Palmer of Cambridge University have performed the first autopsies on divers that looked specifically for central nervous system damage. They have already found lesions on some spinal cords that appear to have resulted from diving insults, and they are now examining the brain tissue.

The divers themselves have their own theories on neurological deficits. "Divers are crazy to begin with," says Andre S. Galerne, a 40-year veteran of diving and president of the Association of Diving Contractors. "Anyone who's not crazy should stay out of the business." *—Karen Wright*

Skin Deep

A recombinant growth factor hastens wound healing

A team of investigators has found the first strong evidence that the healing of wounds can be accelerated in humans. The group has demonstrated that application of a genetically engineered version of a hormone found naturally in wounds—epidermal-growth factor—hastened the regrowth of skin in 12 subjects.

The finding, reported in the *New England Journal of Medicine,* raises the hope that one day the hormone may routinely help to treat a variety of wounds, including burns and sores that sometimes lead to gangrene and amputation, such as slow-healing bedsores and the foot ulcers that plague many diabetics.

The team, headed by Gregory L. Brown of Emory University and the University of Louisville and Lillian B. Nanney of Vanderbilt University, removed two essentially identical swatches of healthy skin from each of the subjects (who needed autologous skin grafts), thereby forming comparable "partial-thickness" wounds—ones in which the epidermis (the surface layer of skin) and only part of the underlying dermis are removed. Then an antibiotic was applied to one wound, and the antibiotic combined with the growth factor was applied to the other. The donor sites all healed within from seven to 21 days, but the wounds treated with the growth factor healed an average of a day and a half earlier than their counterparts—not a remarkable acceleration, but still an improvement. Other studies are needed to determine whether the rate of healing can be increased.

Many other questions beg for answers, Nanney says. For instance, did the factor stimulate cell division and thus promote the proliferation of skin cells directly, or did it work indirectly, say by speeding the migration of new cells into the wound? Investigators also hope to learn what makes accelerated cell growth in wound healing different from cell growth in cancer.

Nanney, Brown and others are already beginning to study the effects of epidermal-growth factor on various other wounds, including diabetic ulcers. If the substance is eventually marketed, it will probably be applied topically in many instances. When no skin is spared in a wound, as in third-degree burns, the factor might be applied to skin grafts. Or it might be applied to skin-donor sites. According to Brown, preliminary evidence he collected from four patients who had burns over 80 percent of their bodies indicates that factor-treated donor sites might be harvested five times in 40 days, instead of the more typical three times. Such an improvement presumably could enhance a patient's chances of survival.

Epidermal-growth factor is not the only growth factor present in wounds. Laboratories are studying the role of several such proteins in normal and accelerated wound healing. At some point physicians may be able to mix and match growth factors, tailoring their choices to the problems posed by specific lesions. *—Ricki Rusting*

PROFILE

The Masai

These pastoralists are key to the future of Kenya's wildlife

In mid-June, after the long rains have stopped, the landscape just north of Kenya's Masai Mara National Reserve seems an Edenic world. Zebra, wildebeest, gazelle, giraffe and topi range all across the newly freshened savanna. A minibus packed with safari-hatted tourists cruises through a pack of baboons, then races toward a lion lolling beneath an acacia tree. Nearby, a herd of cattle swarms around three red-robed stick figures—Masai herders.

This vision of man, beast and tourist coexisting in harmony is somewhat deceptive. To the Masai, the pastoralists whose noble, high-cheekboned visages grace so many postcards from Africa, the wild animals are a nuisance, at best. Predators, such as male lions too old or lazy to chase an impala, occasionally attack the cattle and, less frequently, their keepers. Even worse, soon hundreds of thousands of wildebeests will stream north from Tanza-

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Kenya hopes to convince the Masai to eschew farming and keep their land open for wildlife

MASAI WEDDING PARTY gathers at the side of a road in the Narok district. The groom stands in the foreground. His bride (his second—the Masai practice polygamy), her head shaved and adorned with ceremonial jewelry, sits at the far left. In the background is a field of maize. The photograph is by Suzie Gilbert.

nia's Serengeti Plain and flood this region. The annual migration is one of nature's great spectacles—as countless travel-agency brochures and nature films have put it—but to the Masai it is a disaster. The wildebeests trample and chew down the grass, drain the water holes and expose the cattle to infectious diseases.

A century ago the pastoralists might have simply moved to a less crowded area. Now they are bounded to the south by the Masai Mara Reserve, from which they are excluded, and to the north, increasingly, by farmland. All Kenyans are prohibited by law from interfering with game unless it directly endangers them or their livestock. Nevertheless, the Masai have been known to vent their frustration by spearing a lion or elephant. Recently many more, lured by the promise of greater income, have taken an even more drastic step: planting crops on their land and fencing it off.

I recently spent two weeks driving through Kenya and talking to various people—in the government, conservation groups and the tourism industry—about wildlife conservation. The issue is critical: tourists on safari represent a major source of employment and of foreign exchange. The big story in Kenya was the same one making headlines worldwide: the widespread poaching of elephants and rhinoceroses (not by spear-wielding Masai but by paramilitary gangs armed with automatic rifles) and the campaign to stop it by the renowned paleoanthropologist Richard E. Leakey, who became director of Kenya's Wildlife Conservation and Management Department last spring. But Leakey and others I spoke to kept raising another issue that may have a broader long-term significance than the poaching: the ongoing evolution of the Masai. "Over the long run that really is *the* issue for much of the wildlife in Kenya," says David Western of Wildlife Conservation International.

The Masai once roamed across some of the choicest rangeland in western and central Kenya; other tribes, and even European settlers, gave them wide berth out of respect for their fighting skills. Then early in this century, weakened by drought, famine and intertribal strife, the Masai were forced by the British into the southern area where they live today. This area, commonly called Masailand, consists of the Kajiado and Narok districts. The former contains Amboseli National Park, which lies just north of Tanzania's Mount Kilimanjaro; the latter contains the Masai Mara Reserve, which abuts Tanzania's Serengeti National Park. (Parks are owned and managed by the federal government and reserves by the local government; the federal government has a say in the management of reserves as well, however, because it owns all wildlife in Kenya.)

Masailand supports the majority of Kenya's wildlife, which represents one of the largest assemblages of big game in the world; the Serengeti-Mara alone contains an estimated three million animals. This astonishing abundance depends to a great degree on the openness of the land. Much of Masailand is arid and subject to highly variable rainfall, and many species—most notably the wildebeest—quickly exhaust the forage in one area and move on. If the wildlife were prevented from migrating, even a brief drought could wipe out entire herds, says Helen F. de Butts of Friends of Conservation.

The traditional Masai way of life poses few obstacles to the wildlife. As nomadic pastoralists, they eschew fences; they herd their cattle from spot to spot and sleep in mud huts protected by uprooted thornbushes. They fiercely defend themselves and their livestock from predators, and young males sometimes kill lions as part of their passage to manhood. Yet they rarely kill game for meat—or their cattle for that matter; they live off the milk and blood of their cows—tapped by lancing the jugular vein—and generally slaughter steers only for ceremonies. (They eat the meat of sheep and goats more often.) The distaste of most Masai for poaching also has helped keep their land relatively free of that scourge. "They are par excellence conservationists," Leakey says. "If the Masai had not been so tolerant, we wouldn't have any wildlife in the Masai Mara today."

Tolerating the wildlife was easier for the Masai, however, when the land was less crowded. A phenomenon that contributes to overcrowding results from the odd gravitation of many wild ungulates toward land grazed by cattle. It seems the ungulates prefer grass that has recently been cropped and grown sweet new spears to grass that is longer and more fibrous; the gazelle, zebra and impala can also see predators farther away on closely cropped plains. The lions and cheetahs, naturally, follow their prey. This phenomenon occurs most strikingly in the Masai Mara region. For much of the year the reserve itself is virtually empty—a vast, unmowed lawn. Almost all of the game—and the tourists, who follow the wildlife just as the lions

***MASAILAND* (red) *contains the Masai Mara National Reserve* (a) *and the Amboseli National Park* (b) *and abuts Tsavo National Park* (c).**

follow their prey—is north of the reserve, sharing the land with the Masai and their livestock.

Yet the pressures on the Masai are largely self-generated. Some 300,000 Masai now live in Kenya, and their population is swelling at nearly the national rate of 4 percent a year. (Kenya has one of the fastest-growing populations in the world.) Since the land cannot sustain an equivalent growth in the cattle population, the number of cattle per Masai—and thus the per capita income from pastoralism—has begun to drop. This trend is forcing the Masai to seek new sources of food and income. Many young males are abandoning rural life entirely and migrating to towns and cities to find jobs.

More significant, as far as the wildlife is concerned, is the growing number of Masai who are abandoning pastoralism for farming. In the Amboseli region, Masai have begun cultivating land to the east of the park and to the south, in the foothills of Mount Kilimanjaro. Even more land has been converted in the Mara region, which receives more rainfall than the area surrounding Amboseli. Masai here generally lease their land to non-Masai farmers rather than cultivating it themselves. As one drives northeast from the Masai Mara Reserve toward Narok, the district seat, the open plains give way to fenced-in fields of wheat and maize. The more prosperous Masai landowners live not in the mud huts that tourists find so picturesque but in big ranch-style houses surrounded by trucks and four-wheel-drive vehicles. Iowa comes to mind. "Most people think the Masai like striding across the plains, playing the noble savage," says Allan E. Earnshaw of Ker & Downey Safaris Ltd., "but they'd rather drive a Land Cruiser just like the rest of us."

The government has sought to induce the Masai to keep their land open to wildlife by giving them an ever greater share of the benefits from tourism. (There is an irony here: previously, and especially before the Kenyans won independence from the British in 1963, the government tried to convince the Masai to take up farming—to settle down, so to speak—and the Masai stubbornly resisted.) The government distributes the fees gathered at the entrances to Amboseli and the Masai Mara and a tax levied on tourist lodges to the two councils that represent the Kajiado and Narok districts. These so-called county councils, whose members are elected, were created by the British to hold all of Masailand in trust for the nomadic tribe and to negotiate on its behalf with the government. The councils have used funds from tourism to dig wells and establish cattle-inoculation programs; the funds also help to build schools, medical facilities and roads.

The government's strategy has had notable failures, however. When Amboseli Park was created in 1974, for example, the Wildlife Department promised to provide the displaced Masai with new water sources to compensate them for sources in the park that were now off limits. The arrangement seemed to work at first, but then the department neglected to maintain the pumps and pipes that brought water to the local herders. Moreover, the Kajiado County Council did not distribute the entrance fees and other funds generated by tourism to the Masai near the park, who most deserved compensation. In protest, some Masai began killing rhinoceroses and elephants. "In some cases the Masai just get fed up with conservation," says Thomas O. McShane of the World Wildlife Fund.

In recent years the government has sought to distribute the benefits of tourism more fairly. The Wildlife Department has begun providing funds generated by tourism not only to the county councils, which many Masai feel represent them poorly, but also to so-called group ranches, formed by families of Masai who share a common grazing area. The government agreed to relocate the headquarters of Amboseli—and the schools, medical clinics and other resources built for the park employees—outside the parks where the local Masai could use them as well. Perhaps the most encouraging trend, according to Western, is that the Masai themselves have become more "entrepreneurial," setting up campsites and shops outside the parks that cater directly to tourists.

The Masai should also benefit from Leakey's ambitious program to boost the profits from tourism. In addition, Leakey plans to negotiate a new agreement with the Masai that will provide them with a higher percentage of the profits. He says he does not want to bribe the Masai into an atavistic retreat from modern life, as some critics have claimed. Quite the contrary. "I hope to make it clear to them," he says, "that they have a far better chance of sending their kids to universities by keeping wildlife on their land than by putting wheat on it."

But with whom will Leakey negotiate? Beginning in the 1970's, the county councils began formally transferring the ownership of large tracts of land to the group ranches. Now some of these ranches are subdividing their land still further—into lots as small as five acres—and distributing it to individuals. Eventually, all of Masailand may be parceled into individual lots, according to William Ole Ntimama, Kenya's minister of local government and one of its highest-ranking Masai. At that point, the county councils may no longer have any political power, and the Masai may have no unified voice. "It's very easy to deal with one committee compared with 400 individuals," Ntimama says.

Some conservationists fear that without a coherent policy the Kajiado and Narok districts will become a patchwork of farms and grazing land in which animals and humans are in constant confrontation. Eventually, the wildlife might be confined to tightly managed, fenced-in reserves more akin to zoos or "Safari-World" parks than the wild open range that still characterizes much of Masailand. Ntimama is not quite so pessimistic. He thinks the majority of the Masai will decide to keep their land open to game. "We now get some share of the proceeds from wildlife, and we think we'll continue to benefit," he says. But he notes that the ongoing assimilation of the Masai into modern life makes predicting the future difficult. "We've got very strong traditions," he says, "but now, with the education of children, we are changing. In 25 or 30 years, I think we will all be changed." —*John Horgan*

SCIENTIFIC AMERICAN September 1989 Volume 261 Number 3

Managing Planet Earth

Introducing a single-topic issue that explores the prospects for sustainable human development on a planet with finite resources and a fragile environment

by William C. Clark

Every form of life continually faces the challenge of reconciling its innate capacity for growth with the opportunities and constraints that arise through its interactions with the natural environment. The remarkable success of our own species in meeting that challenge is reflected in the striking image that graces the cover of this single-topic issue of *Scientific American*. That initial success, however, is only the beginning of the story.

As we seek to imagine different ways in which that story might unfold, analogies can be helpful. The global pattern of light created by today's civilizations is not unlike the pattern of exuberant growth that develops soon after bacteria are introduced to a nutrient-rich petri dish. In the limited world of the petri dish, such growth is not sustainable. Sooner or later, as the bacterial populations deplete available resources and submerge in their own wastes, their initial blossoming is replaced by stagnation or collapse.

The analogy breaks down in the fact that bacterial populations have no control over, and therefore no responsibility for, their ultimate collision with a finite environment. In contrast, the same wellsprings of human inventiveness and energy that are so transforming the earth have also given us an unprecedented understanding of how the planet works, how our present activities threaten its workings and how we can intervene to improve the prospects for its sustainable development. Our ability to look back on ourselves from outer space symbolizes the unique perspective we have on our environment and on where we are headed as a species. With this knowledge comes a responsibility not borne by the bacteria: the responsibility to manage the human use of planet earth.

At the individual level, people have begun to respond to increased awareness of global environmental change by altering their values, beliefs and actions. Changes in individual behavior are surely necessary but are not enough. It is as a global species that we are transforming the planet. It is only as a global species—pooling our knowledge, coordinating our actions and sharing what the planet has to offer—that we have any prospect for managing the planet's transformation along pathways of sustainable development. Self-conscious, intelligent management of the earth is one of the great challenges facing humanity as it approaches the 21st century.

MANAGING PLANET EARTH will require answers to two questions: What kind of planet do we want? What kind of planet can we get? To resolve these questions human beings must understand how their activities affect the global environment and must choose strategies for developing the planet. One local aspect of a possible global strategy is symbolized here by a Nepalese woman planting a tree as part of a reforestation project.

Although efforts to manage the interactions between people and their environments are as old as human civilization, the management problem has been transformed today by unprecedented increases in the rate, scale and complexity of those interactions. What were once local incidents of pollution now involve several nations—witness the concern for acid deposition in Europe and in North America. What were once acute episodes of relatively reversible damage now affect multiple generations—witness the debates over chemical- and radioactive-waste disposal. What were once straightforward confrontations between ecological preservation and economic growth now involve multiple linkages—witness the feedbacks among energy consumption, agriculture and climatic change that are thought to enter into the greenhouse effect.

We have entered an era characterized by syndromes of global change that stem from the interdependence between human development and the environment. As we attempt to move

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from merely causing these syndromes to managing them consciously, two central questions must be addressed: What kind of planet do we want? What kind of planet can we get?

What kind of planet we want is ultimately a question of values. How much species diversity should be maintained in the world? Should the size or the growth rate of the human population be curtailed to protect the global environment? How much climatic change is acceptable? How much poverty? Should the deep ocean be considered an option for hazardous-waste disposal?

Science can illuminate these issues but cannot resolve them. The choice of answers is ours to make and our grandchildren's to live with. Because different people live in different circumstances and have different values, individual choices can be expected to vary enormously. As pointed out by Gro Harlem Brundtland in the closing essay to this issue, poor people and rich people are especially likely to place different values on economic growth and environmental conservation. Recently, however, the long-standing debate over growth versus environment has matured considerably. A broad consensus has begun to emerge that interactions between people and their environments should be managed with the goal of sustainable development.

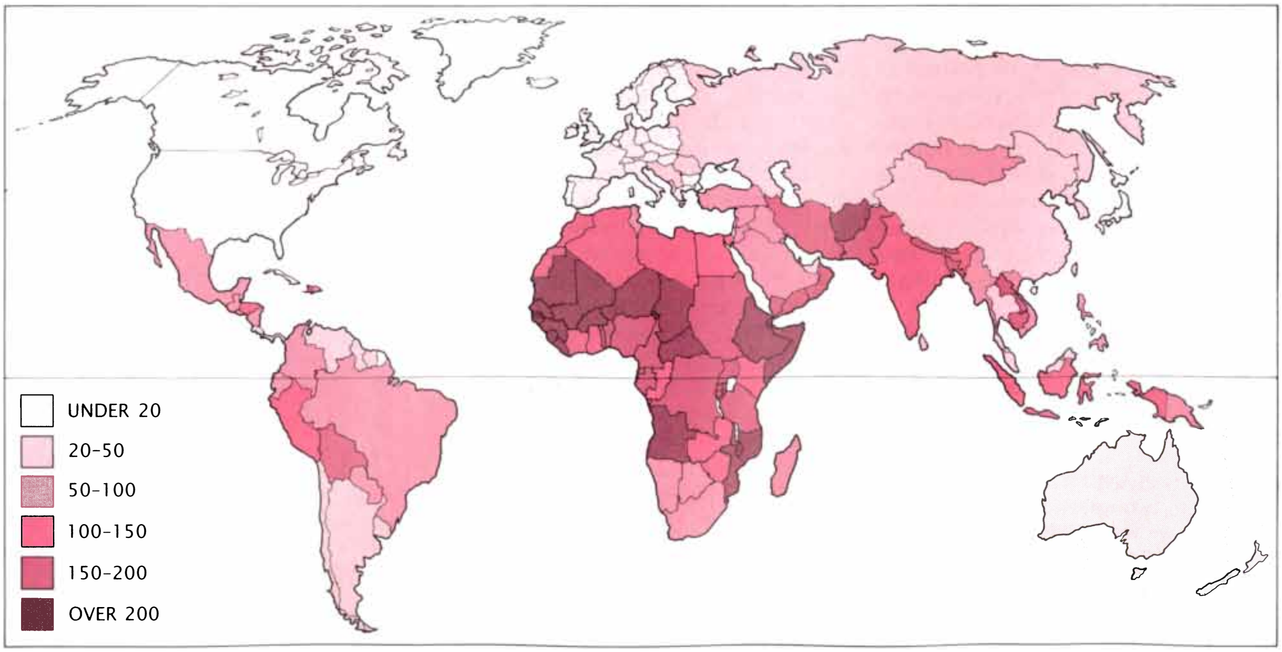
The World Commission on Environment and Development (WCED), chaired by Prime Minister Brundtland, characterizes sustainable development as paths of social, economic and political progress that meet "the needs of the present without compromising the ability of future generations to meet their own needs." Sustainable development thus reflects a choice of values for managing planet earth in which equity matters—equity among peoples around the world today, equity between parents and their grandchildren.

Managing the planet toward sustainable development is an undertaking made no less daunting by its urgency. The basic human dimensions of the task are explored by Nathan Keyfitz in "The Growing Human Population" on page 118 and by Jim MacNeill in "Strategies for Sustainable Economic Development" on page 154. The broad picture, although familiar, bears recounting. The planet today is inhabited by somewhat more than five billion people who each year appropriate 40 percent of the organic material fixed by photosynthesis on land, consume the equivalent of two tons of coal per person and produce an average of 150 kilograms of steel for each man, woman and child on the earth. The distribution of these people, their well-being and their impact on the environment vary significantly among countries [*see illustrations below and on next three pages*].

At one extreme, the richest 15 percent of the world's population consumes more than one third of the planet's fertilizer and more than half of its energy. At the other extreme, perhaps one quarter of the world's population goes hungry during at least some seasons of the year. More than a third live in countries where the mortality for young children is greater than one in 10. The vast majority exist on per capita incomes below the official poverty level in the U.S.

As we look to the future, it is encouraging that the growth rate of the human population is declining virtually everywhere. Even if the trends responsible for the decline continue, however, the next century will probably see a doubling of the number of people trying to extract a living from planet earth. Nearly all of the increase will take place in today's poorer countries. According to the WCED, a fivefold to tenfold increase in world economic activity during the next 50 years will be required to meet the basic needs and aspirations of the future population. The implications of this desperately needed economic growth for the already stressed planetary environment are at least problematic and are potentially catastrophic.

Efforts to manage the sustainable development of the earth must therefore have three specific objectives.



CHILD MORTALITY is one measure of a population's well-being. The map shows deaths per 1,000 live births for children younger than five years. More than one third of the world's people live in countries where the mortality is greater than one in 10. The data, estimated for 1985 to 1990, are from the U.N.'s Department of International Economic and Social Affairs.

One is to disseminate the knowledge and the means necessary to control human population growth. The second is to facilitate sufficiently vigorous economic growth and equitable distribution of its benefits to meet the basic needs of the human population in this and subsequent generations. The third is to structure the growth in ways that keep its enormous potential for environmental transformation within safe limits—limits that are yet to be determined.

If the goals of sustainable development describe the type of planet people want, the second question still remains: What kind of planet can we actually get? When we address this question, the focus shifts from what we value to what we know.

In the end the strategies for sustainable development must translate into local action if they are to have any impact at all. As I have noted, however, many of today's most intractable challenges to sustainability involve time scales of decades or centuries and global spatial scales. Any significant improvements in our ability to manage planet earth will require that we learn how to relate local development action to a global environmental perspective.

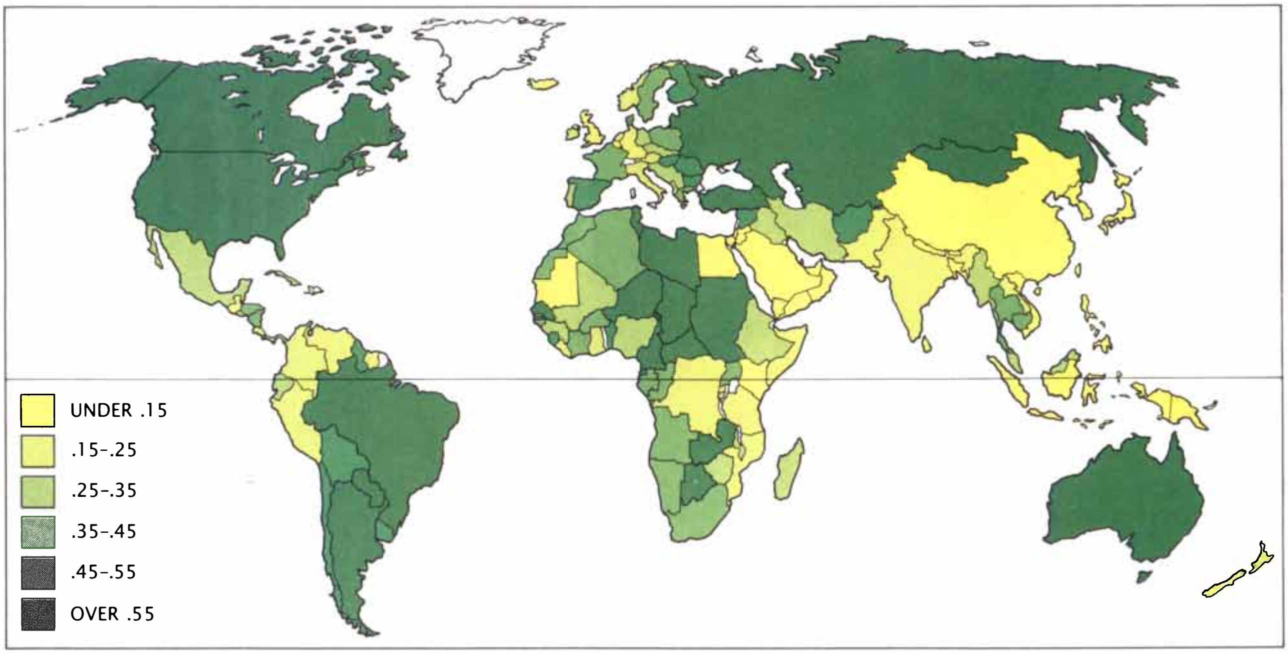
Fortunately, understanding of global environmental change has been revolutionized in recent years. The revolution has its roots in the 1920's, with the Russian mineralogist Vladimir I. Vernadsky's seminal writings on the biosphere. It received important impetus from the International Geophysical Year of 1957 and is now being carried forward through a lively array of research and monitoring efforts around the world, capped by an ambitious new International Geosphere Biosphere Program. Although the "global change" revolution is far from complete, its broad outlines can be summarized in the illustration on page 52.

The view of environmental change outlined in the illustration shows a planet dominated through decades and centuries by the interactions of climate and chemical flows of major elements, interactions that are woven together by the global hydrological cycle and are significantly influenced by the presence of life.

The climate system incorporates atmospheric and oceanic processes that govern the global distribution of wind, rainfall and temperature. Processes central to human transformation and management of planet earth include changes in concentrations of greenhouse gases and their impact on temperature; the effect of ocean circulation on the timing and distribution of climatic changes; and the role of vegetation in regulating the flux of water between land and atmosphere [see "The Changing Climate," by Stephen H. Schneider, page 70].

A second important component of the planet's environment is the global circulation and processing of major chemical elements such as carbon, oxygen, nitrogen, phosphorus and sulfur. These elements are the principal components of life. In chemical forms such as carbon dioxide, methane and nitrous oxide, they also exert a major influence on climate. Even in the absence of human influences, the earth's climate and chemistry have undergone abrupt and tightly linked changes such as those reflected in the ice-core records shown on page 75. When added to these natural fluctuations, human activities have created disturbances in global chemical flows that manifest themselves as smog, acid precipitation, stratospheric ozone depletion and other problems [see "The Changing Atmosphere," by Thomas E. Graedel and Paul J. Crutzen, page 58].

The third component of the illustration, the hydrological cycle, includes the processes of evaporation and precipitation, runoff and circulation. Water is a key agent of topographic change and an overall regulator of global chemistry and climate. As described by J. W. Maurits la Rivière in "Threats to the World's Water" on page 80, human impacts on the hydrological cycle that require attention include pollution of groundwater, surface waters and oceans, redistribution of water flows on the earth's surface



CROPLAND PER CAPITA is an index of the flexibility societies have to adjust their land-use practices. Shown here is cropland in hectares per capita for the mid-1980's. Countries with less than about .2 hectare per capita are especially limited in their options for managing the environment. Data are from the United Nations Food and Agriculture Organization (FAO).

and potential sea-level changes induced by global warming.

Life, the final component in the illustration on page 52, has found the environment of planet earth to be replete with possibilities, resulting in the evolution of an astounding—but rapidly decreasing—degree of biological diversity [see "Threats to Biodiversity," by Edward O. Wilson, page 108]. It has not been widely appreciated until recently that life is also a key player in conditioning and regulating the global environment, through its influence on the chemical and hydrological cycles. Finally, one form of life—the human species—has grown over the past several centuries from a position of negligible influence at the planetary scale to one of great significance as an agent of global change.

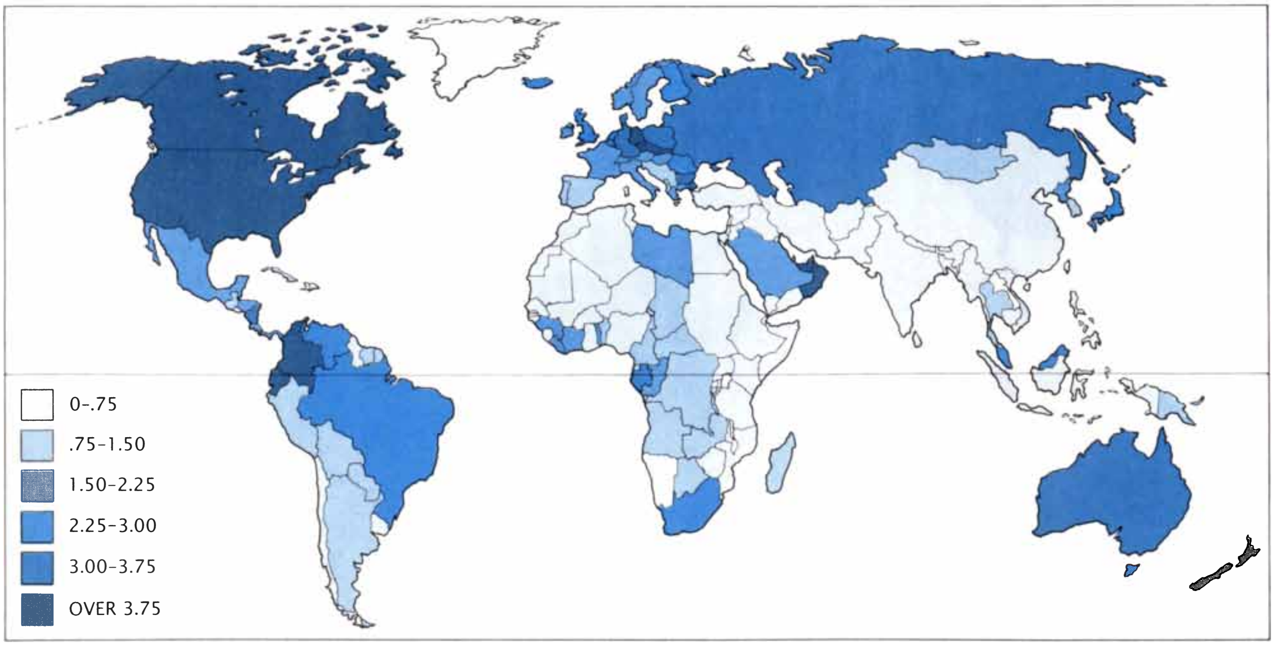
Although our knowledge of the earth system is quickly expanding, we do not yet know enough about it to say with any certainty how much change the system as a whole can tolerate or what its capacity may be for sustaining human development. We do, however, know a good deal about interactions between individual components of the global environment and specific human activities. This admittedly incomplete knowledge provides some useful perspectives on questions of planetary management.

Since the beginning of the 18th century, the human population has increased by a factor of eight; average life expectancy has at least doubled. During the same period human economic activity has become increasingly global, with demands for goods and services in one part of the planet being met with supplies from half a world away. The volume of goods exchanged in international trade has increased by a factor of 800 or more and now represents more than a third of the world's total economic product.

The three components of this growth and globalization of human activity that have had greatest impact on the environment are agriculture, energy and manufacturing, each of which is discussed at length in subsequent articles. Agriculture has been the dominant agent of global land transformation; since the middle of the last century, nine million square kilometers of the earth's surface have been converted into permanent croplands [see "Strategies for Agriculture," by Pierre R. Crosson and Norman J. Rosenberg, page 128]. Energy use has risen by a factor of 80 over the same period, with profound consequences for the planet's chemical flows of carbon, sulfur and nitrogen [see "Strategies for Energy Use," by John H. Gibbons, Peter D. Blair and Holly L. Gwin, page 136]. Finally, the world's industrial production has increased more than 100-fold in 100 years, supported by long-term growth rates of more than 3 percent a year in the utilization of such basic metals as lead, copper and iron [see "Strategies for Manufacturing," by Robert A. Frosch and Nicholas E. Gallopoulos, page 144].

The transformation of the planetary environment induced by this explosion of human activity is particularly evident in changes to the physical landscape. Since the beginning of the 18th century, the planet has lost six million square kilometers of forest—an area larger than Europe. Land degradation has increased to a significant but uncertain degree [*see illustration on opposite page*]. Sediment loads have risen threefold in major river systems and eightfold in smaller basins that support intense human activity; the resulting flow of carbon to the sea is between one and two billion tons a year. During the same period the amount of water humans withdraw from the hydrological cycle has increased from perhaps 100 to 3,600 cubic kilometers per year—a volume equivalent to that of Lake Huron.

Many substantial changes in the planet's other chemical flows have taken place. In the past 300 years agricultural and industrial development has doubled the amount of methane in the atmosphere and increased the concentration of carbon dioxide by 25 percent. The global flows of major elements such as sulfur and nitrogen that result from human activity are comparable to or



CARBON DIOXIDE EMISSIONS are one impact of human activities on the environment. Shown are carbon dioxide releases from energy use, industrial activities and deforestation expressed as tons of carbon per person per year. Highest are East Germany and the U.S. Lowest are Burundi and Bhutan. Data were compiled by the author's student Susan Subak.

greater than the natural flows of these elements. Among the trace metals, many of which are toxic to life, Jerome O. Nriagu of the Canadian National Water Research Institute and Jozef M. Pacyna of the Norwegian Institute for Air Pollution Research have shown that human emissions of lead, cadmium and zinc exceed the flux from natural sources by factors of 18, five and three, respectively. For several other metals, including arsenic, mercury, nickel and vanadium, the human contribution is now as much as two times that from natural sources. Finally, of the more than 70,000 chemicals synthesized by humans, a number—such as the chlorofluorocarbons and DDT—have been shown to affect the global environment significantly, even at very low concentrations.

Assessment of the prospects for sustainable development of the earth shows that the change in the rates at which human activities are transforming the planet may be as important as the absolute magnitudes involved. B. L. Turner, Robert W. Kates and I have analyzed historical transformation rates for several components of the global environmental system. For each component, we first characterized the recency of change—the date by which half of the total human transformation from prehistoric times to the present had taken place. Next, we assessed the acceleration of change by comparing the present rate of transformation with that of a generation ago. The dominant impression from this analysis is the relative recency of most global environmental change. None of the components we reviewed had reached 50 percent of its total transformation before the 19th century. Most passed the 50 percent level only in the second half of the 20th century.

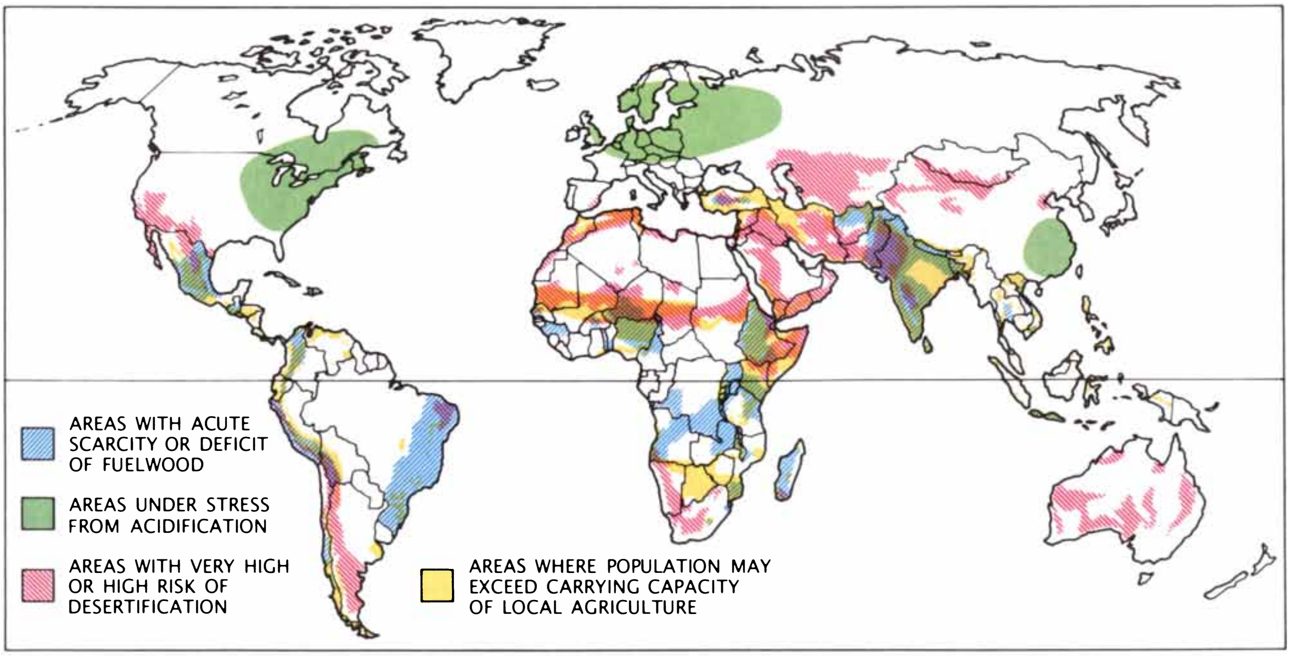
Beyond this general conclusion, four broad patterns of transformation emerge. The first pattern, characterized by relatively long-established and still accelerating change, includes deforestation and soil erosion. The second, established relatively recently and still accelerating, includes the destruction of floral diversity, withdrawal of water from the hydrological cycle, sediment flows and human mobilization of carbon, nitrogen and phosphorus. There is little reason to believe that human society has yet learned to manage on a global scale any of these accelerating transformations of the environment.

More encouraging are two decelerating trends. Human-induced extinctions of terrestrial vertebrates reached half of their present total by the late 19th century and are apparently occurring more slowly today than they were a generation ago. The remaining group of transformations we examined—releases of sulfur, lead, radioactive fallout, a representative organic solvent and extinction of marine mammals—also represents primarily phenomena of the 20th century that are now decelerating.

The crude measure of long-term deceleration presented here gives no assurance that the declining transformation rates reflect increasing competence in planetary management. (Specific transformation rates could, for example, decline simply because there are no more species to exterminate or because we turn to cheaper fuels that happen to emit different pollutants.) Nevertheless, for most of the cases I have cited, at least some fraction of the deceleration can be attributed to deliberate large-scale, long-term efforts at environmental management.

The global patterns sketched so far provide a necessary but insufficient perspective from which to reflect on the prospects for improving the management of planet earth. Also needed is an appreciation of the regional faces of change. To analyze regional situations in any detail is beyond the scope of this essay; still, it will be helpful to recall the extraordinary range of local circumstances that will have to be dealt with if the human transformation of the planet is to be steered along paths of sustainable development.

Any classification of regional perspectives on sustainable development



LAND DEGRADATION results from a variety of human activities. Shown are regions threatened by desertification, overharvesting of firewood, acid rain and stress induced by efforts to feed more people than the land is actually able to support. The data are from the U.N.'s Food and Agriculture Organization and the Scientific Committee on Problems of the Environment.

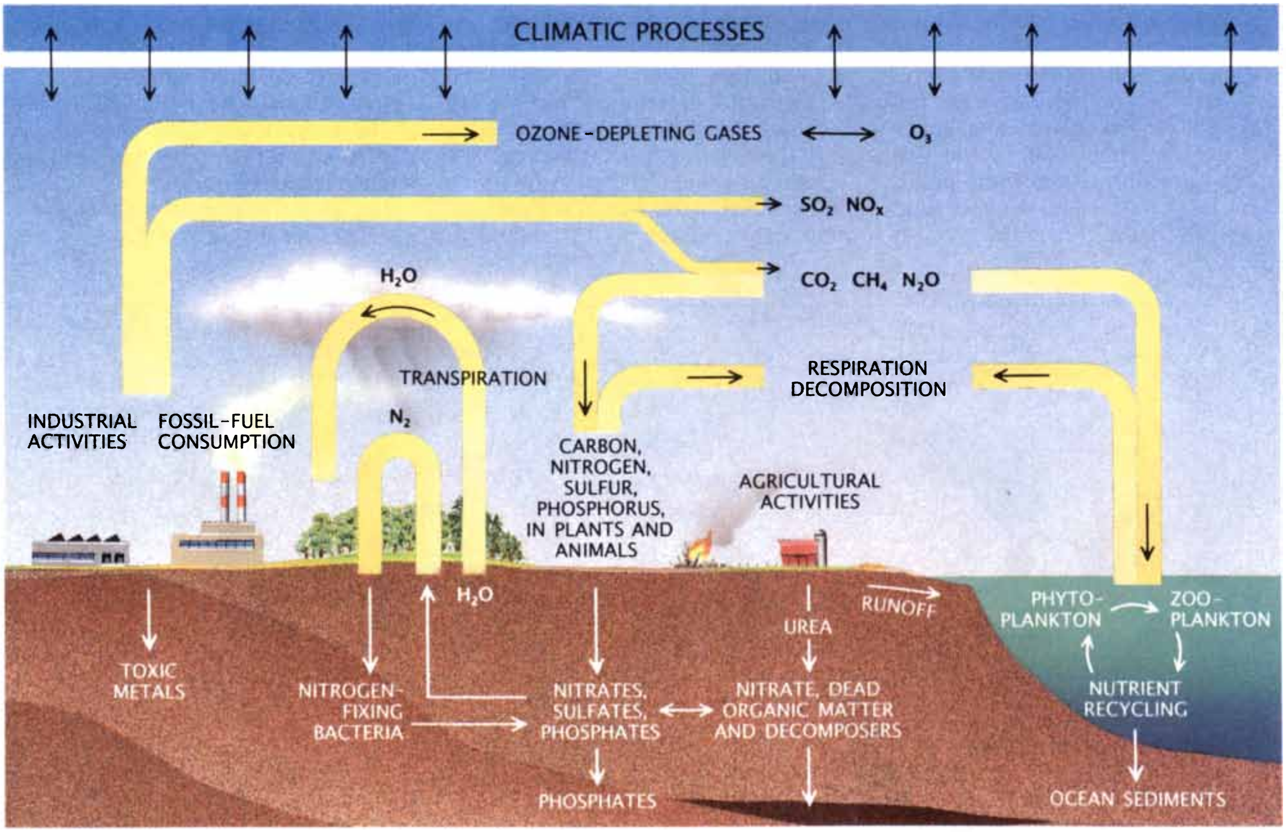
will inevitably oversimplify reality. But one of the most instructive simplifications distinguishes interactions between environment and development that are associated with poverty from those associated with affluence. Another distinguishes interactions involving low population densities from those with high population densities. Combining the two simplifications yields the classification illustrated on the opposite page.

Low-income, low-density areas such as Amazonia and Malaya-Borneo constitute settlement frontiers still available for use by people in the less developed countries. Until recently, such regions supported sparse populations, and intrusions from the industrialized world were confined to small plantation and mining sites. The situation has changed dramatically during the past 20 years as humans engaged in large-scale timber clearing and livestock raising have invaded these regions. The resulting mix of subsistence and commercial agriculture plus industrial resource extraction has led to a unique pattern of landscape transformation, the full implications of which cannot yet be assessed. Reduction of biological diversity and degradation of biological productivity nonetheless seem inevitable [see "Threats to Biodiversity," by Edward O. Wilson, page 108]. The poverty of the landless farmers engaged in land clearing and the relative paucity of indigenous institutions that might guide the sustainable development of such regions will make them especially problematic components of any strategy for planetary management.

In contrast, regions with low population density but high investments in sophisticated technology are illustrated by the classic harsh environments of the earth. Such environments include the circumpolar arctic areas, deserts, mineral-extraction platforms and off-shore "fish factories." The large-scale transformation of these regions has become possible only within the past several decades as knowledge, prices and technology have converged to induce development.

Of the environmental changes associated with such development—oil spills, river diversions and landscape transformation—some have received widespread attention. Others, such as atmospheric pollution and cultural dislocation, have received less. The knowledge base for management remains poor. But since a relatively few, wealthy corporate actors seem likely to be involved in most transformations of consequence, the possibilities for institutionalizing sustainable-development strategies for such regions may be relatively good.

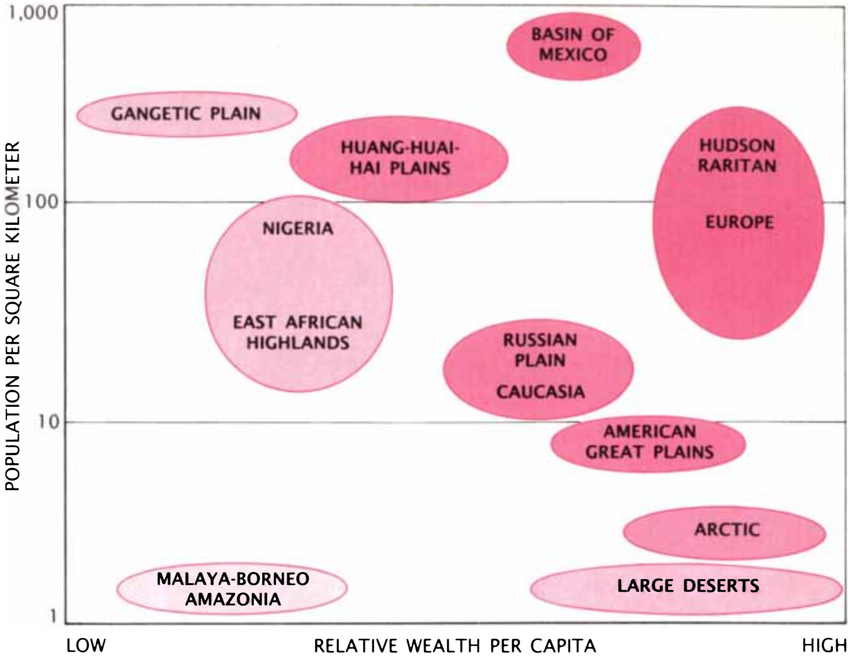
Typical of low-income, high-density regions are the Gangetic Plain of the Indian subcontinent and the Huang-Huai-Hai Plains of China. Here intensive agricultural development has been under way for centuries and has been joined in the past several decades by the rapid rise of industrial development in growing urban centers. Landscape degradation is the



INTERACTIONS between the climate and major chemical flows dominate global environmental change over tens to hundreds of years. The interactions are mediated by the living biota and the water cycle, in which water is taken out of the atmosphere by precipitation and returned by evaporation and transpiration. The oceans play major roles by imparting a great inertia to climatic change and acting as a reservoir for carbon and water. Human agriculture affects the planetary system by altering the flows of nitrates, phosphates and carbon compounds. Respiration and decomposition liberate methane (CH_4). The combustion of fossil fuels releases large quantities of stored carbon to the atmosphere as CO_2, which like CH_4 tends to warm the planet. Emissions such as sulfur dioxide (SO_2) and nitrogen oxides (NO_x) are important causes of acid rain. Industrial emissions of gases like the chlorofluorocarbons (CFC's) deplete ozone (O_3) and also contribute to climatic change.

central problem as more and more people are employed on agricultural land that is already exploited to capacity. In addition, the rapid rise of heavy industry in such areas has led to pollution problems comparable to those that Europe faced several decades ago. The critical management challenge here is to provide employment that generates income and takes pressure off the land without aggravating urbanization problems or increasing regional competition for "smokestack" industries.

The greatest responsibility and the greatest immediate potential for the design of sustainable-development strategies may be in the high-income, high-density regions of the industrialized world. As is repeatedly stated in discussions of stratospheric ozone depletion and the greenhouse effect, advanced industrialized societies have been responsible for imposing a disproportionate share of global environmental burdens on the planet. Over the past several decades, however, places as different as Sweden, Japan and the northeastern U.S. have all achieved significant improvement in numerous aspects of their regional environments. Forests have expanded, sulfur emissions have declined, locally extinct species have been successfully reintroduced. Some of these environmental victories are clearly the unintended by-product of unrelated economic changes. Others reflect the export of environmentally destructive activities to less fortunate parts of the world. Increasingly, however, such regions are benefiting from systematic strategies to mitigate the impacts of uncontrolled development and are beginning to design the kinds of environments in which their people want to live.



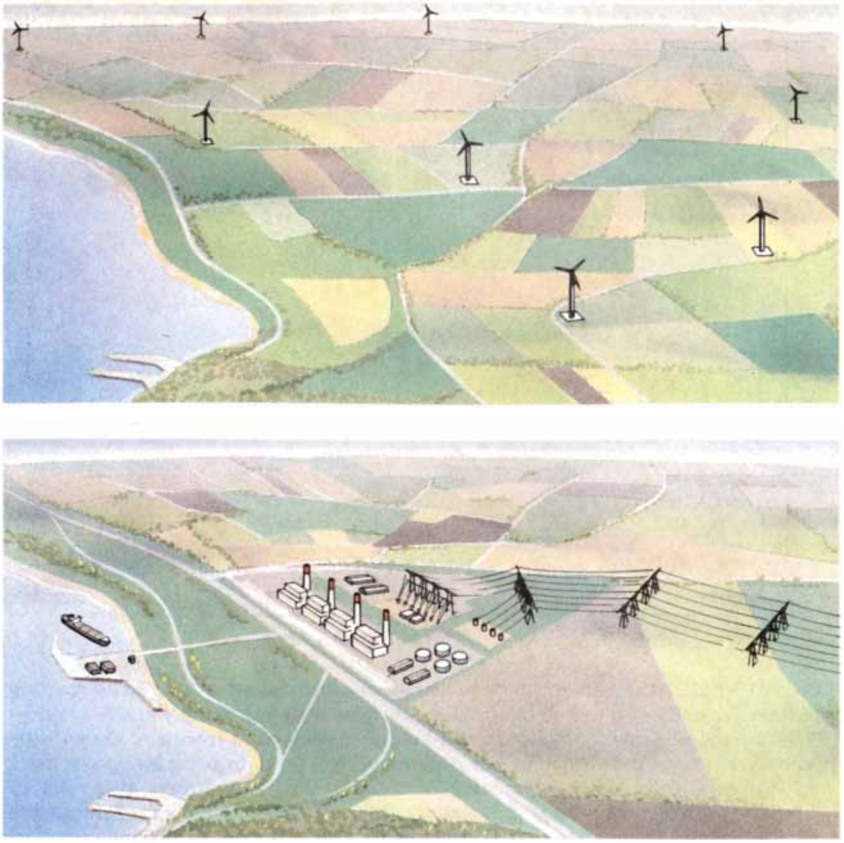
REGIONAL VARIETIES of environmental transformation can be visualized by plotting population density versus relative wealth. Regions with low density and low industrialization include many of the earth's remaining settlement frontiers where widespread agricultural development has only recently begun. In contrast, low-density areas with relatively high investments tend to be the harsh environments exploited by corporate developers of fuel and minerals. High-density, low-income regions have long histories of agricultural development; their challenge is to produce increasing food yields while relieving existing stresses on the land. The greatest responsibility for designing sustainable-development strategies lies with the high-density, wealthy regions that have imposed a disproportionate burden on the planet's environment. The figure is from work by B. L. Turner, Robert W. Kates and the author.

What kind of environments can such strategies attain? What kinds of development can they sustain? Apart from a basic knowledge of how the global environment works and how human development interacts with it, an understanding is also required of the impact policy can have on environmental change.

At the outset, it cannot be overemphasized that policy for managing planet earth must above all else be adaptive [see "Toward a Sustainable World," by William D. Ruckelshaus, page 166]. Our understanding of the science behind global change is incomplete and will remain so into the foreseeable future. Surprises like the stratospheric ozone hole will continue to appear and will demand action well in advance of scientific certainty. Our understanding of the economic and social processes that contribute to global environmental change is even weaker. Conventional forecasts of population and energy growth could turn out to be conventional foolishness. Science can help, but it is our capacity to shape adaptive policies able to cope with surprises that will determine our effectiveness as managers of planet earth. Building such a capacity will require cultivation of leadership and of institutional competence in at least four areas.

The first requirement is to make the information on which individuals and institutions base their decisions more supportive of sustainable-development objectives. Part of the task, it cannot be said often enough, is simply to support the basic scientific research and planetary monitoring activities that underlie our knowledge of global change. Also essential is to improve the flow of information implicit in existing systems of prices, regulations and economic incentives. The failure of current economic accounts to track the real environmental costs of human activities encourages the inefficient use of resources. The artificially high prices maintained for many agricultural products have significantly exacerbated problems of land degradation and pollution in many parts of the world. Narrowly targeted government subsidies have been directly responsible for a significant fraction of today's global deforestation. All of these distorted information signals need to be addressed in designing adaptive policies for sustainable development.

A second requirement for adaptive planetary management is the invention and implementation of technologies for sustainable development. Such technologies will need to be resource-conserving, pollution-preventing or environment-restoring and at the same time economically sustainable. The articles on agriculture, energy and manufacturing in this issue show that significant technical progress has already been made toward delivering desired end-use services at significantly lower environmental costs. Surprisingly often, the economic costs of the "conserving technolo-



PAINTING THE FUTURE is the title of a Swedish study in which environmentalist Lars Emmelin and artist Gunnar Brusewitz collaborated to paint the Swedish landscape as it might appear under various paths of development. In these two paintings, based on Brusewitz's originals, the Dybäck region of southern Sweden is shown as it might look in 2015. At the top is the area in a "Solar Sweden" scenario of wind power and biomass plantations; at the bottom is one vision of the "Nuclear Sweden" scenario.

gies" also turn out to be lower: cost advantages—not environmental concerns—are responsible for halving the ratio of energy consumption to the gross national product in the U.S. since it peaked in the early 1920's.

Technologies for the restoration of environments degraded by salinization, acidification and mining have also been developed and are being effectively employed at a regional scale. The policy need is to tailor technological innovations to the specific local conditions encountered in various environment-development conflicts around the world.

A third requirement for adaptive planetary management is the construction of mechanisms at the national and international level to coordinate managerial activities. The need for formal international agreements in this area has been highlighted by the Montreal Protocol on Substances that Deplete the Ozone Layer and discussion of a possible international law of the atmosphere. In fact, a dozen or more global conventions for protection of the environment are now in effect.

Beneath this orderly surface, however, a large and rapidly growing number of nongovernmental bodies, governmental agencies and international organizations are scrambling to play some part in the management of planet earth. Pluralism has much to recommend it. But are we not nearing a point of diminishing returns where too many meetings, too many declarations and too many visiting experts leave too few people with too few resources and too little time to actually do anything? The immediate need at the international level is for a forum in which ministerial-level coordination of environmental-management activities can be regularly discussed and implemented, much as is already done for international economic policy. As in the case of economic policy, the existence of such a formal, high-level governmental summit on global issues of environment and development could provide an occasion for parallel discussions involving nongovernment and private-sector interests.

Finally, building a capacity for adaptive management of planet earth will require a desire and an ability to reflect continually on the values and objectives that guide our efforts. In an important sense, there has turned out to be more to the notion of sustainable development than even the wise members of the World Commission intended. Individuals, organizations and entire nations have taken the concept as a point of departure for rethinking their interactions with the global environment.

In the Soviet Union, issues of ecological deterioration became a central point of debate in the first Congress of People's Deputies. In Kenya, an innovative project sponsored by the African Academy of Sciences has begun to explore and articulate alternative possibilities for the continent's development in the 21st century. In West Germany, a high-level commission representing all political parties and the scientific community evolved a consensual *Vorsorge*, or prevention, principle to guide the nation's environmental policies. In Sweden, a national best-seller and focal point for political debate emerged when environmental scientists and artist Gunnar Brusewitz collaborated in "painting the future" of Swedish landscapes under alternative paths of development.

The impact that these and similar explorations being conducted around the world will ultimately have in guiding the human transformation of the environment is far from clear. But there can be no question that, against all expectations, the explorations all reflect an emerging commitment to get on with the task of responsibly managing planet earth.

FURTHER READING

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Bon ami
Cleaning Cake
Bon ami
Cleaning Powder
Bon ami
POLISHING CLEANSER

The Changing Atmosphere

Human activity is altering the complex mixture of gases in the atmosphere. Some effects, such as acid rain and smog, are already evident. Unwelcome surprises may be lurking

by Thomas E. Graedel and Paul J. Crutzen

The earth's atmosphere has never been free of change: its composition, temperature and self-cleansing ability have all varied since the planet first formed. Yet the pace in the past two centuries has been remarkable: the atmosphere's composition in particular has changed significantly faster than it has at any time in human history.

The increasingly evident effects of the ongoing changes include acid deposition by rain and other processes, corrosion of materials, urban smog and a thinning of the stratospheric ozone (O_3) shield that protects the earth from harmful ultraviolet radiation. Atmospheric scientists expect also that the planet will soon warm rapidly (causing potentially dramatic climatic shifts) through enhancement of the greenhouse effect—the heating of the earth by gases that absorb infrared radiation from the sun-warmed surface of the planet and then return the radiation to the earth.

Surprisingly, these important phenomena do not stem from modifications in the atmosphere's major constituents. Excluding the widely varying content of water vapor, the concentrations of the gases that make up more than 99.9 percent of the atmosphere—nitrogen (N_2), oxygen (O_2) and totally unreactive noble gases—have been nearly constant for much longer than human beings have been on the earth. Rather, the effects are caused in large part by changes, mainly increases, in the levels of several of the atmosphere's minor constituents, or trace gases. Such gases include sulfur dioxide (SO_2), two nitrogen oxides known collectively as NO_x—nitric oxide (NO) and nitrogen dioxide (NO_2)—and several chlorofluorocarbons (compounds that contain chlorine, fluorine, carbon and sometimes hydrogen).

Sulfur dioxide, for example, rarely constitutes as much as 50 parts per billion of the atmosphere, even where its emissions are highest, and yet it contributes to acid deposition, to the corrosion of stone and metal and to the aesthetic nuisance of decreased visibility. The NO_x compounds, which are similarly scarce, are important in the formation of both acid deposition and what is called photochemical smog, a product of solar-driven chemical reactions in the atmosphere. The chlorofluorocarbons, which as a group account for just one part per billion or so of the atmosphere, are the agents primarily responsible for depleting the stratospheric ozone layer. In addition, rising levels of chlorofluorocarbons, together with methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2)—by far the most abundant trace gas at 350 parts per million—are enhancing the greenhouse effect.

The hydroxyl radical (OH), a highly reactive molecular fragment, also influences atmospheric activity even though it is much scarcer than the other gases, with a concentration of less than .00001 part per billion. Hydroxyl plays a different role, however: it contributes to the cleansing of the atmosphere. Its abundance in the atmosphere may diminish in the future.

Certainly some fluctuation in the concentrations of atmospheric constituents can derive from variations in rates of emission by natural sources. Volcanoes, for instance, can release sulfur- and chlorine-containing gases into the troposphere (the lower 10 to 15 kilometers of the atmosphere) and the stratosphere (extending roughly from 10 to 50 kilometers above the surface). The fact remains, however, that the activities of human beings account for most of the rapid changes of the past 200 years. Such activities include the combustion of fossil fuels (coal and petroleum) for energy, other industrial and agricultural practices, biomass burning (the burning of vegetation) and deforestation.

So much is clear, but which human activities generate which emissions? How do altered concentrations of trace gases give rise to such an array of effects? How much have the problems grown, and what are their consequences for the planet? Although complete answers to these questions are still forthcoming, multidisciplinary efforts by chemists, meteorologists, solar and space physicists, geophysicists, biologists, ecologists

THOMAS E. GRAEDEL and PAUL J. CRUTZEN are pioneers in the study of atmospheric chemistry. Graedel is Distinguished Member of the technical staff at AT&T Bell Laboratories. He was the first atmospheric chemist to study the gas-phase chemistry of sulfur, the chemical interactions that occur in raindrops and the reactions involved in atmospheric corrosion. Crutzen, the codeveloper of the "nuclear winter" theory, is director of the air chemistry division of the Max-Planck-Institute for Chemistry in Mainz, West Germany, and a visiting professor at the University of Chicago. Studies he began in the early 1970's of photochemical processes in the troposphere and stratosphere helped to establish the field of modern atmospheric chemistry. Earlier this year Crutzen received the prestigious Tyler Prize for his contributions to environmental science.

BURNING OF VEGETATION, a common practice in the tropics, releases soot and several gases, particularly carbon dioxide (CO_2), carbon monoxide (CO), hydrocarbons, nitric oxide (NO) and nitrogen dioxide (NO_2). This and other human activities—such as the burning of fossil fuels—account to a great extent for dramatic increases over the past two centuries in the atmospheric concentrations of many trace gases. These increases are giving rise to such environmental perturbations as acid deposition, urban smog and depletion of the stratospheric ozone layer that absorbs damaging ultraviolet radiation. Warming of the planet is also expected, from the buildup of greenhouse gases that trap infrared radiation.

and others are making good headway.

Multidisciplinary collaboration is crucial because the factors influencing the fates of the gases in the atmosphere and their interactions with the biosphere are complex and incompletely understood. For instance, the chemical reactions a gas undergoes in the atmosphere can vary depending on the local mixture of gases and particles, the temperature, the intensity of the sun, the presence of different kinds of clouds or precipitation and patterns of airflow (which move chemicals horizontally and vertically). The reactions, in turn, influence how long a gas remains in the atmosphere and hence whether the gas or its end products have global or more localized effects on the environment.

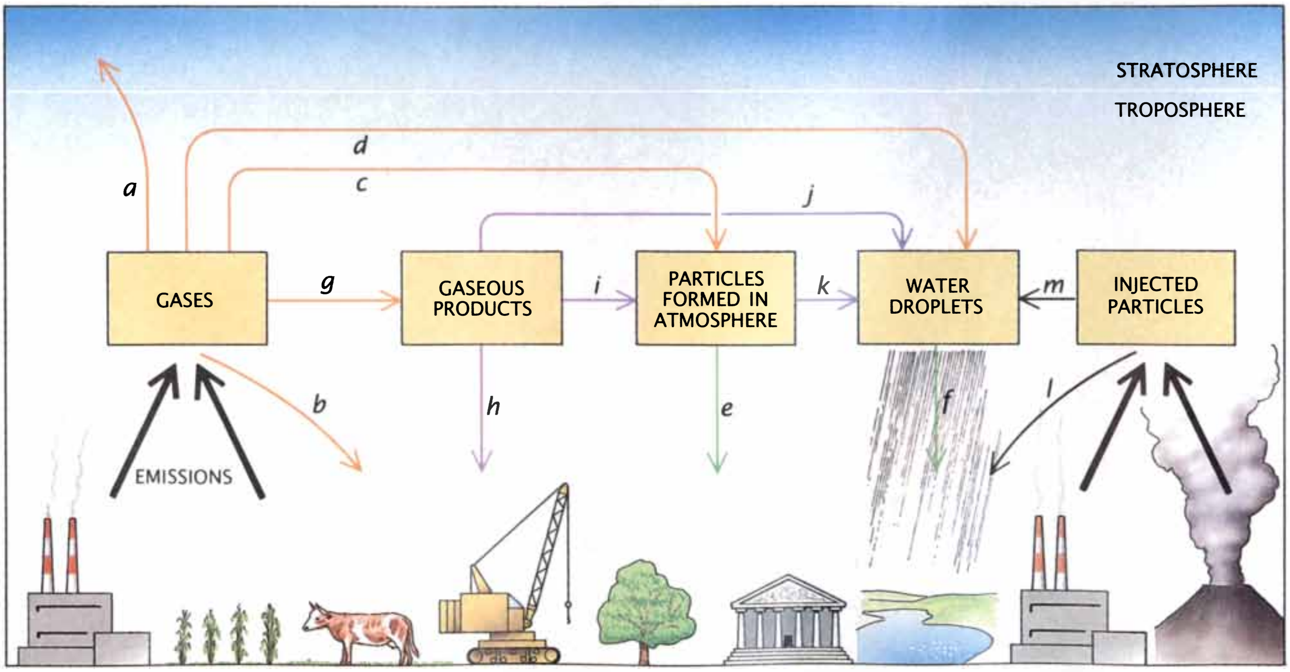
Among the fruits of the investigations has been an improved understanding of the emissions produced by specific human activities. The combustion of fossil fuels for energy is known to yield substantial amounts of sulfur dioxide (particularly from coal), nitrogen oxides (which form when nitrogen and oxygen in the air are heated) and carbon dioxide. If the burning is incomplete, it also yields carbon monoxide (CO), a variety of hydrocarbons (including methane) and soot (carbon particles). Other industrial activities release additional sulfur dioxide (smelting is an example) or inject such substances as chlorofluorocarbons or toxic metals into the air.

Agricultural practices lead to the emissions of several gases as well. The burning of forests and savanna grasses in tropical and subtropical regions to create pastures and cropland yields additional large amounts of carbon monoxide, methane and nitrogen oxides. Moreover, soil exposed after forests are cleared emits nitrous oxide, as do nitrogen-rich fertilizers spread over fields. The breeding of domestic animals is another major source of methane (from oxygen-shunning bacteria in the digestive tract of cattle and other cud-chewing animals), as is the cultivation of rice, which is a staple food for many people in the tropics and subtropics.

Recent investigations have also led to a better understanding of the effects produced by increased anthropogenic emissions. For example, the much studied phenomenon of "acid rain" (by which we mean also acid snow, fog and dew) is now known to develop mainly as a by-product of atmospheric interactions involving the NO_x gases and sulfur dioxide. Through various reactions, such as combination with the hydroxyl radical, these gases can be converted within days into nitric acid (HNO_3) and sulfuric acid (H_2SO_4), both of which are dissolved readily in water. When the acidified droplets fall to the earth's surface, they constitute acid rain.

Because water droplets are removed from the atmosphere rapidly, acid rain is a regional or continental, rather than global, phenomenon. In contrast, the atmospheric lifetimes of several other trace gases, including methane, carbon dioxide, the chlorofluorocarbons and nitrous oxide, are much longer [*see bottom chart on page 62*], and so the gases spread rather evenly throughout the atmosphere, causing global effects.

Since the beginning of the Industrial Revolution in the mid-18th century, the acidity of precipitation (as measured by the concentration of hydrogen



FATE OF EMISSIONS in the atmosphere can vary. A gas (*orange arrows*) that is unreactive and insoluble in water (*a*) will spread through the troposphere (the lower 10 to 15 kilometers) and in some cases into the stratosphere, which extends approximately from 10 to 50 kilometers above the surface, although a fraction may be taken up by land and water surfaces (*b*). If the gas is soluble, it may instead dissolve in moisture on particles (*c*) or in water droplets (*d*), mainly in clouds. The particles and droplets then carry the gas to the earth (*green arrows*) directly (*e*) or in rain, snow, fog or dew (*f*). Most gases are reactive enough to undergo chemical changes in the atmosphere (*g*), driven primarily by interactions with the hydroxyl radical (OH). The resulting gaseous products (*purple arrows*) can sometimes be deposited dry on the earth (*h*), but because they are generally more soluble than their precursors, they are also more readily incorporated into wetted particles (*i*) and, directly (*j*) or indirectly (*k*), into water droplets. The gaseous products thereby tend to be removed (*e,f*) quickly and are much less likely than their predecessors to diffuse above the troposphere. The fate of injected particles (*right*) is similar to that of gases. They can be deposited directly (*l*) or else incorporated into water (*m*) and returned to the earth in precipitation (*f*).

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This technology is an inevitable step in the human journey. It has only been with us in a practical sense for 43 years, so there is still an amount of skepticism surrounding it. Yet its potential is as limitless as the imagination.

Like all forms of energy, radiation must be dealt with responsibly. At Nordion, we have set many of the standards and procedures in this field.

We know that this energy is too important to be ignored or taken for granted. It is the first step in a new era for medicine, waste disposal and many other things that are yet to be discovered.

No one can say precisely what the future will bring. But one thing you can be sure of is that Nordion will play a major role in new methods and discoveries. At Nordion, we are preparing for the next step in the human journey.

ions) has increased in many places. For example, it has roughly quadrupled in the northeastern U.S. since 1900, paralleling increased emissions of sulfur dioxide and the NO_x gases. Similar increases have been found elsewhere in the industrialized parts of the world. Acid rain has also been detected in the virtually unindustrialized tropics, where it stems mainly from the release of the NO_x gases and hydrocarbons by biomass burning.

Wet deposition is not the only way sulfuric and nitric acids in the troposphere find their way to the earth's surface. The acids can also be deposited "dry," as gases or as constituents of microscopic particles. Indeed, a growing body of evidence indicates that dry deposition can cause the same environmental problems as the wet form.

Acid deposition clearly places severe stress on many ecosystems. Although the specific interactions of such deposition with lake fauna, soils and different vegetation types are still incompletely understood, acid deposition is known to have strongly increased the acidity of lakes in Scandinavia, the northeastern U.S. and southeastern Canada, thereby leading to reductions in the size and diversity of fish populations. Such deposition also appears to play some role in the forest damage that has been discovered in parts of the northeastern U.S. and Europe.

There is little doubt that acids deposited from the troposphere also contribute to the corrosion of outdoor equipment, buildings and works of art, particularly in urban areas—costing tens of billions of dollars each year for repairs and equipment replacement in the U.S. alone. Particles containing sulfate (SO_4^{2-}) have other effects as well. By scattering light efficiently, they decrease visibility; by influencing cloud albedo, they may have important implications for climate [see "The Changing Climate," by Stephen H. Schneider, page 70].

In and around cities photochemical smog is another negative consequence of modern life. The term technically refers to the undesirable mixture of gases formed in the lower troposphere when solar radiation acts on anthropogenic emissions (particularly the NO_x gases and hydrocarbons from vehicle exhaust) to produce reactive gases that can be destructive to living organisms.

Ozone is a major product of such photochemical reactions and is itself the main cause of smog-induced eye irritation, impaired lung function and damage to trees and crops. The severity of smog is therefore generally assessed on the basis of ground-level ozone concentrations. In other words, the same three-oxygen molecule that is critically important for absorbing ultraviolet radiation in the stratosphere, where some 90 percent of atmospheric ozone is concentrated, is a problem when it accumulates in excess near the earth's surface.

Investigators have measured ozone levels in the atmosphere since the late 19th century, first from the ground and then within the atmosphere, aided by sophisticated airborne devices. Some of the earliest data showed that the "natural" level of ozone close to the ground at one measuring post in Europe roughly a century ago was about 10 parts per billion. Today the typical ground-level concentrations in Western Europe are from two to four times higher. Abundances more than 10 times higher than the natural level are now often recorded in Western Europe, California, the eastern U.S. and Australia.

Photochemical smog is also appearing in broad regions of the tropics and subtropics, particularly because of the periodic burning of savanna grasses; the same territories may be set afire as often as once a year. This practice releases large amounts of precursors to smog. Because solar radiation is plentiful and strong in those regions and photochemical reactions occur quickly, ozone levels can readily climb to perhaps five times higher than normal. As the populations in the tropics and subtropics grow, unhealthy air should become even more widespread there. Such a prospect is particularly worrisome because the properties of the soil in those regions may make the ecosystems there more vulnerable than the ecosystems in the middle latitudes to smog's effects.

Although a decrease in ozone near the ground would benefit polluted regions, any decrease in stratospheric ozone is disturbing, because the resulting increase in ultraviolet radiation reaching the earth could have many serious effects. It could elevate the incidence of skin cancer and cataracts in human beings, and it might damage crops and phytoplankton, the microscopic plants that are the basis of the food chain in the ocean.

So far, the extent of stratospheric ozone depletion has been most dramatic over Antarctica, where an ozone "hole," a region of increasingly severe ozone loss, has appeared each south-

CHEMICAL REACTIONS IN THE ATMOSPHERE

OXIDIZERS AS DETERGENTS. The molecular species that initiate most atmospheric reactions ("oxidizers" in the chemist's terminology) can be regarded as detergents because they transform gases into water-soluble products, thereby facilitating their removal in precipitation. Ozone (O_3) is one important oxidizer and also participates in the formation of another detergent: the hydroxyl radical (OH), which interacts with nearly every molecular species in the atmosphere. Much of the trace gases that have been emitted into the atmosphere would still be there were it not for these substances. The hydroxyl radical forms after ultraviolet light (*hv*) dissociates ozone, releasing a highly energetic - and hence highly reactive - oxygen atom (O*) that then combines with a water molecule:

a) $O_3 \xrightarrow{hv} O^* + O_2$ b) $O^* + H_2O \longrightarrow 2OH$

STRATOSPHERIC OZONE: GENERATION AND LOSS. Ozone forms when oxygen molecules (O_2) are dissociated by ultraviolet radiation and the resulting oxygen atoms combine with other oxygen molecules:

a) $O_2 \xrightarrow{hv} O + O$ b) $O + O_2 \longrightarrow O_3$

Chlorine atoms from chlorofluorocarbon compounds released into the atmosphere play a central role in one of the most efficient ozone-destroying catalytic cycles in the stratosphere. The cycle begins with the breakup of an ozone molecule by atomic chlorine and the formation of chlorine monoxide (ClO) and molecular oxygen:

a) $Cl + O_3 \longrightarrow ClO + O_2$

Then the chlorine monoxide reacts with an oxygen atom (formed by the photodissociation of another ozone molecule) and liberates the chlorine, which can initiate the cycle again:

b) $ClO + O \longrightarrow Cl + O_2$

Nitrogen oxides destroy ozone as well, but they can also interfere with this cycle. For example, nitrogen dioxide can remove chlorine monoxide from circulation by combining with it to form chlorine nitrate ($ClNO_3$).

GAS	GREENHOUSE EFFECT	STRATOSPHERIC OZONE DEPLETION	ACID DEPOSITION	SMOG	CORROSION	DECREASED VISIBILITY	DECREASED SELF-CLEANSING OF ATMOSPHERE
CARBON MONOXIDE (CO)							+
CARBON DIOXIDE (CO_2)	+	+/−					
METHANE (CH_4)	+	+/−					+/−
NO_x: NITRIC OXIDE (NO) AND NITROGEN DIOXIDE (NO_2)		+/−	+	+		+	−
NITROUS OXIDE (N_2O)	+	+/−					
SULFUR DIOXIDE (SO_2)	−		+		+	+	
CHLOROFLUORO-CARBONS	+	+					
OZONE (O_3)	+			+			−

GAS	MAJOR ANTHROPOGENIC SOURCES	ANTHROPOGENIC/ TOTAL EMISSIONS PER YEAR (MILLIONS OF TONS)	AVERAGE RESIDENCE TIME IN ATMOSPHERE	AVERAGE CONCENTRATION 100 YEARS AGO (PPB)	APPROXIMATE CURRENT CONCENTRATION (PPB)	PROJECTED CONCENTRATION IN YEAR 2030 (PPB)
CARBON MONOXIDE (CO)	Fossil-Fuel Combustion, Biomass Burning	700/2,000	Months	?, N. Hem. 40 to 80, S. Hem. (Clean Atmospheres)	100 to 200, N. Hem. 40 to 80, S. Hem. (Clean Atmospheres)	Probably Increasing
CARBON DIOXIDE (CO_2)	Fossil-Fuel Combustion, Deforestation	5,500/~5,500	100 Years	290,000	350,000	400,000 to 550,000
METHANE (CH_4)	Rice Fields, Cattle, Landfills, Fossil-Fuel Production	300 to 400/550	10 Years	900	1,700	2,200 to 2,500
NO_x GASES	Fossil-Fuel Combustion, Biomass Burning	20 to 30/ 30 to 50	Days	.001 to ? (Clean to Industrial)	.001 to 50 Clean to Industrial)	.001 to 50 (Clean to Industrial)
NITROUS OXIDE (N_2O)	Nitrogenous Fertilizers, Deforestation, Biomass Burning	6/25	170 Years	285	310	330 to 350
SULFUR DIOXIDE (SO_2)	Fossil-Fuel Combustion, Ore Smelting	100 to 130/ 150 to 200	Days To Weeks	.03 to ? (Clean to Industrial)	.03 to 50 (Clean to Industrial)	.03 to 50 (Clean to Industrial)
CHLOROFLUORO-CARBONS	Aerosol Sprays, Refrigerants, Foams	~1/1	60 to 100 Years	0	About 3 (Chlorine atoms)	2.4 to 6 (Chlorine atoms)

TRACE GASES and the environmental perturbations with which they are associated are listed (*top*). Plus signs indicate a contribution to the effect; minus signs indicate amelioration. Sometimes a gas's effect varies, as is indicated by dual signs (+/−). In particular, the effects of carbon dioxide, the NO_x gases and nitrous oxide on stratospheric ozone depletion depend on altitude. Methane generally ameliorates the effect, except in the ozone hole, and its tendency to diminish the self-cleansing of the atmosphere (by reducing the abundance of hydroxyl) is different in the north and south; methane diminishes self-cleansing in the Southern Hemisphere but has the opposite effect in the Northern Hemisphere. The concentrations of many gases, given in parts per billion (ppb), are expected to be significantly higher 40 years from now (*bottom*) if anthropogenic emissions continue to increase. For gases with lifetimes of years, estimated global averages are listed. The concentrations of the NO_x gases and sulfur dioxide over highly industrial sites may not rise much in 40 years, but the number of polluted sites can be expected to grow, particularly in the developing nations. Chlorofluorocarbon concentrations are given in terms of chlorine atoms because the molecules generally contain more than one ozone-destroying chlorine atom.

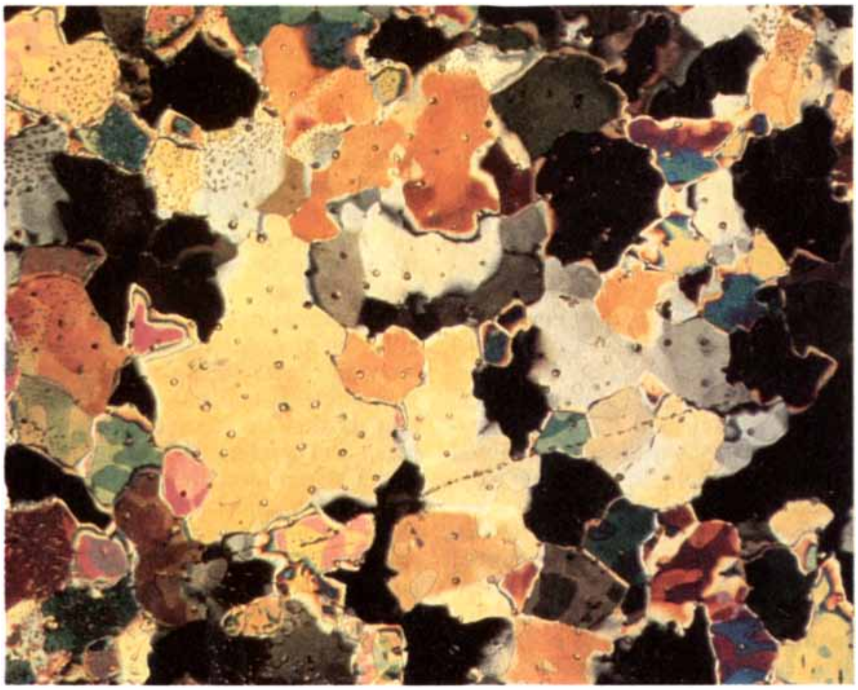
ern spring since about 1975. In the past decade springtime ozone levels over Antarctica have diminished by about 50 percent [see "The Antarctic Ozone Hole," by Richard S. Stolarski; SCIENTIFIC AMERICAN, January, 1988]. A more global assessment of the stratospheric ozone layer is still in a preliminary stage, but in the past 20 years depletions of from 2 to 10 percent have apparently begun to occur during the winter and early spring in the middle-to-high latitudes of the Northern Hemisphere, with the greatest declines in the higher latitudes.

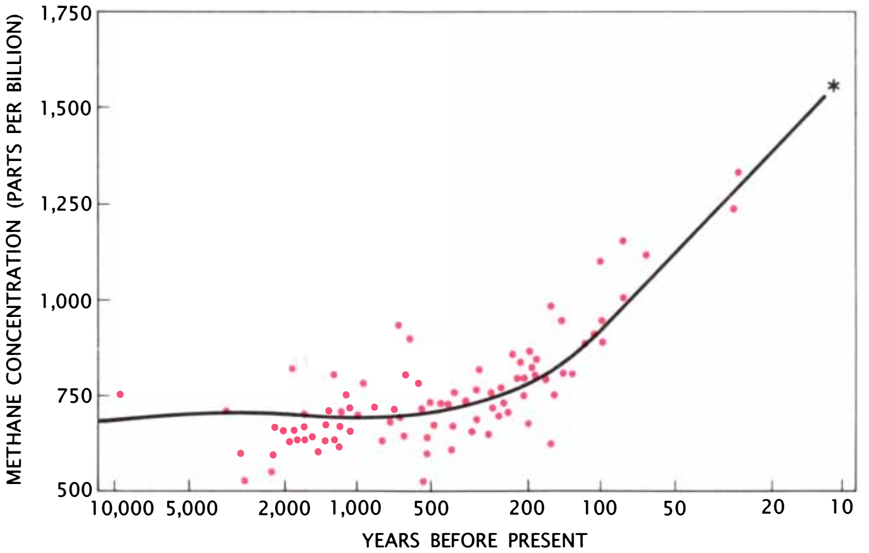
It is now quite evident that chlorofluorocarbons, particularly CFC-11 ($CFCl_3$) and CFC-12 (CF_2Cl_2), are the major culprits responsible for ozone depletion. These anthropogenic chemicals, whose emissions and atmospheric concentrations have grown rapidly since their introduction several decades ago, are widespread as refrigerants, aerosol propellants, solvents and blowing agents for foam production, in part because they have what initially seemed to be a wonderful property: they are virtually unreactive in the lower atmosphere, and so they pose no direct toxic threat to living organisms.

Unfortunately, the very same characteristics that render chlorofluorocarbons rather inert enable them to reach the stratosphere unchanged. There they are exposed to strong ultraviolet radiation, which breaks them apart and liberates chlorine atoms that can destroy ozone by catalyzing its conversion to molecular oxygen. (Catalysts accelerate chemical reactions but are freed unaltered at the end.) Indeed, every chlorine atom ultimately eliminates many thousands of ozone molecules. Primarily because of the emission of chlorofluorocarbons, the level of ozone-destroying chlorinated compounds in the stratosphere is now four to five times higher than normal and is increasing at a rate of approximately 5 percent a year—developments that highlight the profound effect human activity can have on the stratosphere.

Stratospheric ozone (O_3) is formed initially when an oxygen molecule (O_2) absorbs shortwave radiation, which splits it into two oxygen atoms (O); each atom then combines with another oxygen molecule to form ozone. Usually, photochemical reactions catalyzed by the NO_x gases remove ozone at a rate equal to the rate of its formation. Chlorine catalytic cycles, which are growing rapidly in importance in the atmosphere, disturb this natural balance and result in a net ozone loss [*see box on page 61*].

Particularly in Antarctica and to a lesser extent in the Arctic, frigid temperatures hasten the chlorine-catalytic cycles by removing nitrogen oxides, which strongly interfere with them. (Paradoxically, then, although the NO_x gases can destroy ozone, their presence in the stratosphere often ameliorates chlorine-catalyzed ozone destruction.) Together with water molecules, the NO_x gases freeze to form particles making up what are known as polar stratospheric clouds. Worse yet, the cloud particles actually facilitate chemical reactions that release chlorine from compounds that do not





CRYSTALS OF ICE in a sample taken from the Greenland ice sheet and photographed in polarized light are about 1,000 years old. The very small air bubbles that are visible hold clues to the ancient concentrations of trace gases, including the greenhouse gases carbon dioxide and methane. Studies of ice cores from Greenland and Antarctica indicate that the average global concentration of methane held steady near 700 ppb between 10,000 and 300 years ago and then began a dramatic climb about 100 years ago (*bottom*). The red dots represent data from the ice; the asterisk represents the average global value for the late 1970's: about 1,500 ppb. The micrograph was made by Chester C. Langway, Jr., of the State University of New York at Buffalo.

themselves react with ozone, such as hydrochloric acid (HCl) and chlorine nitrate ($ClNO_3$).

Even if chlorofluorocarbon emissions stopped today, chemical reactions causing the destruction of stratospheric ozone would continue for at least a century. The reason is simple: the compounds remain that long in the atmosphere and would continue to diffuse into the stratosphere from the tropospheric reservoir long after emissions had ceased.

The depletion of global stratospheric ozone seems to be the handiwork primarily of a single class of industrial products—the chlorofluorocarbons—but several different emissions combine to raise the specter of a rapid greenhouse warming of the earth. Exactly how high global temperatures might climb in the years ahead is not yet clear. What is clear is that the levels of such infrared-absorbing trace gases as carbón dioxide, methane, the chlorofluorocarbons and nitrous oxide have mounted dramatically in the past decades, making added heating inevitable.

The trapping of heat near the surface of the planet by naturally emitted trace gases is a vital process: without it the planet would be too cold for habitation. Yet the prospect of a sudden temperature increase of even a few degrees Celsius is disquieting because no one can accurately predict its environmental effects, such as what the precise changes will be in precipitation around the world and in sea level. Any effects will probably be rapid, however, making it extremely difficult or impossible for the world's ecosystems and for human societies to adapt.

The extraordinary pace of the recent increases in greenhouse gases becomes strikingly evident when modern levels are compared with those of the distant past. Such comparisons have been made for several gases, including carbon dioxide—which alone accounts for more than half of the heat trapped by trace species—and methane, which is a more efficient infrared absorber than carbon dioxide but is significantly less abundant.

The histories of carbon dioxide and methane can be reconstructed on the basis of their concentrations in bubbles of air trapped in ice in such perpetually cold places as Antarctica and Greenland. Because the gases are long-lived and hence are spread fairly evenly throughout the atmosphere, the polar samples reveal the approximate global average concentrations of previous eras.

Analyses of the bubbles in ice samples indicate that carbon dioxide and methane concentrations held steady from the end of the last ice age some 10,000 years ago until roughly 300 years ago, at close to 260 parts per million and 700 parts per billion, respectively. Some 300 years ago the methane levels began to climb, and roughly 100 years ago the levels of both gases began to soar to their current levels of 350 parts per million for carbon dioxide and 1,700 parts per billion for methane. Moreover, direct worldwide measurements made by several investigators during the past decade have shown that atmospheric methane levels are growing more rapidly than those of carbon dioxide, at the remarkably high rate of about 1 percent a year.

The increases of both gases in the 20th century must be attributed in large part to the many expanding human influences on emissions. For carbon dioxide the sources are mainly fossil-fuel combustion and deforestation in the tropics; for methane, mainly rice cultivation, cattle breeding, biomass burning in tropical forests and savannas, microbial activity in municipal landfills and leakage of gas during the recovery and distribution of coal, oil and natural gas. As the world's population grows during the next century—and with it the demand for more energy, rice and meat products—the atmospheric concentration of methane could double. The climatic warming caused by methane and other trace gases could well approach that caused by carbon dioxide.

What are the expected trends for other trace gases? We as well as several other workers have extrapolated from the past and the present to make projections for the future, taking into account such factors as estimated increases both in population and in energy consumption. The estimates indicate that increases can be expected in the atmospheric concentrations of virtually all trace species in the next 100 years if new technologies and major energy-conservation efforts are not instituted to diminish the expected dependence on high-sulfur coal, an environmentally disadvantageous fuel, as the world's major energy source.

For example, as part of a multicenter collaboration, we have looked at past sulfur dioxide concentrations over the eastern U.S. and Europe (estimated prior to the mid-1960's on the basis of emission rates) and have speculated about future levels there and over the little-industrialized Gangetic Plain of India [*see illustration on page 68*]. The historical assessment for the U.S. shows a marked increase in sulfur dioxide concentrations between 1890 and 1940, paralleling the buildup of "smokestack" industries and the construction of many new power plants. The amount of sulfur dioxide then leveled off and decreased in the 1960's and early 1970's. To a great extent, the decrease reflects the increased exploitation of oil (which is low in sulfur) for energy as well as the success of clean-air legislation in curbing sulfur emissions.

The concentrations of sulfur dioxide increased over Europe between 1890 and the mid-1900's but then leveled off; they did not decline appreciably, because until recently emission-control efforts were less vigorous than in the U.S. For the Gangetic Plain, where industrialization is rather recent, sulfur dioxide concentrations over some places have climbed from almost nothing in 1890 to levels that are now approaching those over the northeastern U.S.

The average sulfur dioxide concentrations over all three large regions are expected to increase, in part because low-sulfur fuels will probably become scarcer (although extremely stringent emission controls could stabilize levels over the U.S. and Europe for a few decades). The increases could be most marked over India and other developing countries that have rapidly growing populations and access to abundant supplies of high-sulfur coal, which is relatively inexpensive. Clearly, major measures must be introduced in the energy sector to prevent sulfur dioxide concentrations from rising extremely high.

Increases may also occur in a gas we have not yet discussed in detail: carbon monoxide, which has the power to decrease the self-cleansing ability of the atmosphere. A rise in carbon monoxide concentrations is likely because its sources—fossil-fuel combustion, biomass burning and atmospheric reactions involving methane—are all expected to increase. On the other hand, a significant (but still not well-quantified) amount of the gas is formed in the atmosphere over the tropics from the breakdown of hydrocarbons emitted by vegetation, a source that human activities are removing. The future concentrations of carbon monoxide are therefore uncertain, although on balance many workers foresee a rise over the Northern Hemisphere.

Carbon monoxide undermines the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self-cleansing ability of the atmosphere by lowering the concentration of the hydroxyl radical, which is an important "detergent" because it reacts with nearly every trace-gas molecule in the atmosphere, including substances that would otherwise be inert. Without hydroxyl, the concentrations of most trace gases would become much higher than those of today, and the atmosphere as a whole would have totally different chemical, physical and climatic properties.

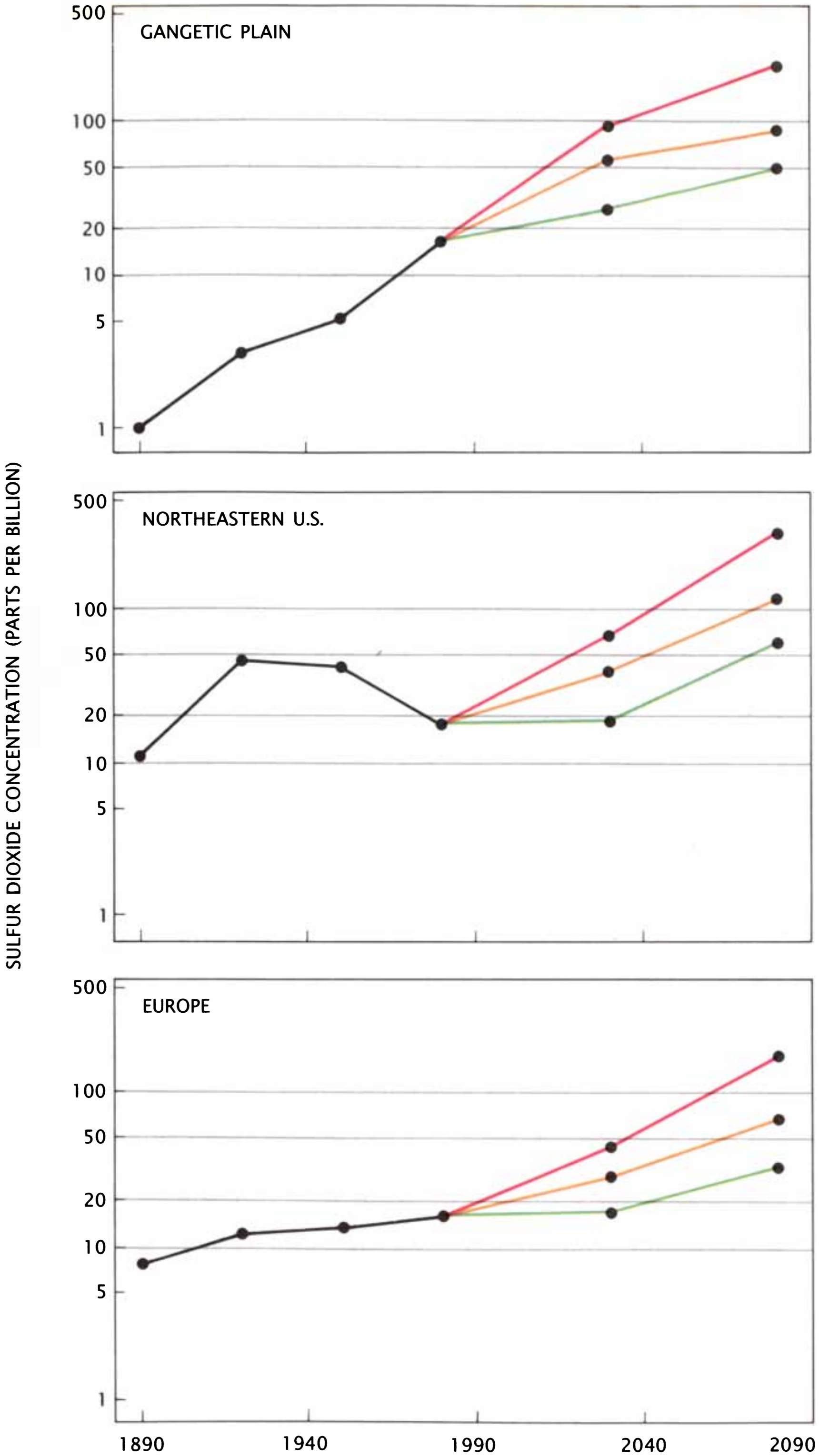
Our projections for the future are discouraging, then, if one assumes that human activities will continue to emit large quantities of undesirable trace gases into the atmosphere. Humanity's unremitting growth and development not only are changing the chemistry of the atmosphere but also are driving the earth rapidly toward a climatic warming of unprecedented magnitude. This climatic change, in combination with increased concentrations of various gases, constitutes a potentially hazardous experiment in which everyone on the earth is taking part.

What is particularly troubling is the possibility of unwelcome surprises, as human activities continue to tax an atmosphere whose inner workings and interactions with organisms and nonliving materials are incompletely understood. The Antarctic ozone hole is a particularly ominous example of the surprises that may be lurking ahead. Its unexpected severity has demonstrated beyond doubt that the atmosphere can be exquisitely sensitive to what seem to be small chemical perturbations and that the manifestations of such perturbations can arise much faster than even the most astute scientists could expect.

Nevertheless, some steps can be taken to counteract rapid atmospheric change, perhaps lessening the known and unknown threats. For example, evidence indicates that a major decrease in the rate of fossil-fuel combustion would slow the greenhouse warming, reduce smog, improve visibility and minimize acid deposition. Other steps could be targeted against particular gases, such as methane. Its emission could be reduced by instituting landfill operations that prevent its release and possibly by adopting less wasteful methods of fossil-fuel production. Methane emission from cattle might even be diminished by novel feeding procedures.

Perhaps more encouraging is the fact that many people and institutions are now aware that their actions can have not only local but also global consequences for the atmosphere and the habitability of the planet. A few recent events exemplify this aware-

PHOTOCHEMICAL SMOG, here shrouding São Paulo, Brazil, is a problem in many urban areas. It forms when solar radiation acts on emissions—notably nitrogen oxides and hydrocarbons from vehicle exhaust—to produce an undesirable mixture of gases near the ground. The major component is ozone (O_3), which can harm the eyes and lungs and damage trees and crops.



SULFUR DIOXIDE concentrations over newly industrializing regions, such as the Gangetic Plain of India, as well as over the northeastern U.S. and Europe have been reviewed (*black*) and projected 100 years ahead (*colors*). The projections assume that each region's population and energy consumption will grow and that the burning of coal for energy (a major source of sulfur dioxide) will increase. The projections differ according to how stringent emission controls might be: mild (*red*), moderate (*orange*) or severe (*green*). The findings indicate that sulfur dioxide levels are likely to increase, although extremely stringent control efforts could delay the rise over the U.S. and Europe. With increases also expected for several other trace gases, the authors emphasize the importance of global cooperation to minimize undesirable emissions and, thereby, their associated environmental perturbations.

ness: in the Montreal protocol of 1987, dozens of nations agreed to halve their chlorofluorocarbon emissions by the end of the century, and several countries and the major chlorofluorocarbon manufacturers have more recently announced their intention to eliminate the chemicals by that deadline. Some of the same nations that have been involved in the Montreal protocol are now discussing the possibility of an international "law of the atmosphere." It would be directed at limiting the release of several greenhouse and chemically active trace gases, including carbon dioxide, methane and nitrous oxide, as well as sulfur dioxide and the NO_x gases.

We and many others think the solution to the earth's environmental problems lies in a truly global effort, involving unprecedented collaboration by scientists, citizens and world leaders. The most technologically developed nations have to reduce their disproportionate use of the earth's resources. Moreover, the developing countries must be helped to adopt environmentally sound technologies and planning strategies as they elevate the standard of living for their populations, whose rapid growth and need for increased energy are a major cause for environmental concern. With proper attention devoted to maintaining the atmosphere's stability, perhaps the chemical changes that are now occurring can be kept within limits that will sustain the physical processes and the ecological balance of the planet.

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The Changing Climate

Global warming should be unmistakable within a decade or two. Prompt emission cuts could slow the buildup of heat-trapping gases and limit this risky planetwide experiment

by Stephen H. Schneider

In 1957 Roger Revelle and Hans E. Suess of the Scripps Institution of Oceanography observed that humanity is performing a "great geophysical experiment," not in a laboratory, not in a computer, but on our own planet. The outcome of the experiment should be clear within decades, but it essentially began at the start of the Industrial Revolution. Since then human beings have increased the atmospheric content of carbon dioxide by about 25 percent by burning coal, oil and other fossil fuels and by clearing forests, which releases carbon dioxide as the litter is burned or decays.

Carbon dioxide makes up only a thirtieth of 1 percent of the atmosphere, but together with water vapor and other gases present in much smaller quantities, such as methane and the chlorofluorocarbons (CFC's), it plays a major role in determining the earth's climate. As early as the 19th century it was recognized that carbon dioxide in the atmosphere gives rise to a greenhouse effect. The glass of a greenhouse allows sunlight to stream in freely but blocks heat from escaping, mainly by preventing the warm air inside the greenhouse from mixing with outside air. Similarly, carbon dioxide and other greenhouse gases are relatively transparent to sunshine but trap heat by more efficiently absorbing the longer-wavelength infrared radiation released by the earth.

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By now the atmosphere's heat-trapping ability has been well established. For example, as seen from space, the earth radiates energy at wavelengths and intensities characteristic of a body at −18 degrees Celsius. Yet the average temperature at the surface is some 33 degrees higher: heat is trapped between the surface and the level, high in the atmosphere, from which radiation escapes. There is virtually no doubt among atmospheric scientists that increasing the concentration of carbon dioxide and other gases will increase the heat trapping and warm the climate.

What, then, is the question that the ongoing geophysical experiment will settle? Even though there is virtually no debate among scientists about the greenhouse effect as a scientific proposition, there is controversy. Will the rising concentrations of greenhouse gases raise the earth's temperature by one, five or eight degrees C? Will the increase take 50, 100 or 150 years? Will it be drier in Iowa or wetter in India? There is still more controversy when it comes to policy: Should steps be taken to reduce the greenhouse warming or to anticipate its effects? What steps, and when? In the face of so much controversy, an understanding of what is well known, known slightly and not known at all about the greenhouse warming is essential.

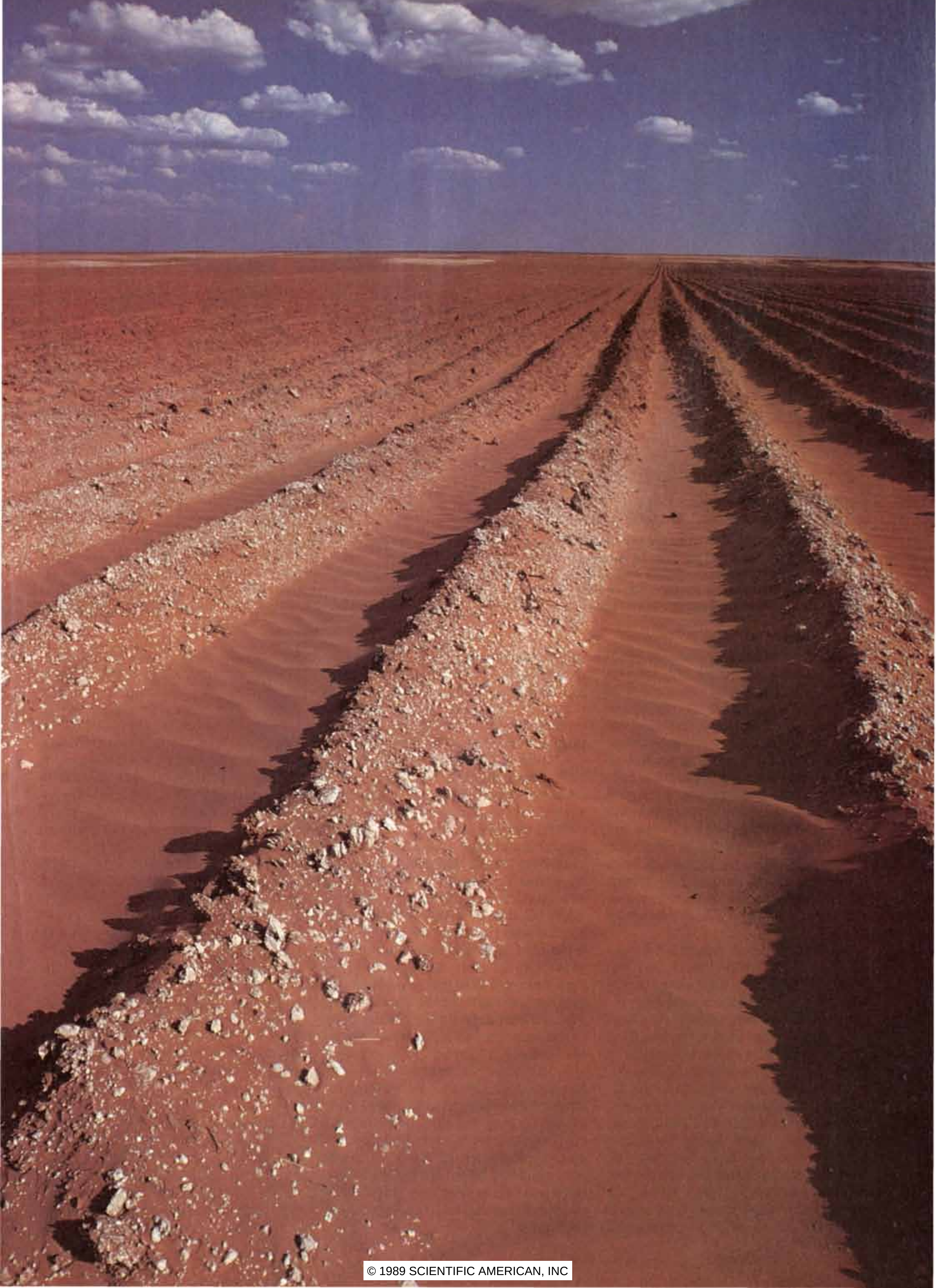
Circumstantial evidence from the geologic and historical past bears out a link between climatic change and fluctuations in greenhouse gases. Between 3.5 and four billion years ago the sun is thought to have been about 30 percent fainter than it is today. Yet life evolved and sedimentary rock formed under the faint young sun: at least some of the earth's surface was above the freezing point of water. Some workers have proposed that the early atmosphere contained as much as 1,000 times today's level of carbon dioxide, which compensated for the sun's feeble radiation by its heat-trapping effect.

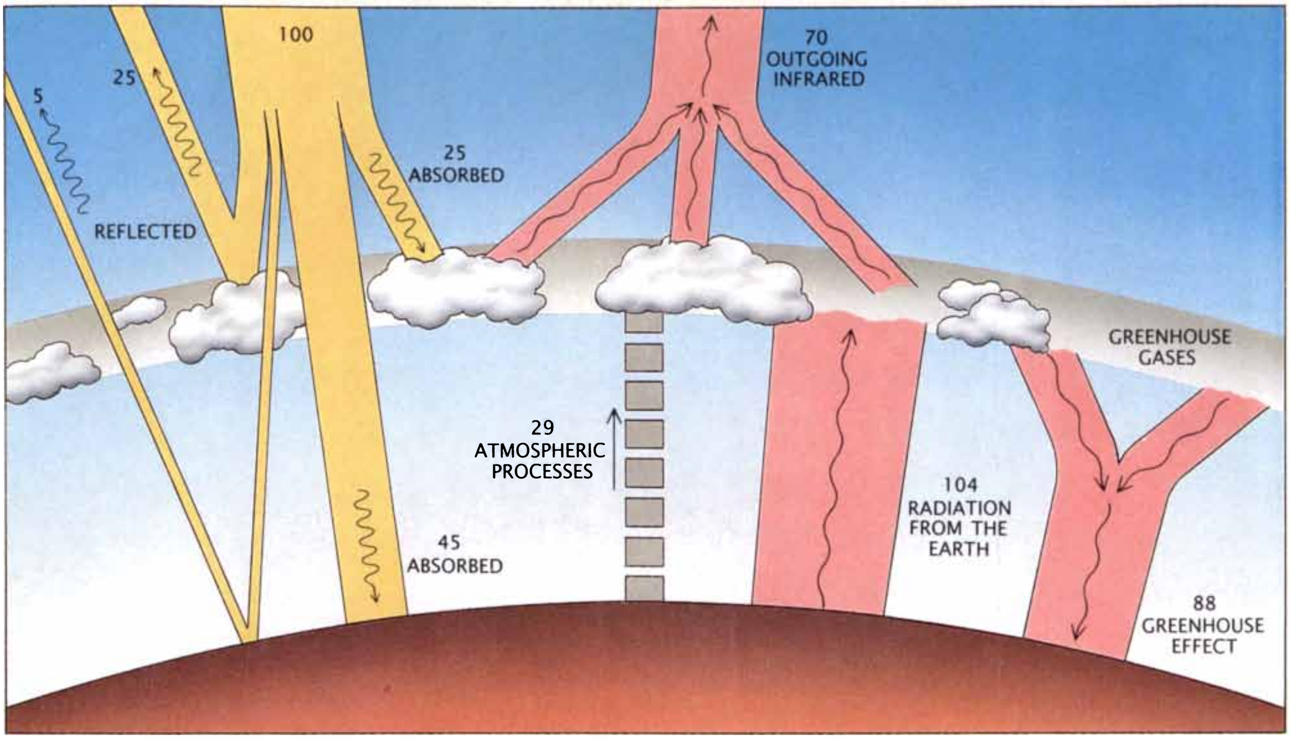
Later an enhanced greenhouse effect may have been partly responsible for the warmth of the Mesozoic era—the age of the dinosaurs—which fossil evidence suggests was perhaps 10 or 15 degrees C warmer than today. At the time, 100 million years ago and more, the continents occupied different positions than they do now, altering the circulation of the oceans and perhaps increasing the transport of heat from the Tropics to high latitudes. Yet calculations by Eric J. Barron, now at Pennsylvania State University, and others suggest that paleocontinental geography can explain no more than half of the Mesozoic warming.

Increased carbon dioxide can readily explain the extra heating, as Aleksandr B. Ronov and Mikhail I. Budyko of the Leningrad State Hydrological Institute first proposed and as Barron, Starley L. Thompson of the National Center for Atmospheric Research (NCAR) and I have calculated. A geochemical model constructed by Robert A. Berner and Antonio C. Lasaga of Yale University and the late Robert M. Garrels of the University of South Florida suggests that the carbon dioxide may have been released by unusually heavy volcanic activity on the mid-ocean ridges, where new ocean floor is created by upwelling magma [see "The Geochemical Carbon Cycle," by Robert A. Berner and Antonio C. Lasaga; SCIENTIFIC AMERICAN, March].

Direct evidence linking greenhouse gases with the dramatic climatic changes of the ice ages comes from bubbles of air trapped in the Antarctic ice sheet by the ancient snowfalls that

PARCHED FIELDS turn to sand during a 1983 dry spell in Texas. Such images could multiply if, as several computer models predict, global warming reduces soil moisture in midcontinental regions, where grain production is concentrated.





HEAT TRAPPING in the atmosphere dominates the earth's energy balance. Some 30 percent of incoming solar energy is reflected (*left*), either from clouds and particles in the atmosphere or from the earth's surface; the remaining 70 percent is absorbed. The absorbed energy is reemitted at infrared wavelengths by the atmosphere (which is also heated by updrafts and cloud formation) and by the surface. Because most of the surface radiation is trapped by clouds and greenhouse gases and returned to the earth, the surface is currently about 33 degrees Celsius warmer than it would be without the trapping.

built up to form the ice. A team headed by Claude Lorius of the Laboratory of Glaciology and Geophysics of the Environment, near Grenoble, examined more than 2,000 meters of ice cores—a 160,000-year record—recovered by a Russian drilling project at the Vostok Station in Antarctica. Laboratory analysis of the gases trapped in the core showed that carbon dioxide and methane levels in the ancient atmosphere varied in step with each other and, more important, with the average local temperature (determined from the ratio between hydrogen isotopes in the water molecules of the ice).

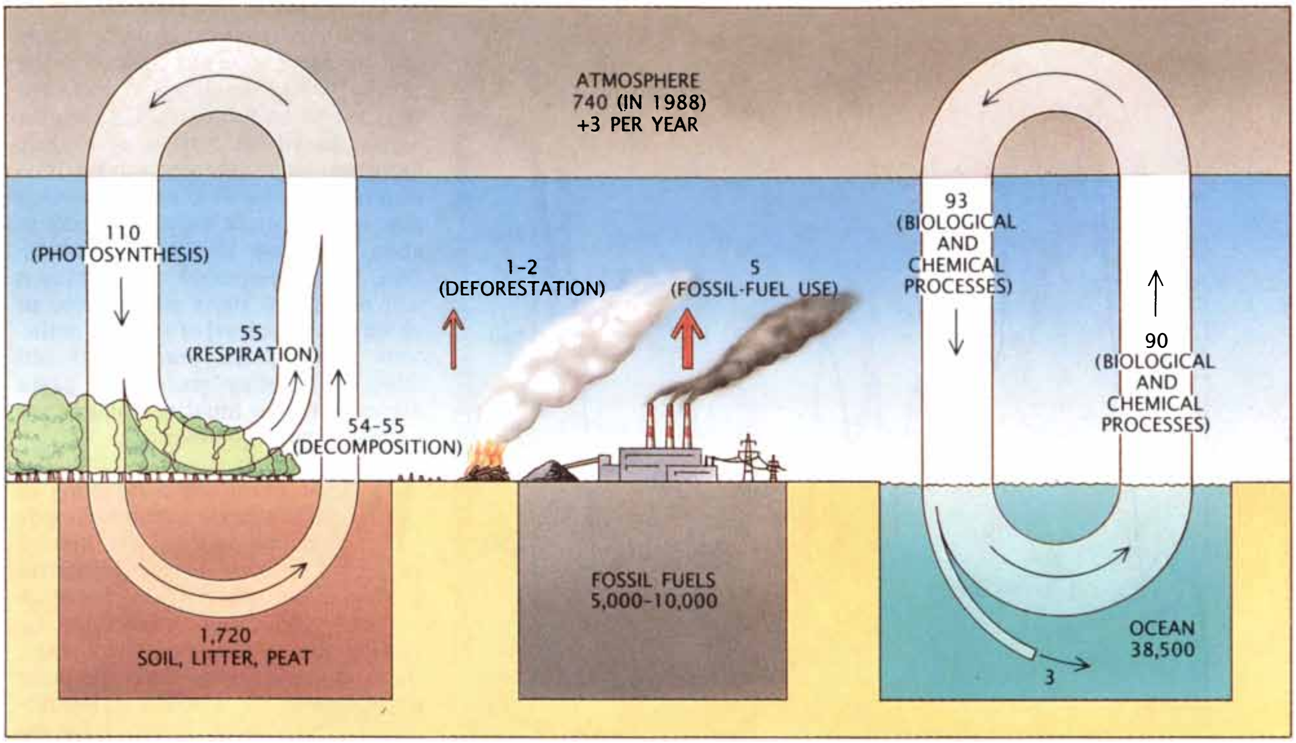
During the current interglacial period (the past 10,000 years) and the previous one, a 10,000-year period around 130,000 years ago, the ice recorded a local temperature about 10 degrees C warmer than at the height of the ice ages. (The earth as a whole is about five degrees warmer during interglacials.) At the same time, the atmosphere contained about 25 percent more carbon dioxide and 100 percent more methane than during the glacial periods. It is not clear whether the greenhouse-gas variations caused the climatic changes or vice versa. My guess is that the ice ages were paced by other factors, such as changes in the earth's orbital parameters and the dynamics of ice buildup and retreat, but biological changes and shifts in ocean circulation in turn affected the atmosphere's trace-gas content, amplifying the climatic swings.

A still more detailed record of greenhouse gases and climate comes from the past 100 years, which have seen a further 25 percent increase in carbon dioxide above the interglacial level and another doubling of atmospheric methane. Two groups, one led by James E. Hansen at the National Aeronautics and Space Administration's Goddard Institute for Space Studies and the other by T. M. L. Wigley at the Climatic Research Unit of the University of East Anglia, have constructed records of global average surface temperature for the past century. The workers drew on data from many of the same recording stations around the globe (the Climatic Research Unit also included readings made at sea), but they had different techniques for analyzing the records and compensating for their shortcomings. Certain recording stations were moved over the course of the century, for example, and readings from city centers may have been skewed by heat released by machinery or stored by buildings and pavement.

This "urban heat island" effect is likely to have been disproportionately large in developed countries such as the U.S., but even when the same correction calculated for the U.S. data (by Thomas R. Karl of the National Climatic Data Center in Asheville, N.C., and P. D. Jones of East Anglia) is applied to the global data set, about half a degree C of unexplained "real" warming over the past 100 years remains in both records. In keeping with the trend, the 1980's appear to be the warmest decade on record and 1988, 1987 and 1981 the warmest years, in that order.

Is this the signal of the greenhouse warming? It is tempting to accept it as such, but the evidence is not definitive. For one thing, instead of the steady warming one might expect from a steady buildup of greenhouse gases, the record shows rapid warming until the end of World War II, a slight cooling through the mid-1970's and a second period of rapid warming since then.

What trajectory will the temperature curve follow now? Three basic questions must be answered in forecasts of the climatic future: How much carbon dioxide and other greenhouse gases will be emitted? By how much will atmospheric



CARBON IS EXCHANGED between the atmosphere and reservoirs on the earth. The numbers give the approximate annual fluxes of carbon (in the form of carbon dioxide) and the approximate amount stored in each reservoir in billions of metric tons. The existing cycles—one on land and the other in the oceans—remove about as much carbon from the atmosphere as they add, but human activity (deforestation and fossil-fuel burning) is currently increasing atmospheric carbon by some three billion metric tons yearly. The numbers are based on work by Bert Bolin of the University of Stockholm.

levels of the gases increase in response to the emissions? What climatic effects will the resulting buildups have, after natural and human factors that might mitigate or amplify those effects are taken into account?

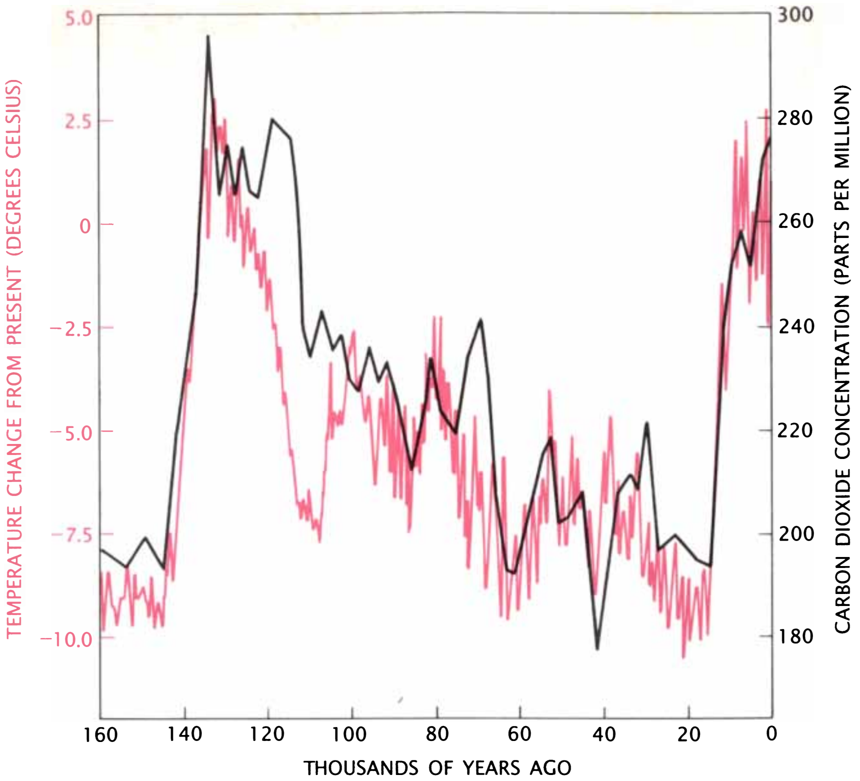
Projecting emissions is an intricate exercise in social science. How much carbon dioxide humanity as a whole will be emitting in the future depends primarily on the global consumption of fossil fuels and the rate of deforestation (which accounts for perhaps half of the buildup since the year 1800 and 20 percent of current emissions). Each factor in turn is affected by many others. Growth in fossil-fuel use, for example, will reflect population growth, the rate at which alternative energy sources and conservation measures are adopted and the state of the world economy. Typical projections assume that global fossil-fuel consumption will continue increasing at about its current pace—much slower than it grew before the energy crisis of the 1970's—yielding increases in carbon dioxide emissions of between .5 and 2 percent a year for the next several decades at least.

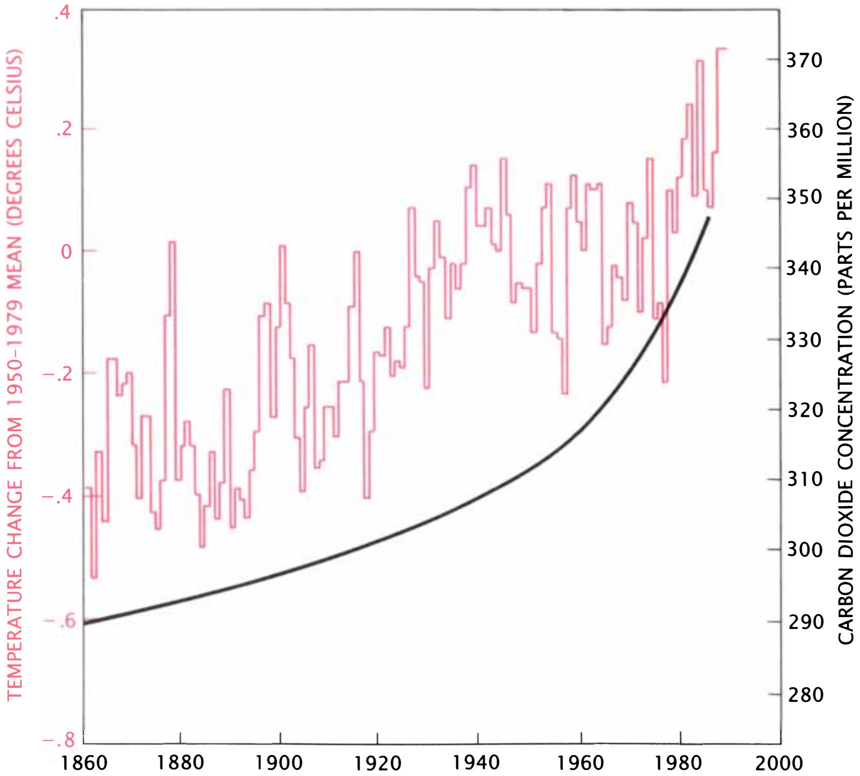
Other greenhouse gases, such as methane, the CFC's, oxides of nitrogen and low-level ozone, together could contribute as much to global warming as carbon dioxide, even though they are emitted in much smaller quantities: they are much better at absorbing infrared radiation. But predicting future emissions for these gases is even more complicated than it is for carbon dioxide. The sources of some gases, such as methane, are not well understood; the production of other gases, such as the CFC's and low-level ozone, could rise or fall sharply depending on whether specific technological or policy steps are taken.

Given a plausible scenario for future carbon dioxide emissions, how fast will the atmospheric concentration increase in response? Atmospheric carbon dioxide is continuously being absorbed by green plants and by chemical and biological processes in the oceans. The rate of carbon dioxide uptake is likely to change as the atmospheric concentration changes; that is, feedback processes will enter the equation. Because carbon dioxide is a raw material of photosynthesis, an increased concentration might speed the uptake by plants, counteracting some of the buildup. Similarly, because the carbon dioxide content of the oceans' surface waters stays roughly in equilibrium with that of the atmosphere, oceanic uptake will slow the buildup to some extent. (The slower the buildup is in the first place, the more effective, proportionally, oceanic uptake is likely to be.)

It is also possible, however, that an increased concentration of carbon dioxide and other greenhouse gases will trigger positive feedbacks that would add to the atmospheric burden. Rapid change in climate could disrupt forests and other ecosystems, reducing their ability to draw carbon dioxide down from the atmosphere. Moreover, climatic warming could lead to rapid release of the vast amount of carbon held in the soil as dead organic matter. This stock of carbon—at least twice as much as is stored in the atmosphere—is continuously being decomposed into carbon dioxide and methane by the action of soil microbes. A warmer climate might speed their work, releasing additional carbon dioxide (from dry soils) and methane (from rice paddies, landfills and wetlands) that would enhance the warming. Large quantities of methane are also locked up in continental-shelf sediments and below arctic permafrost in the form of clathrates—molecular lattices of methane and water. Warming of the shallow waters of the oceans and melting of the permafrost could release some of the methane.

In spite of all these uncertainties,





CARBON DIOXIDE AND TEMPERATURE are very closely correlated over the past 160,000 years (*top*) and, to a lesser extent, over the past 100 years (*bottom*). The long-term record, based on evidence from Antarctica, shows how the local temperature (*color*) and atmospheric carbon dioxide rose nearly in step as an ice age ended about 130,000 years ago, fell almost in synchrony at the onset of a new glacial period and rose again as the ice retreated about 10,000 years ago. The recent temperature record shows a slight global warming (*color*), as traced by workers at the Climatic Research Unit of the University of East Anglia. Whether the accompanying buildup of carbon dioxide in the atmosphere caused the half-degree warming is hotly debated.

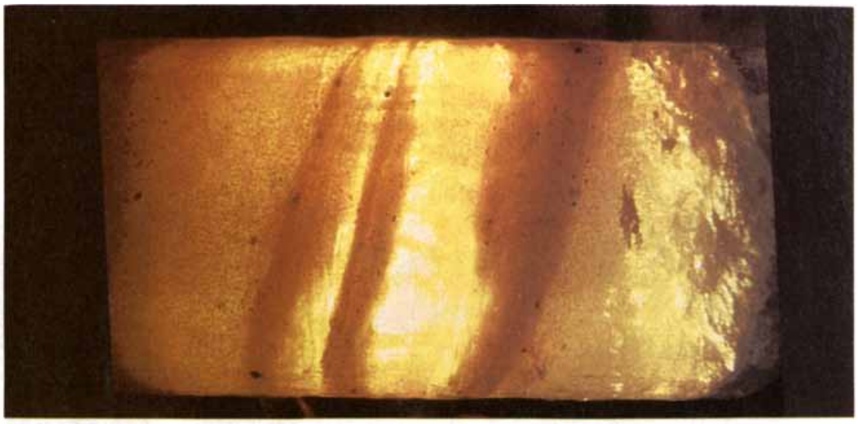
many workers expect uptake by plants and by the oceans to moderate the carbon dioxide buildup, at least for the next 50 or 100 years. Typical estimates, based on current or slightly increased emission rates, put the fraction of newly injected carbon dioxide that will remain in the atmosphere at about one half. Under that assumption, the atmospheric concentration will reach 600 parts per million, or about twice the level of 1900, by sometime between the years 2030 and 2080. Some other greenhouse gases are expected to build up faster than carbon dioxide, however.

What effect will a doubling of atmospheric carbon dioxide have on climate? The historical record offers no clear quantitative guidance. Nor can climate—the product of complicated interactions involving the atmosphere, the oceans, the land surface, vegetation and polar ice—be physically reproduced in a laboratory experiment. In exploring the future of the earth's climate, my colleagues and I rely on mathematical climate models.

The models, which have been built at Princeton University's Geophysical Fluid Dynamics Laboratory, the Goddard Institute for Space Studies, here at NCAR and elsewhere, consist of expressions for the interacting components of the ocean-atmosphere system and equations representing the basic physical laws governing their behavior, such as the ideal gas laws and the conservation of mass, momentum and energy. Given values for, say, the input of energy from the sun and the composition of the atmosphere, a model calculates "climate"—temperature and, in sophisticated models, pressure, wind speed, humidity, soil moisture and other variables.

To keep the task computationally manageable, the calculations are done at discrete points in a simplified version of the real world. In the most complicated models—global-circulation models (GCM's), which were first developed for long-term weather forecasts—the atmosphere is represented as a three-dimensional grid with an average horizontal spacing of several hundred kilometers and an average vertical spacing of several kilometers; climate is calculated only at the intersections of the grid lines. In spite of the simplification, running such a GCM for only one simulated year can take many hours on the fastest available supercomputers.

To study the effect of a trace-gas buildup, a modeler simply specifies the projected amount of greenhouse gases and compares the model results with a control simulation of the existing climate, based on the present atmospheric composition. The results of the most recent GCM's are in rough agreement: a doubling of carbon dioxide, or an equivalent increase in other trace gases, would warm the earth's average surface temperature by between 3.0 and 5.5 degrees C. Such a change would be unprecedented in human history; it would match the five-degree warming since the peak of the last ice age 18,000 years ago but would take effect between 10 and 100 times faster.



ICE CORE—a segment of a two-kilometer core drilled from the Antarctic ice sheet at the Soviet Union's Vostok Station—contains trapped bubbles of ancient air. Analysis of the bubbles and of the ratio of hydrogen isotopes in the ice, which varies with local temperature, enabled Claude Lorius and his colleagues at the Laboratory of Glaciology and Geophysics of the Environment, near Grenoble, to reconstruct a 160,000-year record of trace gases and temperature (*see top illustration on opposite page*).

The shortcomings of computer models limit the reliability of such forecasts. Many processes that affect global climate are simply too small to be seen at the coarse resolution of a model. Such climatically important processes as atmospheric turbulence, precipitation and cloud formation take place on a scale not of hundreds of kilometers (the scale of the grid in a GCM) but of a few kilometers or less. Since such processes cannot be simulated directly, modelers must find a way of relating them to variables that can be simulated on the model's coarse scale. They do so by developing a parameter—a proportionality coefficient—that relates, say, the average cloudiness within a grid cell to the average humidity and temperature (something the model can calculate).

This strategy, known as parameterization, has the effect of aggregating small-scale phenomena that could act as feedbacks on climatic change, either amplifying or moderating it. Clouds, for example, reflect sunlight back to outer space (tending to cool the climate) and also absorb infrared radiation from the earth (tending to warm it). Which effect dominates depends on the clouds' brightness, height, distribution and extent. Recent satellite measurements have confirmed two-decade-old calculations showing that clouds currently have a net cooling effect; the earth as a whole would be much warmer under cloudless skies. But climatic change might cause incremental changes in cloud characteristics, altering the nature and amount of the feedback. Present models, crudely reproducing only average cloudiness, can say little that is reliable about cloud feedback—or about the many other feedbacks that depend on parameterized processes.

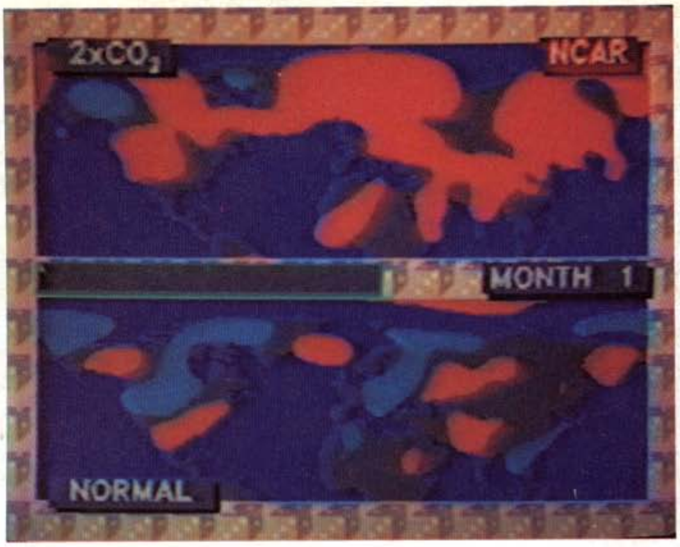
Another shortcoming of present models is their crude treatment of the oceans. The oceans exert potent effects on the present climate and will surely influence climates to come. Their enormous thermal mass will act as a "thermal sponge," slowing any initial increase in global temperature while the oceans themselves warm up. The magnitude of the effect will depend on ocean circulation, which in turn may change as the earth warms. In principle, a climate model should couple a simulated atmosphere with oceans whose dynamics are simulated in equal detail. The computational challenge is staggering, however, and in most GCM's applied to greenhouse warming the dynamics of the oceans are simplified, treated at coarse resolution or left out.

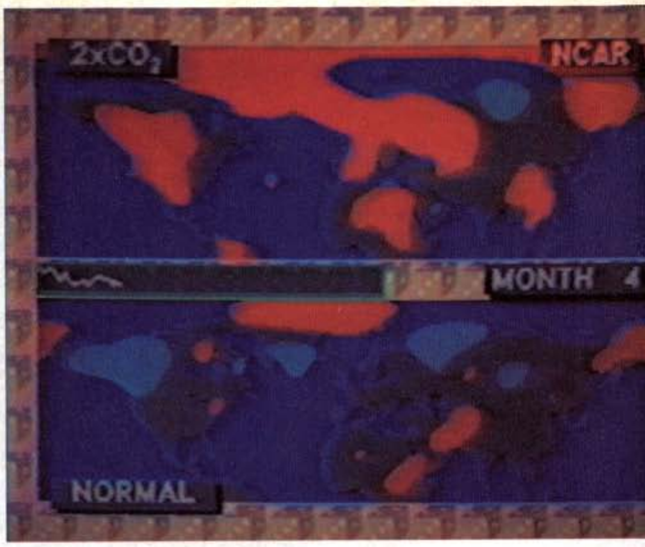
In addition to limiting the reliability of global forecasts, the simplified treatment of the oceans also prevents the models from giving a definitive picture of how climate will change over time in specific regions. Ideally one would like to know not only how much the world as a whole will warm but also whether it will, say, get drier in Iowa, wetter in India or more humid in New York City. Yet, as long as the oceans are out of equilibrium with the atmosphere, their thermal effects will be felt differently at different places. An area in which there is little mixing between surface waters and cold, deep waters might warm quickly; high-latitude regions where deep water is mixed up to the surface might warm more slowly. These thermal effects could in turn affect wind patterns, thereby altering other regional variables, including humidity and rainfall. (Regional forecasts are also compromised in many models by simplified representations of vegetation, which ignore climatically important processes such as the release of water vapor by plants and their effect on surface albedo, or reflectiveness.)

Nevertheless, climatologists have grounds for considerable confidence in their models' forecasts of global surface-temperature change. Individual model elements can be verified by comparing them with the results of a more detailed submodel—a smaller, finer-scale simulation—or with real data. Cloud parameterizations, for example, can be tested against actual measurements of the relation of temperature and humidity to cloudiness within an area corresponding to a cell in the model.

The skill of a model as a whole, and in particular its ability to account for relatively fast processes, such as changes in atmospheric circulation or average cloudiness, can be verified by checking its ability to reproduce the seasonal cycle—a twice-yearly change in hemispheric climate that is larger than any projected greenhouse warming. In spite of parameterization, most GCM's map the seasonal cycle of surface temperature quite well, but their ability to simulate seasonal changes in other climatic variables, including precipitation and relative humidity, has not been studied as thoroughly.

During the course of decades (the expected time scale for unmistakable global warming), other, slower processes that do not affect the seasonal cycle come into play: changes in ocean currents or in the extent of glaciers, for instance. Simulations of past climates—the ice ages or the Mesozoic hothouse—serve as a good check on the long-term accuracy of climate





SNAPSHOTS OF A GREENHOUSE WORLD come from a climate model used by the author and Starley L. Thompson at the National Center for Atmospheric Research. The model traced surface temperatures over the year for an atmosphere with twice the present level of carbon dioxide (*top*); the findings were compared with the results of a yearlong simulation for

models. To such tests of overall validity can be added simulations of the climates of other planets, such as Venus, where a dense greenhouse atmosphere maintains a surface temperature of about 450 degrees C.

The record of the past 100 years provides the only direct test of the models' ability to simulate the effects of the ongoing greenhouse-gas increase. When a climate model is run for an atmosphere with the composition of 100 years ago and then run again for the historical 25 percent increase in carbon dioxide and doubling in methane, does it "predict" the observed half-degree warming? Actually most models yield a somewhat larger warming, of at least a degree.

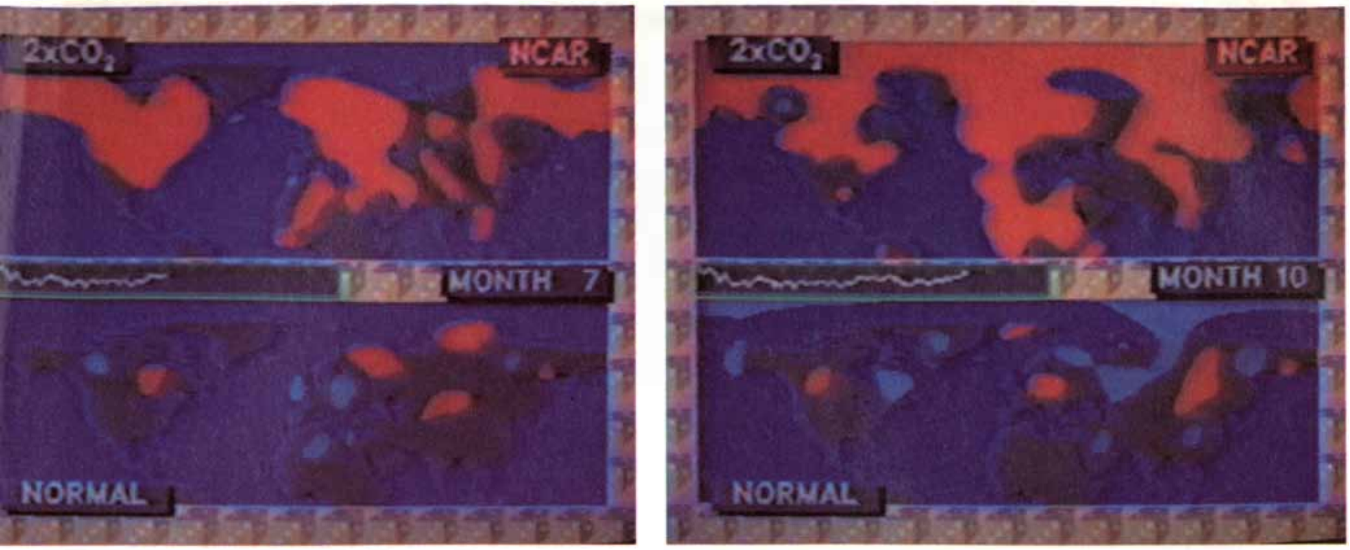
If the observed temperature increase really is a greenhouse warming and not just "noise"—a random fluctuation—one might account for the disparity in various ways. Perhaps the models are simply twice too sensitive to small increases in greenhouse gases, or perhaps the incomplete and inhomogeneous network of thermometers has underestimated the global warming. Conceivably some other factor, not well accounted for in the models, is delaying or counteracting the warming. It might be that the heat capacity of the oceans is larger than current models calculate, that the sun's output has declined slightly or that volcanoes have injected more dust into the stratosphere than is currently known, thereby reducing the solar energy reaching the ground.

It may be significant that the transient cooling interrupting the warming trend began around 1940 and was most pronounced in the Northern Hemisphere, coinciding in time and place with a sharp increase in emissions of sulfur from coal- and oil-burning factories and power plants. The sulfur, a major cause of acid rain, is emitted as a gas, sulfur dioxide, but is transformed into fine sulfate particles once in the atmosphere. The particles can travel long distances and serve as condensation nuclei for the formation of cloud droplets, and so they may make some clouds denser and brighter, increasing their cooling effects. In addition, if no soot is bound to the sulfate, it forms a reflective haze even in cloudless skies. Sulfur emissions could be one factor that has held a greenhouse warming down somewhat in the Northern Hemisphere, especially since World War II.

The discrepancy between the predicted warming and what has been seen so far keeps most climatologists from saying with great certainty (99 percent confidence, say) that the greenhouse warming has already taken hold. Yet the discrepancy is small enough, the models are well enough validated and other evidence of greenhouse-gas effects on climate is strong enough, so that most of us believe that the increases in average surface temperature predicted by the models for the next 50 years or so are probably valid within a rough factor of two. (By "probably" I mean it is a better-than-even bet.) Within a decade or so, warming of the predicted magnitude should be clearly evident, even in the noisy global temperature record. But waiting for such conclusive, direct evidence is not a cost-free proposition: by then the world will already be committed to greater climatic change than it would be if action were taken now to slow the buildup of greenhouse gases. Of course, whether or not to act is a value judgment, not a scientific issue.

Why worry about changes in climate on the scale predicted by the models? Changes in temperature and precipitation could threaten natural ecosystems, agricultural production and human settlement patterns. Particular forest types, for example, grow in geographic zones defined largely by temperature. The belt of spruce and fir that now spans Canada grew far to the south at the end of the last ice age 10,000 years ago, hugging the edge of the ice sheet. As the climate warmed by one or two degrees every 1,000 years and the ice retreated, the forest belt migrated northward, at perhaps one kilometer a year. Forests probably could not sustain the much faster migration required by the projected warming, and many ecosystems cannot migrate in any case: they exist only in preserves, which might become marooned in a newly inhospitable climate zone.

Human activities could be affected directly if a warming speeded the evaporation of moisture, reducing stream runoff; in the western U.S. a temperature increase of several degrees C could decrease runoff in the Colorado basin substantially even if precipitation held steady. As water ran short, faster evaporation would in-



the present atmosphere (*bottom*). The red areas were more than six degrees C warmer than the model-calculated normal for that time of year under existing conditions; the light blue areas were more than six degrees colder. The weather anomalies steadily changed position, shape and size, but heating always predominated in the greenhouse simulation.

crease the demand for irrigation, adding to the strain on water supplies. At the same time, water quality might suffer as the same waste volume was diluted in lower stream volumes.

What is more, several climate models predict that summer precipitation will actually decline in midcontinental areas, including the central plains of the U.S. The late Dean F. Peterson, Jr., of Utah State University and Andrew A. Keller of Keller-Bliesner Engineering in Logan, Utah, estimated the effects on crop production of a three-degree warming combined with a 10 percent drop in precipitation. They found that based on increased crop water needs and a reduction in available water, the viable acreage in arid regions of the western states and the Great Plains would fall by nearly a third. (A western drying might also result in an increased frequency of wildfires.)

Coastal areas, meanwhile, might face a rise in sea level. Most workers expect a global temperature increase of a few degrees C over the next 50 or 100 years to raise sea level by between .2 and 1.5 meters as a result of the thermal expansion of the oceans, the melting of mountain glaciers and the possible retreat of the Greenland ice sheet's southern margins. (Ice could actually build up in Antarctica owing to warmer winters, which would probably increase snowfall.) The rising sea would endanger coastal settlements and ecosystems and might contaminate groundwater supplies with salt. In spite of many local factors that make it difficult to isolate a consistent global signal, one group of workers recently claimed to have found a uniform worldwide rise in sea level of about two millimeters a year in long-term tide-gauge records. That rise is somewhat larger, however, than one would have expected from the warming seen so far.

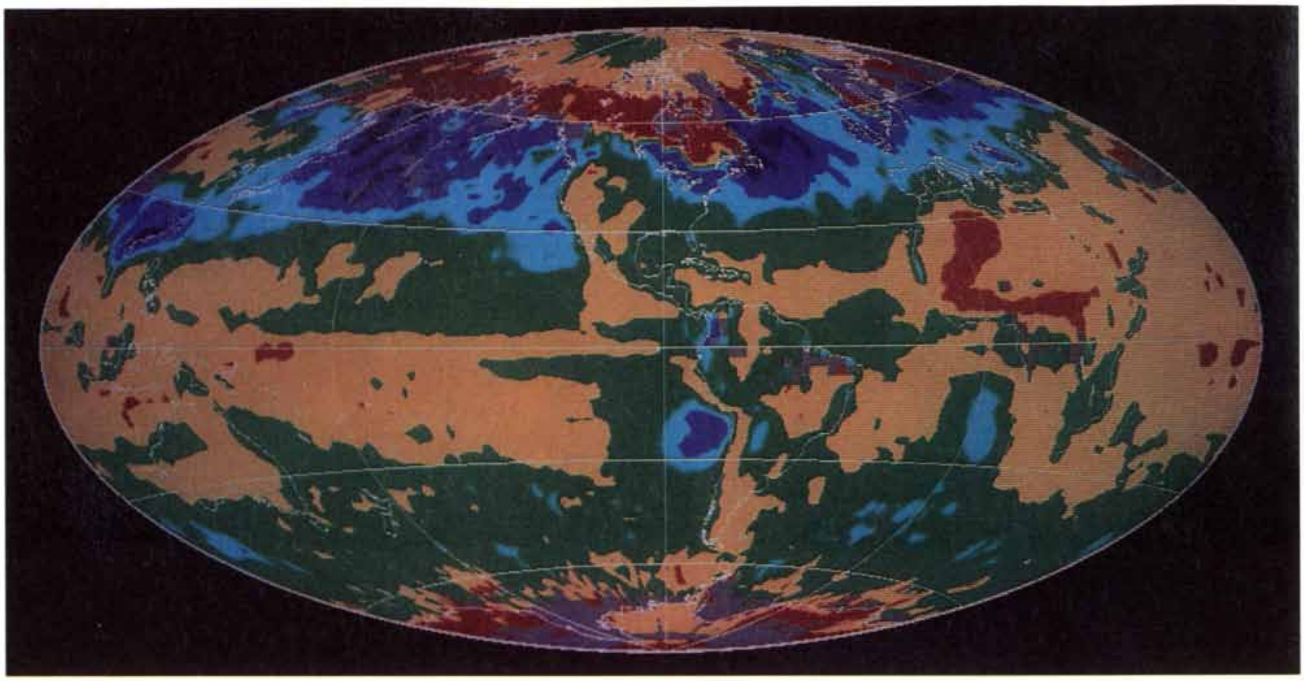
Clearly these direct effects of climatic change would have powerful economic, social and political consequences. A decline in agricultural productivity in the Middle West and Great Plains, for example, could be disastrous for farmers and the U.S. economy. By cutting into the U.S. grain surplus, it might also have serious implications for international security.

To be sure, not everyone would lose. If the corn belt simply moved north by several hundred kilometers, for example, Iowa's billion-dollar loss could become Minnesota's billion-dollar gain. But how could the losers be compensated and the winners charged? The issue of equity would become still more thorny if it spanned borders—if the release of greenhouse gases by the economic activities of one country or group of countries did disproportionate harm to other countries whose activities had contributed less to the buildup.

In the face of this array of threats, three kinds of responses could be considered. First, some workers have proposed technical measures to counteract climatic change—deliberately spreading dust in the upper atmosphere to reflect sunlight, for instance. Yet if unplanned climatic changes themselves cannot be predicted with certainty, the effects of such countermeasures would be still more unpredictable. Such "technical fixes" would run a real risk of misfiring—or of being blamed for any unfavorable climatic fluctuations that took place at the same time.

Many economists tend to favor a second class of action: adaptation, often with little or no attempt to anticipate damages or prevent climatic change. Adaptive strategists argue that the large uncertainties in climate projections make it unwise to spend large sums trying to avert outcomes that may never materialize. They argue that adaptation, in contrast, is cheap: the infrastructure that would have to be modified in the face of climatic change—such as water-supply systems and coastal structures—will have to be replaced in any case before large climatic changes are due to appear. The infrastructure can simply be rebuilt as needed to cope with the changing environment.

Passive adaptation relies mostly on reacting to events as they unfold, but some active adaptive steps could be taken now to make future accommodation easier. An American Association for the Advancement of Science panel on climatic change made a strong, potentially controversial but, I believe, compelling suggestion for active adaptation: governments at all levels should reexamine the technical features of water systems and the economic and legal aspects of water-supply management in order to increase the systems' efficiency and flexibility. As the climate warms and precipita-



CLOUDS AFFECT SURFACE TEMPERATURES because they both reflect sunlight, preventing it from warming the earth, and absorb infrared radiation from the surface, contributing to the greenhouse effect. In this image, based on satellite data gathered in April, 1985, clouds had a net cooling effect in some regions (*blues and green*) and a heating effect in others (*red*). On the whole, clouds cool the planet more than they warm it, but the characteristics of clouds and their effect on climate might change unpredictably in a greenhouse world. The image was provided by V. Ramanathan of the University of Chicago.

tion and runoff change, water shortages may grow more common and needs for regional transfers more complex. Even if climate did not change, more flexible water systems would make it easier to cope with the normal extremes of weather.

The third and most active category of response is prevention: curtailing the greenhouse-gas buildup. Energy-conservation measures, alternative energy sources or a switch from coal to natural gas and other fuels with a lower carbon content could all reduce carbon dioxide emissions, as could a halt to deforestation. Stopping the production of CFC's, already notorious because of their ability to erode the stratospheric ozone layer, would eliminate another component of the buildup. A far-reaching proposal for an international framework for reducing emissions was put forward in 1976 by Margaret Mead and William W. Kellogg of NCAR: a "law of the air," which would keep emissions of carbon dioxide below a global standard by assigning polluting rights to each nation.

Proposals for immediate action are controversial because they often entail large immediate investments as insurance against future events whose details are far from certain. Is there some simple principle that can help us to choose which preventive or adaptive measures to spend our resources on? I believe it makes sense to take actions that will yield "tie-in" benefits even if climatic changes do not materialize as forecast.

Pursuing energy efficiency is a good example of this tie-in strategy. More efficient fossil-fuel use will slow the carbon dioxide buildup, but even if the sensitivity of climate to carbon dioxide has been overstated, what would be wasted by taking this step? Efficiency usually makes economic sense, and a reduction in fossil-fuel use would curb acid rain and urban air pollution and lessen the dependence of many countries on foreign producers. Developing alternative energy sources, revising water laws, searching for drought-resistant crop strains, negotiating international agreements on trade in food and other climate-sensitive goods—all these steps could also offer widespread benefits even in the absence of any climatic change.

Often such steps will nonetheless be costly and politically controversial. Regulations or incentives to foster energy-efficient technologies might burden some groups—coal miners and the poor, perhaps—more than others, and the costs may be proportionally greater for poor countries than for rich ones. Actions to prevent a greenhouse warming will have to be coupled with domestic- and foreign-policy measures that attempt to balance fairness and effectiveness. Still, I believe it is better to fight poverty and foster development through direct investment rather than through artificially low energy prices that neglect the costs of the resulting environmental disruptions.

Some people argue that the free market, not government regulation or tax incentives, should dictate increases in energy efficiency, say, or the elimination of CFC's. But it cannot be logically argued that the market is "free" when it does not include some of the potential costs of environmental damage caused by goods or services. Moreover, even political conservatives agree that an economic calculus must give way to a strategic consciousness when national or global security is at stake.

Security is indeed at stake here, as the implications of a global temperature rise of several degrees or more over the next century make clear. Adding to the predicted threats are surprises that may be lurking in the greenhouse century: a sharp positive feedback in the greenhouse-gas buildup from accelerated decay of soil organic matter, dramatic changes in regional climates because of a shift in ocean circulation, or the outbreak of new diseases or agricultural pests as ecosystems are disrupted. In my value system—and this is a political and not a scientific judgment—effective tie-in actions are long overdue.

I am often asked whether I am pessimistic because it will be impossible to avert some global change: at this stage, it appears, no plausible policies are likely to prevent the world from warming by a degree or two. Actually I see a positive aspect: the possibility that a slight but manifest global warming, coupled with the larger threat forecast in computer models, may catalyze international cooperation to achieve environmentally sustainable development, marked by a stabilized population and the proliferation of energy-efficient and environmentally safe technologies. A much larger greenhouse warming (together with many other environmental disruptions) might thereby be averted.

The developed world might have to invest hundreds of billions of dollars every year for many decades, both at home and in financial and technical assistance to developing nations, to achieve a stabilized and sustainable world. It is easy to be pessimistic about the prospects for an international initiative of this scale, but not long ago a massive disengagement of NATO and Warsaw Pact forces in Europe also seemed inconceivable. Disengagement now seems to me to be possible, even likely. Perhaps the resources such an agreement would free and the model of international cooperation it would provide could open the way to a world in which the greenhouse century exists only in the microchips of a supercomputer.

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Threats to the World's Water

Population growth, ignorance and poverty, along with poor agricultural practices, have endangered water resources. Unless appropriate steps are taken soon, severe shortages will occur

by J. W. Maurits la Rivière

Water is the earth's most distinctive constituent. It set the stage for the evolution of life and is an essential ingredient of all life today; it may well be the most precious resource the earth provides to humankind. One might therefore suppose that human beings would be respectful of water, that they would seek to maintain its natural reservoirs and safeguard its purity. Yet people in countries throughout the world have been remarkably shortsighted and negligent in this respect. Indeed, the future of the human species and many others may be compromised unless there is significant improvement in the management of the earth's water resources.

All the fresh water in the world's lakes and creeks, streams and rivers represents less than .01 percent of the earth's total store of water. Fortunately, this freshwater supply is continually replenished by the precipitation of water vapor from the atmosphere as rain or snow. Unfortunately, much of that precipitation is contaminated on the way down by gases and particles that human activity introduces into the atmosphere.

Fresh water runs off the land and on its way to the ocean becomes laden with particulate and dissolved matter—both natural detritus and the wastes of human society. When the population density in the catchment area is low, waste matter in the water can be degraded by microbes through a process known as natural self-purification. When the self-purifying capacity of the catchment area is exceeded, however, large quantities of these waste substances accumulate in the oceans, where they can harm aquatic life. The water itself evaporates and enters the atmosphere as pure water vapor. Much of it falls back into the ocean; what falls on land is the precious renewable resource on which terrestrial life depends.

The World Resources Institute estimates that 41,000 cubic kilometers of water per year return to the sea from the land, counterbalancing the atmospheric vapor transport from sea to land. Some 27,000 cubic kilometers, however, return to the sea as flood runoff, which cannot be tapped, and another 5,000 cubic kilometers flow into the sea in uninhabited areas. Of the 41,000 cubic kilometers that return to the sea, some amount is retained on land, where it is absorbed by the vegetation, but the precise amount is not known.

This cycle leaves about 9,000 cubic kilometers readily available for human exploitation worldwide. That is a plentiful supply of water, in principle enough to sustain 20 billion people. Yet because both the world's population and usable water are unevenly distributed, the local availability of water varies widely. When evaporation and precipitation balances are worked out for each country, water-poor and water-rich countries can be identified. Iceland, for example, has enough excess precipitation to provide 68,500 cubic meters of water per person per year. The inhabitants of Bahrain, on the other hand, have virtually no access to natural fresh water; they are dependent on the desalinization of seawater. In addition, withdrawal rates per person differ widely from country to country: the average U.S. resident consumes more than 70 times as much water every year as the average resident of Ghana does.

Although the uses to which water is put vary from country to country, agriculture is the main drain on the water supply. Averaged globally, 73 percent of water withdrawn from the earth goes for that purpose. Almost three million square kilometers of land have been irrigated—an area nearly the size of India—and more is being added at the rate of 8 percent a year.

Local water shortages can be solved in two ways. The supply can be increased, either by damming rivers or by consuming capital—by "mining" groundwater. Or known supplies can be conserved, as by increasing the efficiency of irrigation or by relying more on food imports.

In spite of such efforts, there is no doubt that water is becoming increasingly scarce as population, industry and agriculture all expand. Severe shortages occur as demand exceeds supply. Depletion of groundwater is common in, for example, India, China and the U.S. In the Soviet Union the water level of both the Aral sea and

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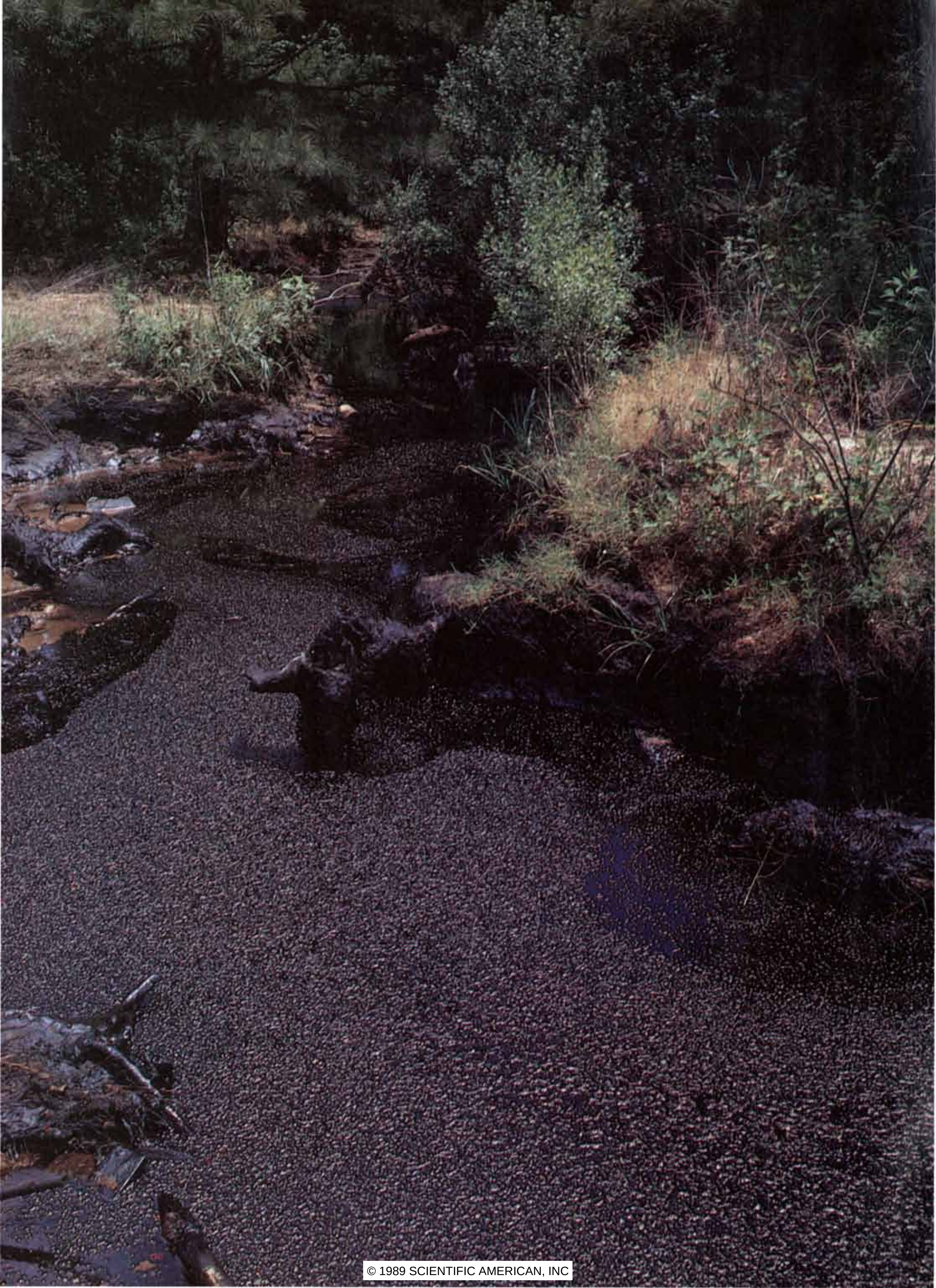
OIL HAS LEAKED from a well in Oklahoma to a nearby creek, where it forms a sticky layer on the water's surface and coats the banks. The oil's toxicity has rendered the water uninhabitable to most forms of life, and it is no longer fit for animals to drink. Although this type of oil spill is minor compared with an oil-tanker spill at sea, it is indicative of the wide-ranging impact human activities can have on the world's water supply.



Lake Baikal is dropping dramatically as a result of agricultural and industrial growth in those areas. Contentious competition for the water of such international rivers as the Nile, the Jordan, the Ganges and the Brahmaputra is a symptom of the increasing scarcity of water.

Another problem brought on by overirrigation is salinization. As water evaporates or is taken up by plants, salt is left behind in the soil. The rate of deposition exceeds the rate at which the salt can be removed by flowing water, and so a residue accumulates. Currently more than a million hectares every year are subject to salinization; in the U.S. alone more than 20 percent of the irrigated land is thus affected.

Human activity in a river basin can often aggravate flood hazards. Deforestation and excessive logging lead not only to increased soil erosion but also to increased runoff; in addition, navigation canals are sometimes dug, which may exacerbate flooding by increasing the amount of water that reaches the floodplain.

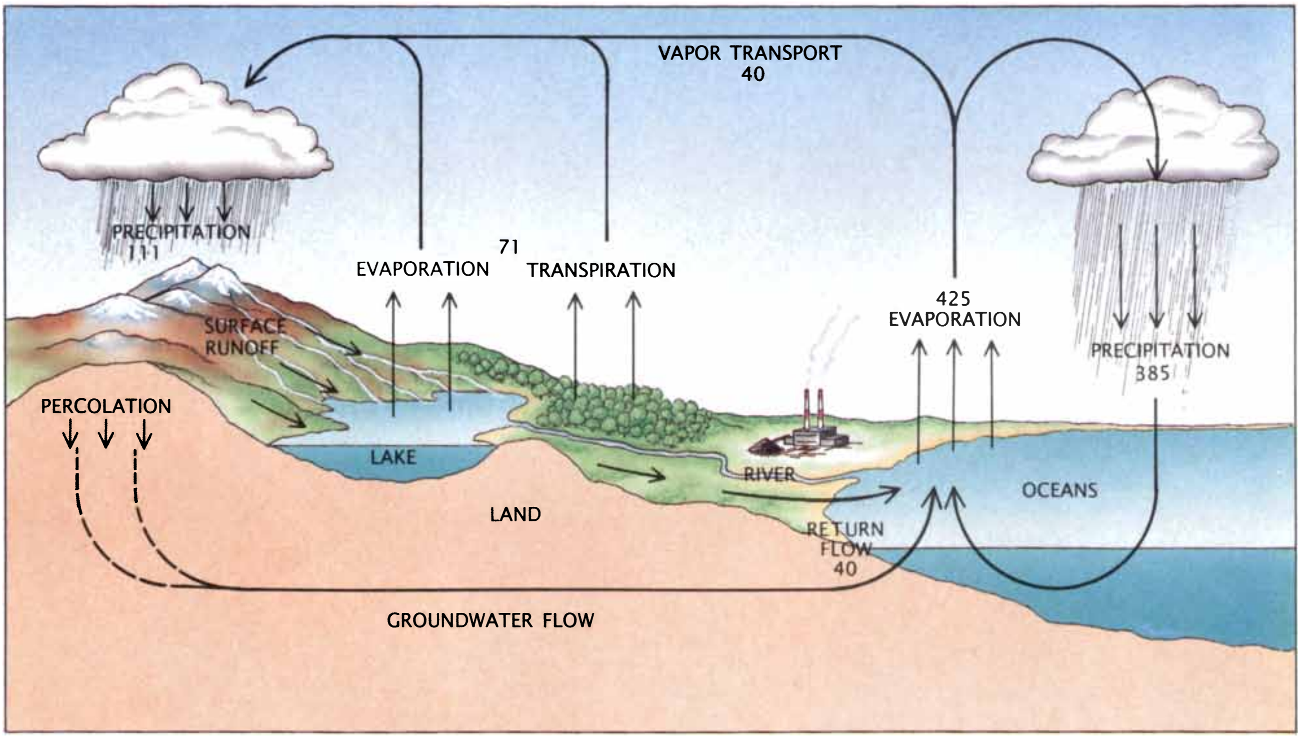
Finally, of course, any human activity that accentuates the greenhouse effect and ensuing climatic change must inevitably influence the global water cycle. A projected sea-level rise of between .5 and 1.5 meters in the next century, for instance, not only would pose a coastal flooding problem but also would lead to salinization of water resources, create new wetlands while destroying existing ones and increase the ratio of salt water to fresh water on the globe. Precipitation could rise by between 7 and 15 percent in the aggregate; the geographic variations are not predictable.

Assuring an adequate supply is not the only water problem facing many countries throughout the world: they need to worry about water quality. In its passage through the hydrological cycle, water is polluted by two kinds of waste. There is traditional organic waste: human and animal excreta and agricultural fibrous waste (the discarded parts—often more than half—of harvested plants). And there is waste generated by a wide range of industrial processes and by the disposal, after a brief or long lifetime, of industry's products.

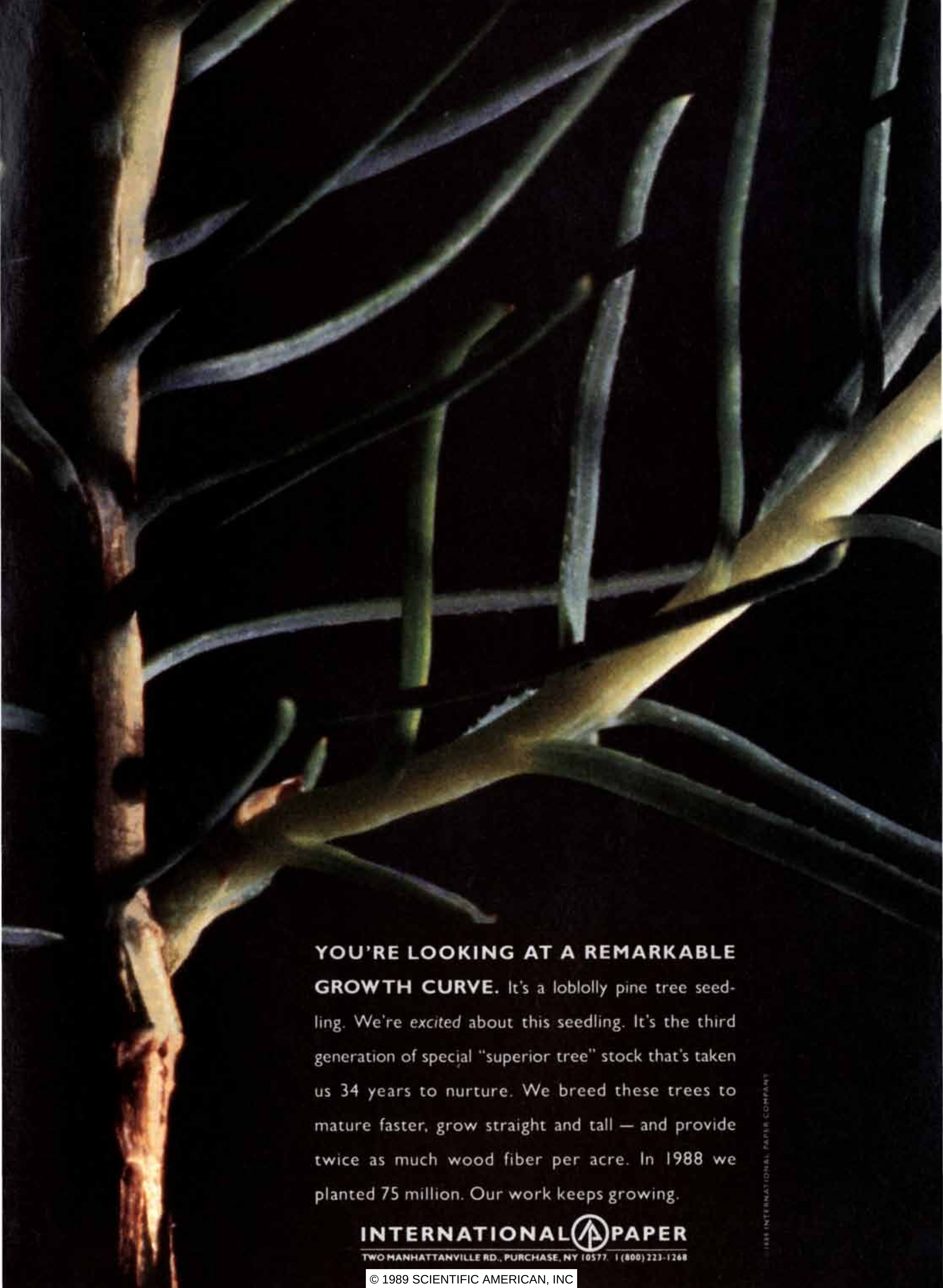
Although organic waste is fully biodegradable, it nonetheless presents a significant problem—and in some places a massive one. Excessive biodegradation can cause oxygen depletion in lakes and rivers. Human excreta contain some of the most vicious contaminants known, including such pathogenic microorganisms as the waterborne agents of cholera, typhoid fever and dysentery.

Industrial waste can include heavy metals and considerable quantities of synthetic chemicals, such as pesticides. These materials are characterized by toxicity and persistence: they are not readily degraded under natural conditions or in conventional sewage-treatment plants. On the other hand, such industrial materials as concrete, paper, glass, iron and certain plastics are relatively innocuous, because they are inert, biodegradable or at least nontoxic.

Wastes can enter lakes and streams in discharges from such point sources as sewers or drainage pipes or from diffuse sources, as in the case of pesticides and fertilizers in runoff water. Wastes can also be carried to lakes and streams along indirect pathways—for example, when water leaches through contaminated soils and transports the contaminants to a lake or river. Indeed, dumps of toxic chemical waste on land have become a serious source of groundwater and surface-water pollution. The metal drums containing the chemicals are nothing less than time bombs that will go off when they rust through. The incidents at Lekkerkerk in the Netherlands and at Love Canal in the U.S. are indicators of the pollution of this kind going on



GLOBAL WATER CYCLE has three major pathways: precipitation, evaporation and vapor transport. Water precipitates from the sky as rain or snow, most of which (385,000 cubic kilometers per year) falls into the oceans; it returns to the atmosphere by evaporation. Some flows from the land to the sea as runoff or groundwater; in the other direction water vapor is carried by atmospheric currents from the sea to the land. Net flow is measured in thousands of cubic kilometers per year.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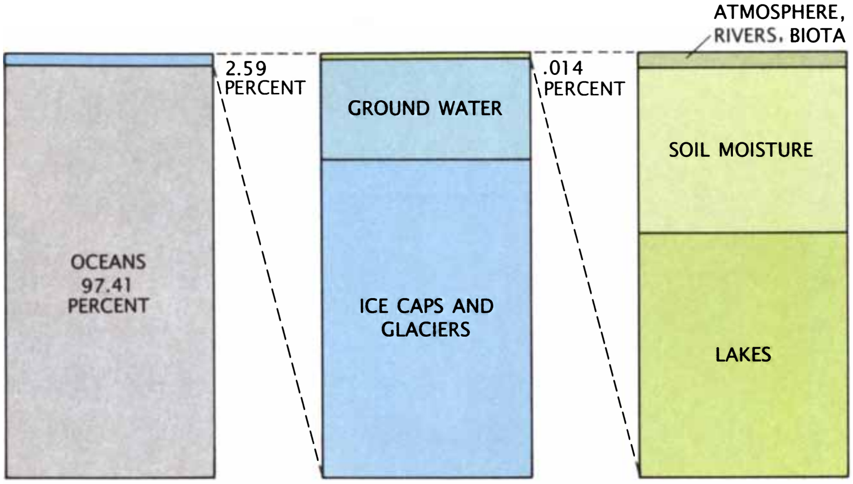
Some pollutants enter the water cycle by way of the atmosphere. Probably best known among them is the acid that arises from the emission of nitrogen oxides and sulfur dioxide by industry and motor vehicles. Acid deposition, which can be "dry" (as when the gases make direct contact with soil or vegetation) or "wet" (when the acid is dissolved in rain), is causing acidification of low-alkalinity lakes throughout the industrialized world. The acid precipitation also leaches certain positively charged ions out of the soil, and in some rivers and lakes ions can reach concentrations that kill fish.

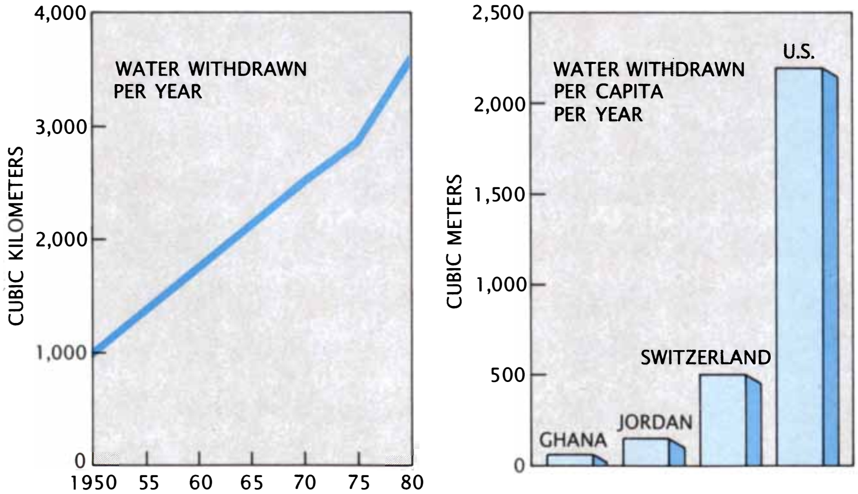
In areas of intensive animal farming, ammonia released from manure is partly introduced into the atmosphere and partly converted by soil microbes into soluble nitrates in the soil. Since nitrate has high mobility (it is soluble in water and does not bind to soil particles), it has become one of the main pollutants of groundwater, often reaching concentrations that exceed guidelines established by the World Health Organization.

The wind can also carry pollutants—fly ash from coal-burning plants, for example, or sprayed pesticides. These can be carried great distances, eventually to be deposited on the surfaces of lakes or of rivers.

Another recently recognized aspect of water pollution is the accumulation of heavy metals, nutrients and toxic chemicals in the bottom mud in deltas and estuaries of highly polluted rivers, such as the Rhine. Because of their high pollution content, sediments that are dredged up cannot be used for such projects as landfills in populated or agricultural areas. Moreover, there is always the danger that natural processes or human activity will trigger chemical reactions that mobilize the pollutants by rendering them soluble, thus allowing them to spread over great distances.



DISTRIBUTION OF WATER on the planet is highly uneven. Most of it (97.41 percent) is in the oceans (*gray*); only a small fraction (2.59 percent) is on the land (*blue*). Even most of the water on land is largely unavailable, because it is sequestered in the form of ice and snow or as groundwater; only a tiny amount (.014 percent) of the earth's total water is readily available to human beings and other organisms (*green*).

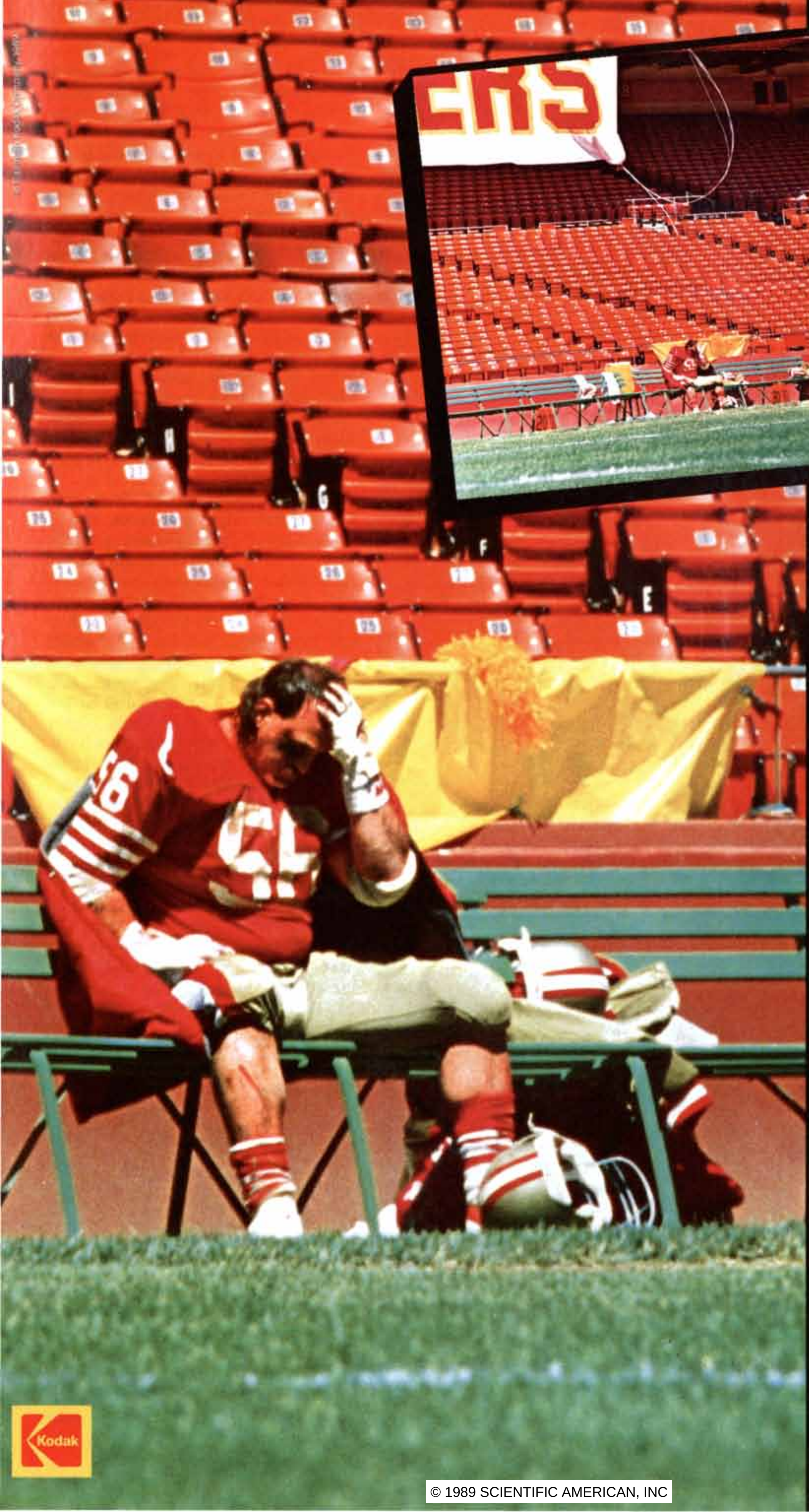


GLOBAL WATER CONSUMPTION is increasing (*left*), largely in response to a growing population and increasing per capita use by agriculture and industry. Although sufficient fresh water (9,000 cubic kilometers) is currently available, sound water management is necessary to ensure an adequate supply for the future. Per capita consumption rates vary drastically (*right*); the average American, for example, consumes more than 70 times as much water as the average resident of Ghana.

The quality of inland waters depends not only on the amount of waste generated but also on the decontamination measures that have been put into effect. The degree of success in the battle for water quality differs from country to country, but it can be generalized into a conceptual formula proposed by Werner Stumm and his co-workers of the Swiss Federal Institute for Water Resources and Water Pollution Control in Zurich. The formula holds that the contamination load of a river basin depends on the population in the basin, the per capita gross national product, the effectiveness of decontamination and the amount of river discharge.

Most rivers in the industrialized world, where the population and per capita GNP are stable and decontamination procedures tend to be fairly effective, are nonetheless polluted by both traditional and industrial wastes. Yet some stabilization—if not improvement—of pollution levels was reported in the early 1980's. (Methods for treatment of traditional wastes consist mostly of sedimentation and aerobic and anaerobic microbial degradation, which are intensified forms of natural self-purification.) Methods for degrading inorganic pollutants such as metals and toxic chemicals, although improving, have not been as promising.

Where increasing industrial activity in a river basin has been matched by increasing waste treatment, a decent level of water quality can be maintained. Yet the balance between contamination and decontamination is a precarious one. A serious accidental discharge, such as the one that followed a 1986 fire at a Sandoz factory on the Rhine in Switzerland, is enough to wipe out large numbers of aquatic



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organisms and force drinking-water purification plants to close their intakes downstream from the accident.

In most newly industrializing countries both organic and industrial river pollution are on the increase, since the annual per capita GNP is rising quickly (as is the population, to a lesser extent) and decontamination efforts are often neglected. In these countries industrialization has had higher priority than reduction of pollution. As a consequence, in some regions (East Asia, for example), degradation of water resources is now considered the gravest environmental problem.

In less developed countries, where the population is growing and where waste treatment is practically nonexistent, water pollution by organic wastes is widespread. As a result, millions of people—and children in particular—die each year from water-related diseases that can be prevented by proper sanitation facilities. These countries still suffer from diseases eradicated in the West long ago. Although the United Nations declared the 1980's to be the International Drinking Water Supply and Sanitation Decade and instituted a program to provide safe drinking water and appropriate sanitation for all by 1990, much remains to be done before the program's ambitious goals are met. Some progress has nonetheless been made in several countries, including Mexico, Indonesia and Ghana.

TOXIC-CHEMICAL DUMPS are a serious source of groundwater and surface-water pollution. Illegal dump sites, such as this one in the U.S., are particularly difficult to monitor. Damage occurs when the drums rust through and release their contents, which enter surface waters and eventually percolate down to the groundwater.

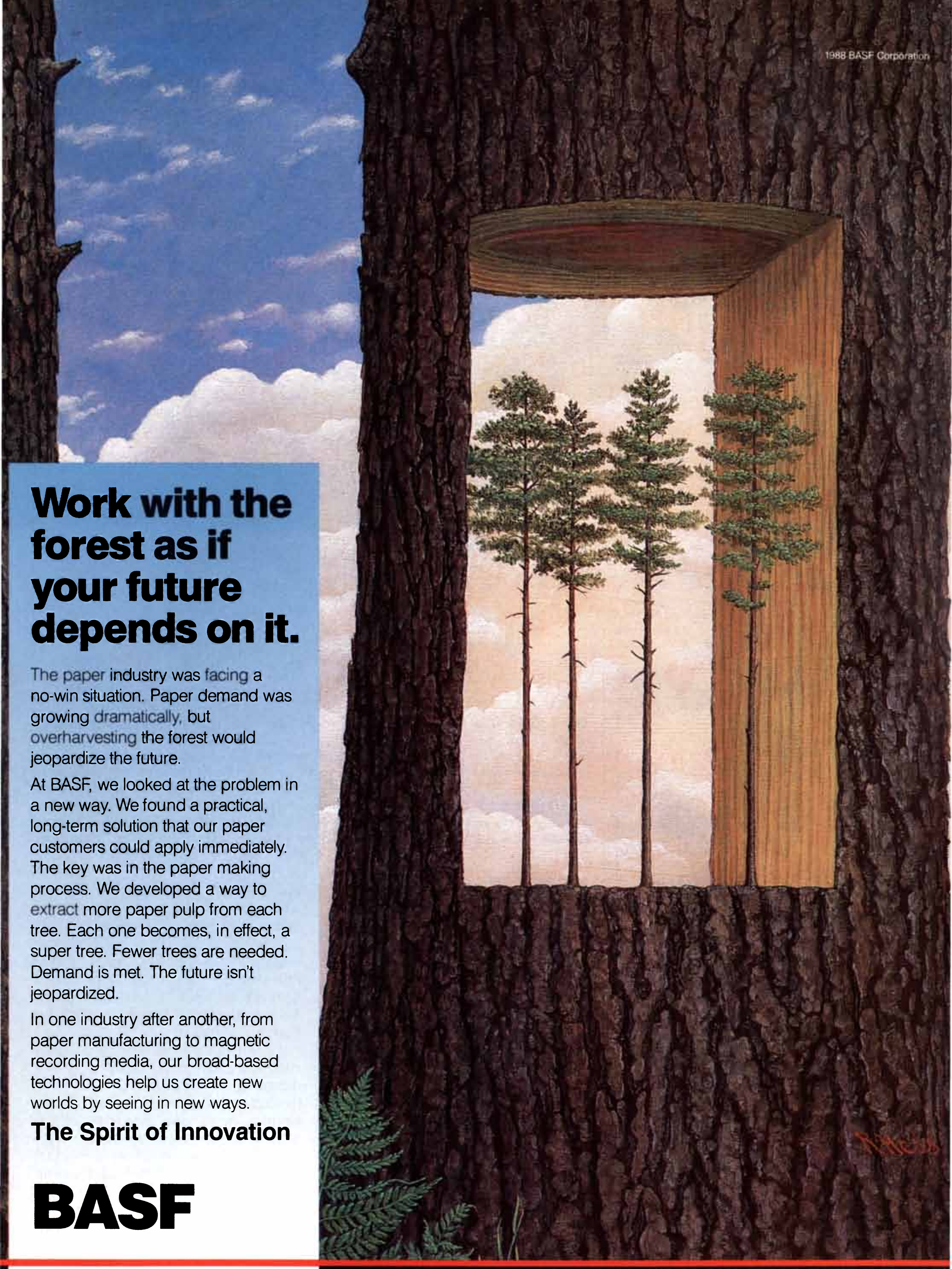
OCEAN POLLUTION is a growing problem, especially in coastal zones. Sewage, which contains abundant nutrients and oxygen-consuming organic matter, is one type of pollutant that can threaten aquatic life, as it has here in the San Francisco Bay.

The quality of the water in lakes is comparable to that in rivers. Thousands of lakes, including some large ones, are currently being subjected to acidification or to eutrophication: the process in which large inputs of nutrients, particularly phosphates, lead to the excessive growth of algae. When the overabundant algae die, their microbial degradation consumes most of the dissolved oxygen in the water, vastly reducing the water's capacity to support life. Experience in Europe and North America has shown that the restoration of lakes is possible—at a price—but that the process takes several years. Liming is effective against acidification; flushing out the excess nutrients and restricting the further inflow of nutrients helps to reduce eutrophication.

Although pollution of rivers and lakes is potentially reversible, that is not the case for groundwater. Actually, little is known about the quality of the earth's vast groundwater reserves, except in those instances where particular aquifers are being actively exploited. In Europe and the U.S., where groundwater represents a significant source of fresh water, between 5 and 10 percent of all wells examined are found to have nitrate levels higher than the maximum recommended value of 45 milligrams per liter. Many organic pollutants find their way into groundwater as seepage from waste dumps, leakage from sewers and fuel tanks or as runoff from agricultural land or paved surfaces in proliferating urban and suburban areas.

Because groundwater is cut off from the atmosphere's oxygen supply, its capacity for self-purification is very low: the microbes that normally break down organic pollutants need oxygen to do their job. Prevention of contamination is the only rational approach—particularly for the developing world, where increased reliance on vast groundwater reserves is likely.

The oceans are part of the world's "commons," exploited by many countries and the responsibility of none and therefore all the more difficult to safeguard. More than half of the world's people live on seacoasts, in river deltas and along estuaries and river mouths, and some 90 percent of the marine fish harvest is caught within 320 kilometers of the shore. Every year some 13 billion tons of silt are dumped into coastal zones at the mouths of rivers. Although most of those sediments would have found their way into the ocean anyway, a growing part of the accumulat-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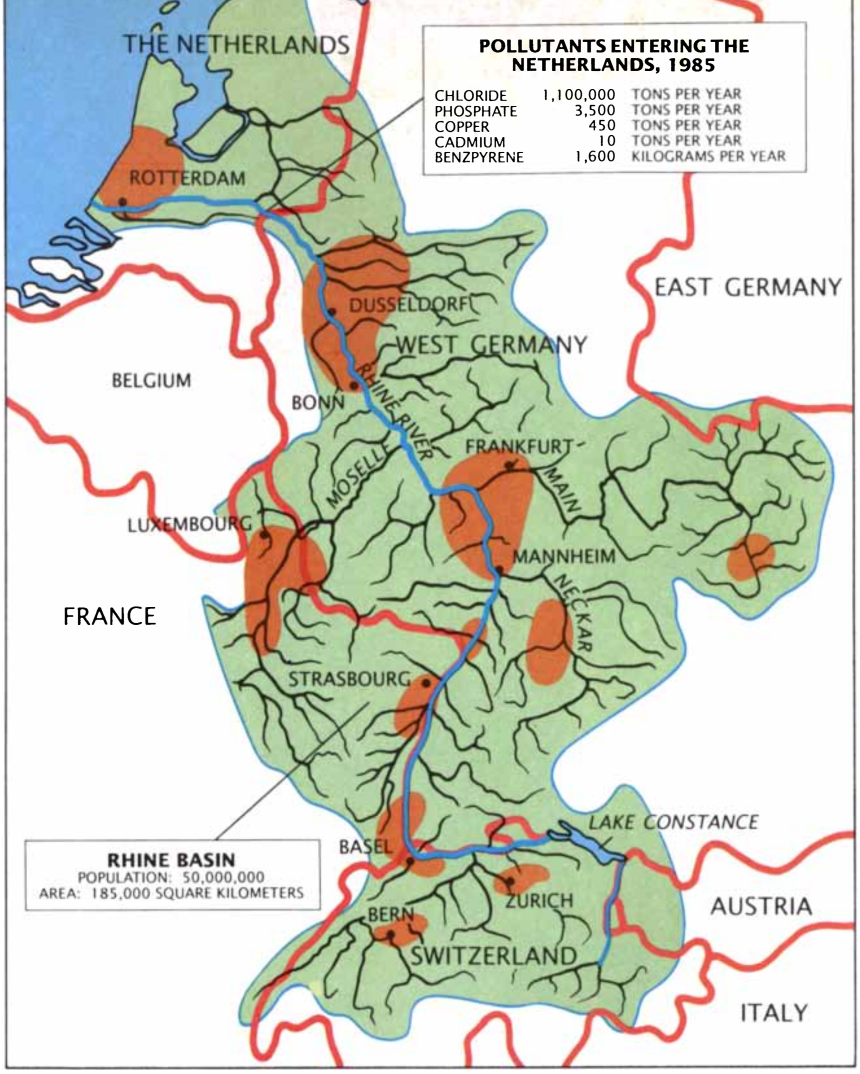

RHINE RIVER drains a vast basin (*green*) in four countries—Switzerland, West Germany, France and the Netherlands—as it runs 1,320 kilometers from the Alps to the North Sea. The basin is heavily industrialized (major urban concentrations are shown here in brown), and the river accumulates and transports into the Netherlands a heavy load of pollutants; since 1980 the amounts of some pollutants have been reduced. Now the four countries are cooperating in a Rhine Action Plan intended to improve the quality of the river's water. The primary effort will be to institute recycling within industry as a substitute for after-the-fact "end of pipe" treatment.

ing silt can be attributed to erosion and deforestation caused by human intervention. Depending on the particular agricultural and industrial activities in the catchment area, a coastal zone can be both fertilized and polluted by the silt and dissolved materials that reach it.

The coastal zone is the site of important physicochemical reactions between saltwater and freshwater flows; it is the zone of highest biological productivity, supporting marine life ranging from plankton to fish, turtles and whales. Aquaculture in the coastal zone now produces some 10 percent of the world's fish harvest. The 240,000 square kilometers of coastal mangrove forest are essential habitats for many economically important fish species during part of their life cycle, and they also provide timber and firewood; reed and cypress swamps are other examples of biologically rich coastal wetlands. Finally, of course, coastal zones support a highly profitable tourist industry and include a growing number of protected areas, such as the Great Barrier Reef Marine Park in Australia.

Aside from river discharges, diffuse runoff, atmospheric transport, waste dumping or burning at sea, offshore mining and shipping accidents are the primary ways that some 20 billion tons of dissolved and suspended matter reach the ocean, where they exert their initial effect on the coastal zone.

Polychlorinated biphenyls (PCB's) and other persistent toxic chemicals, including DDT and heavy-metal compounds, have already spread throughout the world's marine ecosystems, in part through gradual accumulation in the food chain. A ban on the use of DDT and PCB's has been enforced for some 10 years in the industrialized countries and has reduced the concentration of such chemicals in the marine life of North American and European coastal waters. The chemicals are, however, still being used and injected into the marine environment in many tropical regions.

Ocean currents are also vehicles for the transport of trash and pollutants. Examples are the nondegradable plastic bottles, pellets and containers that now commonly litter beaches and the ocean's surface. They cause the death of thousands of birds, fish and marine mammals that mistake them for food or get entangled in them. Less spectacular but possibly more serious are the chemical and biological processes (as yet poorly understood) whereby toxic substances such as radioactive wastes are distributed and accumulated.

Excessive sewage discharges from coastal urban areas lead to eutrophication of coastal waters, which can change the composition of plankton populations. The plankton, provided with abundant nutrients in the sewage, may experience rapid population growth, which depletes the supply of available oxygen and so leads to fish kills. Moreover, the presence of pathogenic bacteria in sewage has forced the closing of many kilometers of beaches to swimmers and has led to prohibitions on the harvesting of shellfish, which concentrate the bacteria in their tissues.

About one tenth of 1 percent of the world's total annual oil production—some five million tons a year, or more than one gram per 100 square meters of the ocean's surface—finds its way to the ocean. Large areas of the ocean would be covered with oil accumulated over the past decades were it not for the fact that the oil eventually evaporates or is degraded by bacteria. Although petroleum is almost entirely biodegradable, it takes the microbes that break it down a long time to accomplish the task, because their activity is limited by the low nutrient concentrations in seawater. In the meantime an oil spill's effects are lethal for a variety of plankton, fish larvae and shellfish, as well as for such larger animals as birds and marine mammals.

It is clear that the quality of the water in coastal zones is seriously endangered and that damage to fisheries and marine wildlife is widespread. Regional seas such as the Bal-

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tic and the Mediterranean, which have more coastline per square kilometer than the high seas do, suffer more from water pollution. Their poor condition demonstrates what may happen in the future to the larger oceans of the world.

Human activity is clearly responsible for widespread damage to marine ecosystems. What is not firmly established is how quickly toxic substances can accumulate in marine organisms or whether such accumulation is reversible. Nor has it been determined precisely how synthetic chemicals are transported through the oceans and what the likelihood is that toxic substances in bottom sediments will find their way into the human food supply. Yet experience so far dictates utmost caution, the more so because restoration of the oceans is incomparably more difficult than that of lakes and inland seas, if not impossible.

Some management of water resources—of both their quantity and quality—is now widely practiced all over the world, but the results, particularly in quality control, have been inadequate. All signals point to further deterioration in the quality of fresh and marine waters unless aggressive management programs are instituted.

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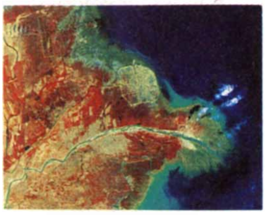

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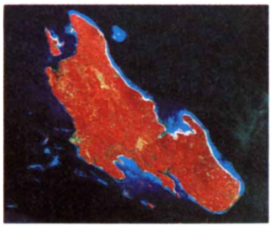

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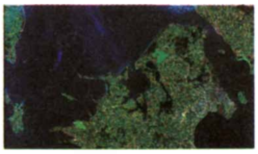

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4300 FORBES BOULEVARD, LANHAM, MARYLAND 20706 water management have evolved from past experience and are well known, and yet their application has lagged. Above all, the need for an integrated approach has become apparent. In every river or lake basin, socioeconomic and environmental aspirations must be orchestrated so that human settlements, industry, energy production, agriculture, forests, fisheries and wildlife can coexist. In many cases varied interests are not necessarily in conflict; they can be synergistic. Erosion control, for example, goes hand in hand with reforestation, flood prevention and water conservation.

An integrated approach calls, of course, for closer cooperation at the governmental and intergovernmental level; it goes against the historical allocation of different tasks to different agencies. In many countries water supply and sanitation are handled by separate departments. Departmental budgets are isolated by money-tight walls, making it hard to balance investments made by one department with any resulting gains or savings accrued to another.

Such obstacles are even more formidable in an international setting. A country is unlikely to make significant investments in the decontamination of a river's water if it is other countries, downstream, that are likely to reap the benefits. The less developed countries may actually have a better opportunity to make progress here than the developed ones, where vested interests have entrenched themselves in rigid administrative structures. The United Nations Environment Program (UNEP), for example, has drawn up an action plan for the Zambezi River based largely on principles of integrated management.

A water-management project should lean toward increasing the efficiency of water consumption rather than toward increasing the supply of water. To increase the supply is often more costly, and in any case it merely postpones a crisis. Indeed, because many countries are already overtaxing their water reserves, increasing efficiency is the only solution in some cases. Irrigation, for example, is terribly inefficient as it is practiced in most countries. Averaged over the world, only about 37 percent of all irrigation water is taken up by agricultural crops; the rest is never absorbed by the plants and can be considered lost. New microirrigation techniques, by which perforated pipes deliver water directly to the plants, provide great opportunities for water

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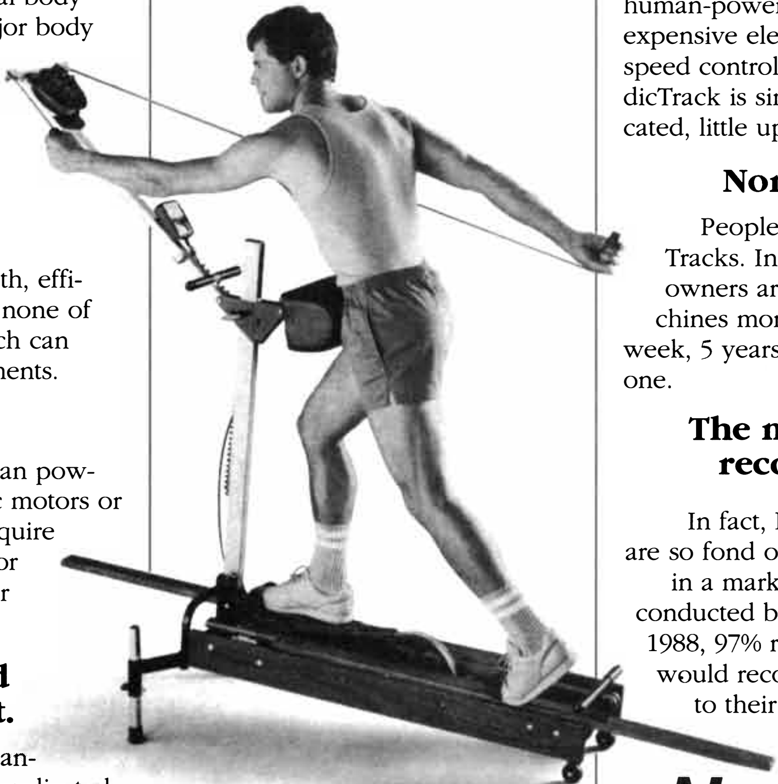

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WATER DECADE, a water-quality program launched by the United Nations, aims to provide the people of the world with safe drinking water and appropriate sanitation by the 1990's. The photograph, which was taken in 1983, depicts a woman drawing drinking water from a new well in Mali. Despite the program's best intentions, however, water quality is still a pressing problem in many parts of the world.

conservation, making it possible to expand irrigated fields without building new dams.

The mining of groundwater in order to increase supply should, of course, be avoided at all costs—unless it can be guaranteed that the aquifer from which the water is taken will be replenished. The protection of groundwater quality also deserves special attention. Government officials are more likely to implement pollution-control measures when they (or their constituents) are presented with highly visible signs of pollution, such as rubbish washed onto a beach. Hidden as it is from view, groundwater can therefore become polluted gradually without eliciting an outcry from the public until it is too late to reverse the damage wrought by the pollution.

It has also become apparent that the prevention of pollution, and the restoration of bodies of water that are already polluted, should gradually take precedence over the development of purification technologies. Water-purifying technology is becoming more complex and costly as the number of pollutants in water increases; the money spent on removing contaminants from drinking water would be better spent on preventing the contaminants from entering the water in the first place. The high cost of restoring polluted water bodies also strengthens the appeal of pollution-prevention programs.

For that reason "end of pipe" remedies for industrial water pollution should be replaced by recycling and reuse. Factories designed to minimize water pollution through waste reduction are often more economic than those that construct their own wastewater treatment plants in order to meet environmental standards. Factories that integrate pollution-control techniques are also likely to be more acceptable to an environmentally conscious populace. As Peter Donath of the Ciba-Geigy Corporation, one of the world's largest chemical companies, said at last year's International Rhine Conference, "Only with environmentally sound products and manufacturing processes will the chemical industry be able to maintain social acceptability in the future." As an example of this new trend in chemical engineering, he cited a novel process for the production of naphthalene sulfonic acids that reduces pollution by more than 90 percent.

Pollution of a river or a regional sea is, of course, more easily perceived than the pollution of the oceans, which are much larger; it is not surprising that the UNEP has already established pollution-control programs for 10 regional seas. Although such programs are a good start, they need to be followed up with protection of the oceans in general. A recent step in this direction is an international agreement forbidding the discarding of plastics from ships, which became effective at the beginning of this year. Other existing international conventions regulating marine resources need to be improved by backing them up with better monitoring schemes and enforcement measures.

Parallel with the need for improved water-resources management is the need for more research on the hydrosphere. For example, ecological and toxicologic studies of marine life are badly needed if we are to improve the husbandry of the oceans and gain better understanding of the ecological effects of long-lived pollutants in ocean waters.

Many aspects of the hydrological cycle, including the fluxes between its compartments and the extent of groundwater reserves, are not accurately known. These problems and others are currently being addressed by the International Hydrological Program of the United Nations Educational, Scientific and Cultural Organization. Moreover, major international research programs to study the interactions between climate and the hydrological cycle have recently been launched by the UNEP as well as by the World Health Organization and the nongovernmental International Council of Scientific Unions.

Predicting what is likely to happen if sound principles of water management are not vigorously implemented is all too easy. We have already seen rivers turn into sewers and lakes into cesspools. People die from drinking contaminated water, pollution washes ashore on recreational beaches, fish are poisoned by heavy metals and wildlife habitats are destroyed. A laissez-faire approach to water management will spell more of the same—on a grander scale. One can only hope recognition of that fact will spur governments and people into action.

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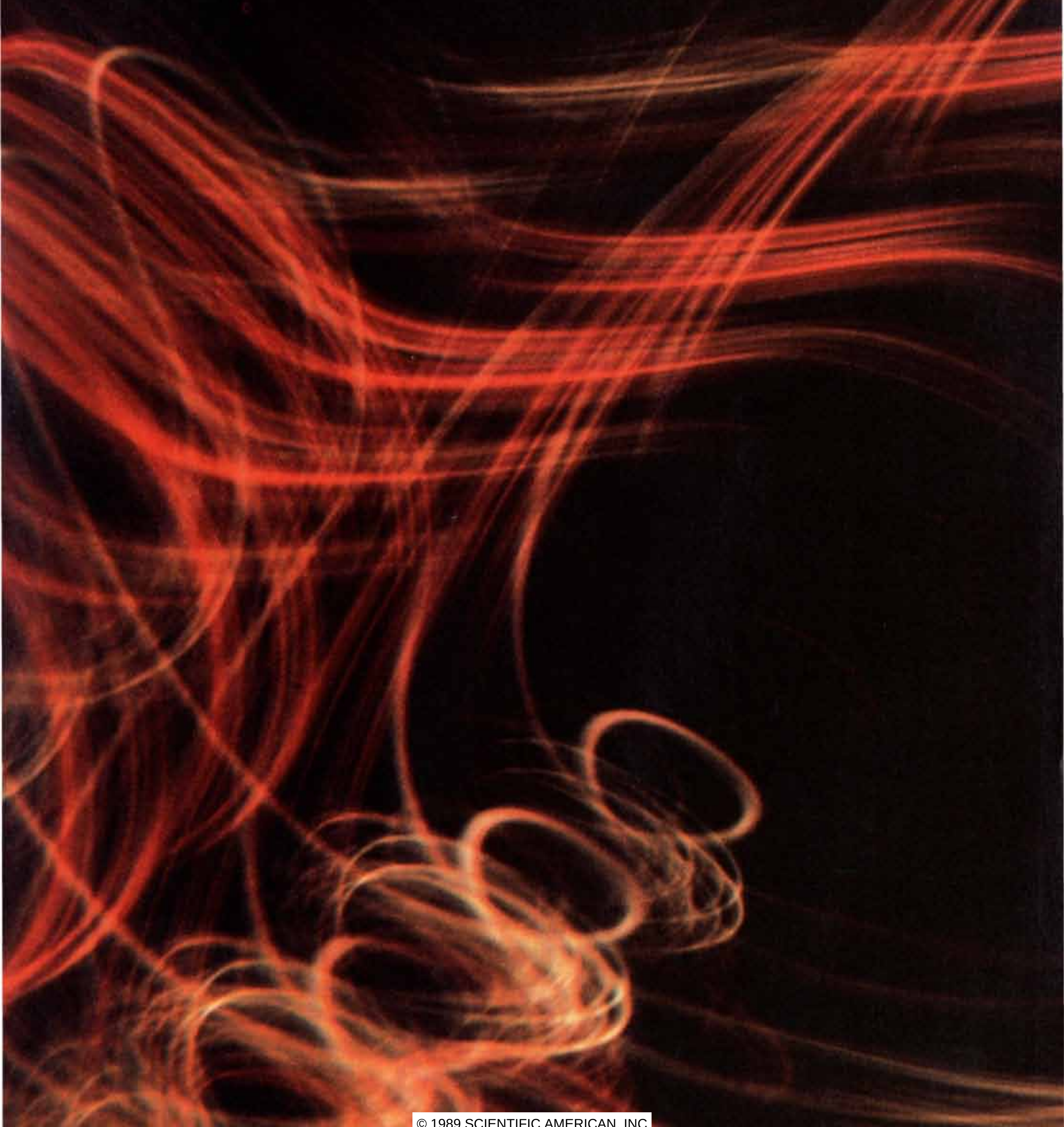
The Dispersion Analysis

This report on research at General Motors first appeared in December, 1982.



The Dispersion Analysis

Exhaust dispersion near a roadway is influenced by the turbulence and heat generated by moving vehicles. Findings at the General Motors Research Laboratories have provided a new understanding of the dispersion process.

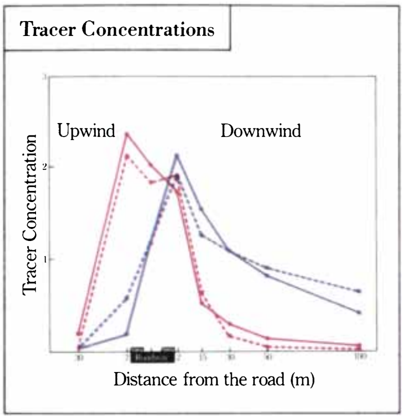


Figure 1: Observed (solid lines) and predicted (dashed lines) tracer concentrations near ground level as a function of distance from the edge of the road. Blue lines indicate the case in which the wind is perpendicular to the road; red lines, when the wind is nearly parallel to the road and opposing the upwind-lane traffic.

Figure 2: This representation of a roadway viewed from above shows the location of large vortices formed by local wind shear when the wind opposes the upwind-lane traffic.

BY USING the conservation-of-mass equation, one can describe the dispersion of gaseous molecules in the atmosphere. The equation includes terms for advection, diffusion, sources and sinks. Advection is the transport of air parcels by the mean wind; diffusion is due mainly to turbulent mixing. But the equation is useful only if we have information about the wind and temperature fields in the atmosphere. Specifically, our ability to predict vehicular exhaust concentrations near a road depends on knowledge of the effects of vehicles on these fields.

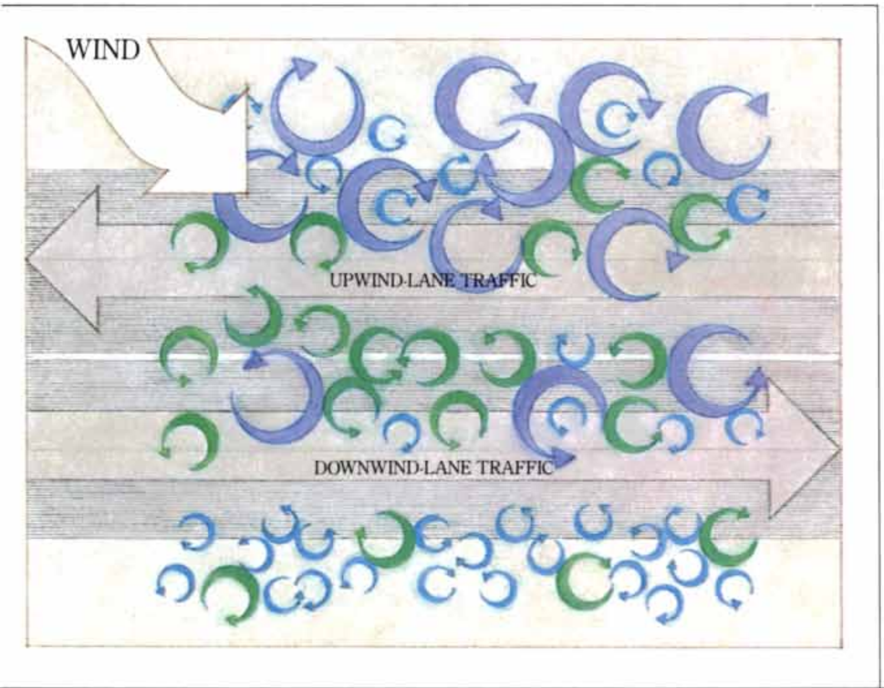
The conservation-of-mass equation for the mean concentration of any species, C, is

$$\underbrace{\frac{\partial C}{\partial t}}_{\text{Local rate of change}} + \underbrace{\sum_i \frac{\partial (U_i C)}{\partial x_i}}_{\text{Advection}} = \underbrace{\sum_{i,j} \frac{\partial}{\partial x_i}\left(K_{ij}\frac{\partial C}{\partial x_j}\right)}_{\text{Diffusion}} + \underbrace{So}_{\text{Sources}} + \underbrace{Si}_{\text{Sinks}}$$

where U_i is the mean wind velocity and K_{ij} is the eddy diffusivity tensor. This equation applies when the length scale of mixing is small compared to that of the variation of the mean concentration. Near a road, this condition is met if the averaging time for the concentration and wind velocity is much longer than the time interval of vehicular passage. For a straight roadway, a long averaging time allows one to assume spatial uniformity in the direction parallel to the road, and to ignore the spatial derivatives in that direction.

The input information for K_{ij} and the mean crossroad and vertical wind components near a roadway became available as a result of a large-scale experiment conducted by the General Motors Research Laboratories. The experiment has provided an understanding of the influence of moving vehicles on mechanical turbulence and buoyancy near a roadway. Dr. David Chock was responsible for the design of the experiment and the analysis of the data. The experiment, which duplicated a heavily traveled, level roadway, was conducted under meterological conditions minimizing dispersion.

Moving vehicles affect the mean crossroad and vertical wind components in the following ways. Vehicles act as an obstacle to the mean wind, causing it to slow and move upward as it approaches the vehicles and downward as it leaves the road. In addition, vehicles release heat, which causes a net upward motion. It was established that the increase in the mean vertical wind component due to the exhaust heat was $(B/U)^{1/2}$, where U is the crossroad wind component.



This research is just one example of GM's commitment to the environment. A simpler model developed by Dr. Chock is being used by countries around the world to assess the impact of proposed highways. Dr. Chock is now concentrating his research on air-quality modeling, particularly on topics related to urban ozone.

The buoyancy flux, B, is proportional to the heat emission rate of the vehicles.

Moving vehicles also enhance both turbulence intensity and mixing. To determine how this modifies the eddy diffusivity tensor, K_{ij}, Dr. Chock invoked a "second-order closure" assumption, which relates eddy diffusivity to Reynolds stresses and the gradients of mean wind velocity and mean temperature. Eddy diffusivity was assumed to be the sum of ambient and traffic contributions. To determine the traffic contribution, the length scale of the traffic-induced turbulence was assumed to be comparable to vehicle height–1.5 m.

USING THE vast data base compiled during the experiment, Dr. Chock was able to specify K_{ij} and the mean crossroad and vertical wind components, and solve the equation numerically. To test the model, half-hour measurements of a tracer gas were used to map out experimentally the exhaust dispersion under various meteorological conditions. The case where the wind speed is low and the wind direction is nearly perpendicular to the roadway is represented by the blue lines in Figure 1. Both the model and the experiment show the same dispersion pattern. The peak concentration is on the downwind roadside.

When the wind is nearly parallel to the road, the situation is much more complicated. Figure 2 shows that when the wind and traffic flow on the upwind lanes oppose each other, a high shear region occurs immediately upwind of the first traffic lane. When the wind and traffic are in the same direction, the high shear region occurs in the median of the road. In these high shear regions, large eddies are generated and turbulent mixing is intense. The red lines in Figure 1 show a comparison of the model's predictions with the tracer data for the case illustrated by Figure 2. Notice that the peak concentration can actually occur on the upwind roadside, due to the exhaust transport by these large eddies. Dr. Chock's model is the first to predict this occurrence.

Under all combinations of wind speeds and directions, the predictions based on the model compare favorably with the measured tracer concentrations. There is little systematic bias with respect to wind direction.

"In light of this new model, exhaust dispersion near a roadway can now be predicted with reliability," says Dr. Chock. "This is of importance for environmentally sound road planning, and opens the door to the investigation of dispersion on city streets, where the presence of tall structures introduces even further complexity."

General Motors

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MARK OF EXCELLENCE

THE MAN BEHIND THE WORK

Dr. David Chock is a Senior Staff Research Scientist in the Environmental Science Department at the General Motors Research Laboratories.

Dr. Chock received his B.A., *summa cum laude*, in chemistry from the University of California at Santa Barbara, and holds a Ph.D. in chemical physics from the University of Chicago. His thesis concerned the quantum mechanics of molecules and molecular crystals. As a postdoctoral fellow at the Free University of Brussels, he did research work on the dynamics of critical phenomena. He did additional postdoctoral work in the fields of solid-state physics and fluid dynamics.

Dr. Chock joined General Motors in 1972. Since then, he has pursued research in atmospheric transport and in statistics of extreme values of time-series data. His current interests include numerical methods and air-quality modeling.

David lives in Bloomfield Hills, Michigan, with his wife and son.

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Dirty Business

How companies are seeking their fortunes in garbage

The city of Kent in Washington State boasts some unforgettable scenery: Mount Rainier looms on the horizon, lush woodlands are close by—as are two toxic-waste dumps and two solid-waste disposals filled with garbage from Seattle and other nearby towns. In recent years, waste companies and consultants have earned millions of dollars cleaning up the worst of Kent's toxic mess, burning off the methane generated by the decomposing trash in the landfills and carting off some of the waste to other facilities. But even though waste-disposal needs will keep growing, Kent is unlikely to allow any more waste disposals or incinerators.

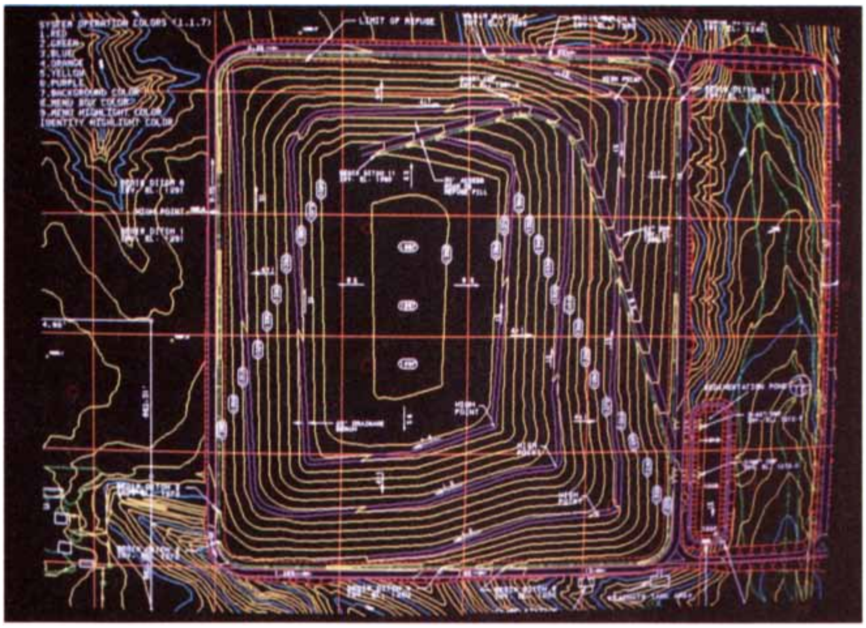
Both the opportunities and difficulties confronting the waste-management business are on display in Kent. The 250 million tons of trash ("solid waste") that U.S. households and companies routinely toss out each year have produced a $20-billion industry, according to Mark H. Sulam, an analyst at Kidder, Peabody, and forecasters are predicting an annual growth of 15 to 20 percent. Hazardous waste feeds a separate $4-billion industry that is likely to grow by 20 to 30 percent each year. (Nuclear waste is yet another problem and a separate business.) Hardly any town or city, however, wants to be part of this boom. Kent's disposal sites "were built in the 1950's and '60's when we were a fairly rural community and had no political clout," says Dean A. Radford, an editor for the *Valley Daily News.* "Now we realize that you can't have that crap in the center of a community."

So what to do with the waste? A host of companies are scrambling to offer alternatives. Whereas there were only four or five publicly traded waste-management corporations about five years ago, there are now more than 40, points out Vishnu Swarup, an analyst at Prudential-Bache Securities. Big companies are wading into the business by buying small waste firms. Venture capitalists are exploring environmental technology: they raised $29 million last year for ventures in waste management, pollution control and recycling; 55 percent went to start new companies, according to Venture Economics research consultants.

Solid-waste problems invite four kinds of solutions, explains Joseph W. Dorrycott, general manager of Westinghouse's Resource Energy Systems division: reduce waste during production, recycle it, convert it to energy by burning, or bury it. Unfortunately, corporate (and residential) efforts to trim waste are nascent; the Environmental Protection Agency concedes it began strongly advocating waste reduction only a few years ago. (The EPA plans to endorse waste reduction more aggressively, however. The agency hopes to publicize general information about how manufacturers can trim waste and let public sentiment cow the manufacturers into compliance.)

Many local governments, such as Kent's, are strongly pushing recycling; on average, however, recycling transforms only 11 percent of America's garbage. A few large solid-waste companies, including Waste Management, routinely recycle materials such as glass, aluminum and paper products. For some materials, notably plastics, companies are forming nonprofit consortiums to share the cost of building recycling facilities. The greater challenge, however, may be finding companies that will use the recycled material. There is, for instance, such a glut of recycled newspapers that some communities have to pay recyclers to pick up old newspapers.

Converting waste—particularly solid waste—to energy by burning it is increasingly popular. Within the past five years, Westinghouse has won orders totaling more than $1 billion for waste-to-energy facilities. These systems have little in common with traditional trash incinerators, Dorrycott says. By controlling the temperature, burning time and turbulence of the combustion, waste-to-energy plants can generate an average of 500 kilowatt-hours of electricity for every ton of garbage. To be sure, that is less than one third as much electricity as is generated by burning a ton of coal.



WASTE-DISPOSAL FACILITY, mapped on a computer, has a perimeter road **(magenta)** ***that encloses a gradually sloped area*** **(yellow contour lines).** ***A road*** **(purple)** ***cuts through the facility. Plateaus*** **(purple with labels)** ***are sloped to enhance drainage and minimize erosion. Image courtesy of Waste Management.***

Queen Victoria

"It's not economical compared with nuclear or oil," Dorrycott adds, but it is an economical way to get rid of garbage.

Although Swarup says that waste-to-energy plants may handle as much as 17 percent of the nation's solid waste by the year 2000, local governments, concerned about hazardous dioxin emissions and ash, are reluctant to grant permits for new sites.

Even if waste is trimmed, recycled or burned, some of it still must be buried, industry leaders say. Space for both solid- and hazardous-waste landfills is rapidly dwindling, and many communities adamantly oppose new facilities in their backyards. Although about 6,000 landfills are in operation today, only 2,000 may still have room for more trash by the end of the century.

To soften public resistance, waste companies are showcasing their state-of-the-art facilities. In Arlington, Ore., Waste Management is finishing a $25-million solid-waste site that will handle garbage from as far away as Portland, some 140 miles east. Covering 700 acres, the facility is lodged in a canyon surrounded by 300-foot ridges. Waste Management had scheduled about a month during the summer to excavate the top soil, compact the clay underneath and lay down layers of gravel and plastic. Underground pipes will collect leachates, and instruments will monitor the site for leaks. Since Arlington receives only about nine inches of rain each year, project manager Rick Daniels expects the trash to decompose slowly; nonetheless, any methane generated will be collected and either burned off or used to power the facility.

For companies in the hazardous-waste industry, the problems grow more acute. Recycling of hazardous wastes, for instance, has a checkered history. As the residents of Kent discovered, the chemical-recycling plants of the 1960's and 1970's too often became storage and dumping grounds for hazardous chemicals; many of those sites are now classified by the EPA as highly contaminated areas that qualify for cleanup funds from the federal government's "Superfund." George Vander Velde, vice-president of science and technology at Chemical Waste Management, a dominant hazardous-waste company, worries that chemical recyclers may still be too sloppy, in part because they are subject to fewer EPA regulations than are other operators in the waste business.

Winning permits to build new incinerators and disposal facilities for hazardous waste is also difficult. Moreover, insurers are skittish about backing such projects. Even USPCI, the hazardous-waste unit of Union Pacific, a $6-billion company, has had trouble finding insurers to back its work, says Jack L. Messman, USPCI chairman. USPCI is not alone, he adds.

Remediation, or cleaning up designated toxic-waste sites, has promised to be lucrative for waste companies; start-up companies are also entering the market with innovative techniques for degrading toxic wastes with bacteria. So far, however, business has been slow. Although the EPA has earmarked about $8.5 billion for cleaning up Superfund sites, most money spent so far has supported studies rather than remediation. The problems at only a few hazardous sites, such as the one in Kent, are being addressed.

"We waste a lot of energy in defining and redefining what needs to be done," says Rhett R. Ripplinger, general manager of Westinghouse's hazardous-waste division. The regulatory muddle, along with raw public emotions and disputes over standards of cleanliness, has held up remediation, he says. One result: most companies specializing in remediation lost money during the first half of 1989. A handful of companies have even quit the industry. Others hope that new EPA administrator William K. Reilly will soon direct Superfund money into remediation projects.

For those who can afford to wait, the business still promises to be a strong one, Messman says. He sees a variety of positive changes. For instance, by October, all states must send the EPA specific plans of how they will dispose of their hazardous waste. As more wastes are designated as hazardous, it becomes harder for companies to ensure that they are handling and treating chemicals properly. As a result, Messman expects even large companies will begin to seek help from waste-treatment specialists.

"The industry is still chaotic," Messman says. It is likely to remain so, as waste firms strive to prove they can cope with the leavings of industrialized society. *—Elizabeth Corcoran*

Look but Don't Touch

Software companies battle over intellectual property rights

For the past year or two, several large U.S. software companies have been preparing to battle competitors big and small. Yet these fights are likely to be waged in courthouses rather than the marketplace.

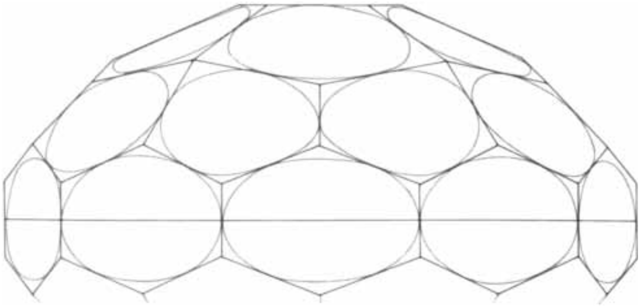
Apple, Ashton-Tate and Lotus Development have initiated separate lawsuits claiming that competitors violated their copyright on particular software products and mimicked what legal observers call the "look and feel" of the software in question. Most of these cases are likely to go to court later this year; the decisions will break new ground in applying copyright law to software, says Ronald J. Palenski, vice-president for ADAPSO, a software-industry association.

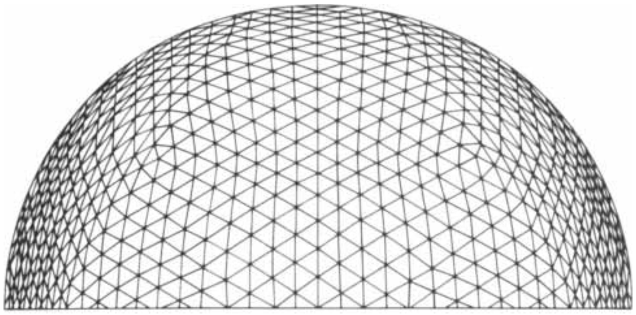
The plantiffs are not accusing their competitors of literally copying the software codes; instead they are typically arguing that the "organization, structure and sequence" of their programs have been duplicated. Does that sound vague? It is, industry sources say. The plantiffs are trying to protect something that lies between an idea (which cannot be copyrighted) and the expression of that idea (namely, specific software codes), Palenski says. As a result, independent software developers say they are worried; aspects of software—such as user interfaces—that they have felt free to adopt for their own programs may become subject to license fees.

Copyright protection, established by the U.S. Constitution, aims to encourage innovation by ensuring that artists receive payment for their work. In 1980 Congress passed the Software Copyright Act and affirmed that software is usually covered by copyright (which protects expressions of ideas) rather than by patent law (which protects inventions). What would be protected and in what fashion was left to the courts.

Each of the ongoing cases pushes the boundaries of copyright law in a slightly different direction, legal experts say. Apple, for one, has charged that Microsoft and Hewlett-Packard improperly adopted the display elements—such as icons or pictures—that show up on screen menus in Apple software. "The Mac has a certain look that people readily recognize," says Chris R. Ottenweller, an attorney for Apple. The suit "focuses on the entirety of what you see," he says.

Lotus, in turn, has sued two small companies—namely, Mosaic and Paperback Software—over spreadsheet programs. The Lotus 1-2-3 package became a legendary success. Yet when Mosaic and Paperback separately began claiming that their packages looked like 1-2-3 but ran faster and cost less, Lotus called its lawyers. "Keystroke for keystroke, the programs are identical," says Tom Lem-





NEWLY PATENTED GEOTANGENT DOME* (left) *is built with pentagons and hexagons; in contrast, traditional geodesic domes* (right) *rely on a multitude of triangles.

berg, Lotus vice-president and general counsel. The software codes written by Mosaic and Paperback engineers to support what the user sees are probably different, Lemberg says. But he argues that there is "no originality" involved when what the user sees looks like 1-2-3.

Ashton-Tate initiated its lawsuit against Fox Software and Santa Cruz Operation over the company's highly successful data-base-management package, dBASE. Ashton-Tate argues that it developed a proprietary language and special user interfaces and syntax for dBASE. "Fox claims it redid the code [that underlies what the user sees]," says Ronald L. Johnston, an attorney for Ashton-Tate. "But some of the most creative [aspects of dBASE] are the design features—what they took—not the coding."

The legal cross fire has angered many software engineers, particularly some who wrote the early programs that the plantiff companies now use. "When we were writing the Mac [software and interfaces], our only concern was to make it as fantastic as we possibly could," says Andy Hertzfeld, who contributed to designing Apple's Macintosh interface and is now an independent consultant. "Today I think twice about copying anything; tomorrow, I'm going to need a lawyer on my staff," he adds.

"There's a tradition in the field of using the best command icons and data displays available," says Richard M. Stallman, a staff member at the Massachusetts Institute of Technology. He worries that a narrow interpretation of copyright protection may discourage programmers from using the best available interfaces. Stallman has organized the League for Programming Freedom to protest the suits launched by the three software companies. In May, Stallman, artificial-intelligence guru Patrick H. Winston and reportedly 150 other M.I.T. workers picketed in front of Lotus. It would be ironic, Palenski says, if broad copyright protection ended up stifling innovation by entrepreneurs who fear they might be sued. —*E.C.*

Surpassing the Buck

Geometry decrees a new dome

"I started with the universe—as an organization of energy systems of which all our experiences and possible experiences are only local instances. I could have ended up with a pair of flying slippers."

—R. BUCKMINSTER FULLER

Buckminster Fuller never did design a pair of flying slippers. Yet he became famous for an invention that seemed almost magical: the geodesic dome, an assemblage of triangular trusses that grows stronger as it grows larger. Some dispute that Fuller originated the geodesic dome; in *Science à la Mode,* physicist and author Tony Rothman argues that the Carl Zeiss Optical Company built and patented the first geodesic dome in Germany during the 1920's. Nevertheless, in the wake of Fuller's 1954 patent, thousands of domes sprung up as homes and civic centers—even as caps on oil-storage tanks. Moreover, in a spirit that Fuller would have heartily applauded, hundreds of inventors have tinkered with dome designs, looking for improved versions. Now one has found a way to design a completely different sort of dome.

In May, J. Craig Yacoe, a retired engineer, won patent number 4,825,602 for a "geotangent dome," made up of pentagons and hexagons, that promises to be more versatile than its geodesic predecessor. Since Fuller's dome is based on a sphere, cutting it anywhere but precisely along its equator means that the triangles at the bottom will tilt inward or outward. In contrast, Yacoe's dome, which has a circular base, follows the curve of an ellipsoid. Builders can consequently pick the dimensions they need, Yacoe says. And his design ensures that the polygons at the base of his dome always meet the ground at right angles, making it easier to build than a geodesic dome. He hopes these features will prove a winning combination.

Although Fuller predicted that a million domes would be built by the mid-1980's, the number is closer to 50,000. Domes are nonetheless still going up in surprising places. A 265-foot-wide geodesic dome is part of a new pavilion at Walt Disney World's Epcot Center in Florida. A bright blue 360-foot-high dome houses a shopping center in downtown Ankara, Turkey. Stockholm, Sweden, boasts a 280-foot-high dome enclosing a new civic center.

Dome design is governed by some basic geometric principles. A sphere can be covered with precisely 20 equilateral triangles; for a geodesic dome, those triangles are carved into smaller ones of different sizes. But to cover a sphere or ellipsoid with various sizes of pentagons and hexagons required another technique, Yacoe says.

Yacoe eventually realized that he could build a dome of polygonal panels guided by the principle that one point on each side of every panel had to be tangent to (or touch) an imaginary circumscribed dome. With the assistance of William E. Davis, a retired mathematician, he set out to describe the problem mathematically.

They began with a ring of at least six congruent pentagons wrapped around the equator of an imaginary ellipse. The task: find the lengths of the sides and the interior angles of the polygons that form the next ring.

To do so for an ellipsoidal dome, they imagined inscribing an ellipse inside each polygon. Each ellipse

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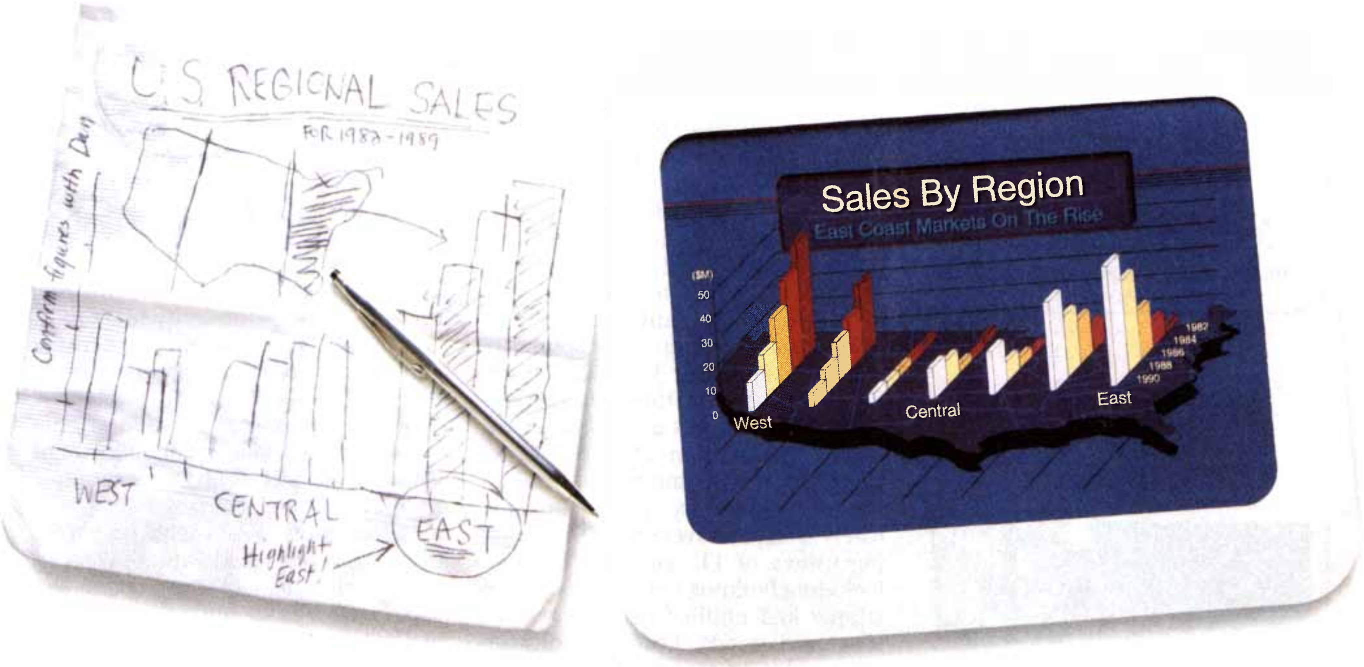

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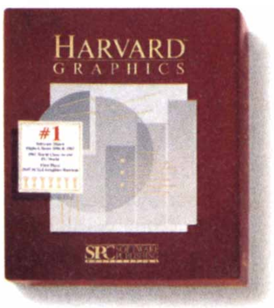

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touched another at one point; at these points, the sides of the polygons would also be tangent to a circumscribed ellipsoid. But where, precisely, should the points be located? Yacoe and Davis guessed, then plugged the numbers into equations that describe ellipses and intersecting planes. Aided by a personal computer, they methodically tested many guesses until the equations balanced. Using the tangent points, Yacoe and Davis could then calculate the dimensions and interior angles of the corresponding polygons and so build the next ring of the dome.

After receiving the patent, Yacoe promptly set up a consulting firm to license his patents. He says dome-home builders have shown considerable interest, as has Spitz, Inc., a maker of planetariums located near Yacoe in Chadds Ford, Pa. Yacoe has also proposed that the National Aeronautics and Space Administration consider a geotangent structure as part of a space station. *—E.C.*

THE ANALYTICAL ECONOMIST

Seasoning leading economic indicators with salt

Predicting the next turn of the economy has become a game of Russian roulette for business. Miscalculations can wreck the best-laid spending and production plans. This year's economy, moreover, has had a particularly mischievous bent: in January, signs of inflation affrighted forecasters; by June, the specter of recession loomed instead. The leading economic indicators that guide such forecasts have performed fairly well in the past, but in recent interviews veteran policymakers such as Paul A. Volcker cautioned that the indicators should be viewed skeptically. Just what is the predictive value of these numbers?

The official index of leading indicators is published monthly by the U.S. Department of Commerce in its *Business Conditions Digest.* It is an intricately weighted average of the changing values of 11 economic factors—including building permits, the money supply and unfilled orders for manufactured goods. Leading indicators lead cycles in the economy because the activity they measure precedes more substantive changes: building permits precede construction, orders precede production and so on. Forecasters also draw on a host of other early indicators, such as gross-manufacturing profit margins, interest rates and part-time industrial work.

Geoffrey H. Moore of the Center for International Business Cycle Research thinks the combined index has acquitted itself well historically; he points out that every sustained drop in leading indicators has presaged either a recession or a significant slowdown in the U.S. economy. Yet when the index erroneously predicted a recession after the 1987 stock-market crash, at least one pundit denounced it as "antiquated and irrelevant."

Indeed, some forecasters largely disregard the Commerce Department's index. Andrew F. Brimmer, a former governor of the Federal Reserve and now a consultant, argues that the individual numbers that make up the index are more informative and available earlier than the monthly tally. Other figures not included in the index, such as interest-rate futures, are equally significant, he adds.

Different indicators may also predict economic activity at different points in the future, notes Victor Zarnowitz of the University of Chicago's business school. Housing permits and gross-manufacturing productivity may lead the economy by as much as a year, Moore says, whereas the prices of raw materials or unemployment claims provide less than six months' notice of coming changes.

"I don't put a lot of weight on particular indicators," said Paul A. Volcker, former chairman of the Federal Reserve Board, in an interview with SCIENTIFIC AMERICAN. The Fed tweaks interest rates to counteract economic trends that its governors find worrisome; as chairman, Volcker watched economic signs from the state of inventories to surveys of consumer expectations. Forecasting a few months into the future is "pretty fuzzy," he said. Paradoxically, Volcker noted, it may often be easier to make some predictions more than a year in advance because certain data are more stable over the longer term.

A number of economists say it is time to abandon the current leading-indicator index, whose basic structure has changed little since Arthur F. Burns and Wesley C. Mitchell first compiled it in 1937. They suggest alternative statistics. Moore, for instance, has constructed a long-leading index (aimed at predicting activity often more than a year into the future) and a short-leading index (focused on changes typically less than six months away). James H. Stock of Harvard's Kennedy School of Government and Mark W. Watson of Northwestern University draw on indicators that lead the economy by varying amounts to create a complex index that measures the likelihood of a recession in six months' time. Early this summer, both Moore's and Stock's indexes were edging essentially sideways: predicting little growth but also a low probability of recession in the autumn.

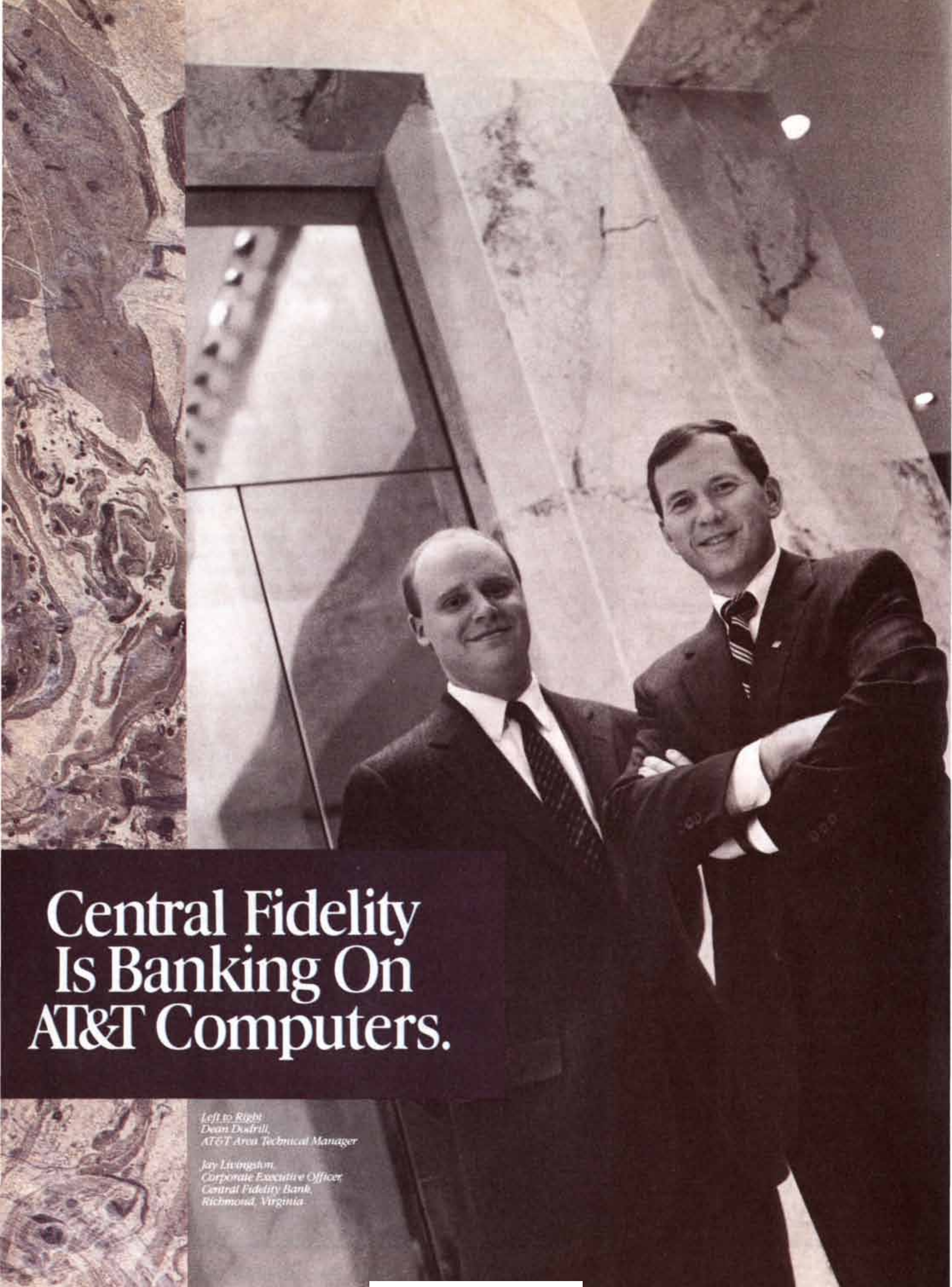
Such advanced indicators will still suffer from another source of uncertainty: as the features of the economy change, the individual indicators that make up an index gain or lose predictive value. In recent years, the supply of money has foreshadowed economic trends better than it had in the past, Zarnowitz says. The U.S. is increasingly a service economy, but almost all leading indicators continue to rely on numbers gathered from the manufacturing sector. An industrial downturn may depress the index without reflecting the condition of the economy at large. Volcker noted that past predictions of recessions may have been wrong because the index exaggerated the importance of downturns in the very cyclical manufacturing business.

But more accurate indicators of activity in the service sector are in short supply, Brimmer says. "I have no good measures for the service component," he concedes. Even measuring the current state of the service sector is difficult, he says. Data on retail sales, which now represent almost a quarter of the measured service-sector activity, can be misleading; retail sales figures are often swamped by cyclical purchases of high-priced goods such as automobiles.

The most recent revision of the Commerce Department's index attempts to address this problem by adding a survey of consumer expectations. But Zarnowitz says he is "not impressed." He argues there is little theoretical justification for including such survey data.

Yet theoretical justification for the index of leading indicators has always been something of a sore point among economists. Veterans like Zarnowitz and Moore contend there is a theoretical basis for each component of the index of leading indicators; newcomers like Stock take pride in the empirical, statistical roots of the index. The index has been around more than 50 years; yet, Stock observes, "no macroeconomic theory has lasted that long."

—Paul Wallich and Elizabeth Corcoran


Central Fidelity
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Left to Right
Dean Dodrill,
AT&T Area Technical Manager
Jay Livingston,
Corporate Executive Officer,
Central Fidelity Bank,
Richmond, Virginia.

Richmond, Virginia
February 2, 1989

Central Fidelity Bank is among the nation's top 100 commercial banks with $4.8 billion in assets. Looking to extend its fourteen-year record earnings streak, the bank commissioned its data processing division to deliver a vital strategic initiative, improve productivity, enhance sales opportunities, and provide faster customer service in the bank's nearly two hundred branch offices. Jay Livingston met recently with Dean Dodrill of AT&T to review their work together.

Jay: Service is what bank customers expect. Faster service improves customer satisfaction and leads to more profitable relationships. When you speed up service, everyone is more productive, and we can spend more time with customers selling the bank's financial products.

Dean: Service and selling both depend on information. Our challenge was to provide the branches with rapid access to customer information and present that information to branch personnel in the most meaningful way. This could only be accomplished with a distributed, networked computing approach.

Jay: That's right. Our first priority was service and sales support in our branches, which meant fast, accurate retrieval and dispersal of information was crucial. AT&T's banking architecture provided that.

Dean: Early on, you talked about cost-effectiveness, return on investment, and a strategy for future growth and functionality. Remember that?

Jay: With an emphasis on profitability. We had major investments in existing systems and a lot of branches. AT&T's open systems approach didn't require trade-offs or expensive host additions, which is one of the reasons you got the business. AT&T's creative alternatives surprised us.

Dean: The ease of networking AT&T WGS computers was fundamental to our proposal. We delivered maximum functionality, flexibility, and reliability to every workstation in each branch.

Jay: And StarLAN was a terrific way to connect and share branch resources. You made the most of our assets, including the intangible ones.

Dean: Like your customer databases—we found ways to further develop relationships with existing customers. The applications development tools we built saved time for your developers. New products and services can now be added quickly to both platform and teller software, so service and sales can continually improve.

Jay: Every bank employee associated with this system has become more productive. In my twenty-three years of banking, I've never seen a vendor provide such high-quality service and support. Central Fidelity Bank and AT&T are well positioned for the future.

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Threats to Biodiversity

Habitat destruction, mostly in the tropics, is driving thousands of species each year to extinction. The consequences will be dire—unless the trend is reversed

by Edward O. Wilson

The human species came into being at the time of greatest biological diversity in the history of the earth. Today as human populations expand and alter the natural environment, they are reducing biological diversity to its lowest level since the end of the Mesozoic era, 65 million years ago. The ultimate consequences of this biological collision are beyond calculation and certain to be harmful. That, in essence, is the biodiversity crisis.

In one sense the loss of diversity is the most important process of environmental change. I say this because it is the only process that is wholly irreversible. Its consequences are also the least predictable, because the value of the earth's biota (the fauna and flora collectively) remains largely unstudied and unappreciated. Every country can be said to have three forms of wealth: material, cultural and biological. The first two we understand very well, because they are the substance of our everyday lives. Biological wealth is taken much less seriously. This is a serious strategic error, one that will be increasingly regretted as time passes. The biota is on the one hand part of a country's heritage, the product of millions of years of evolution centered on that place and hence as much a reason for national concern as the particularities of language and culture. On the other hand, it is a potential source for immense untapped material wealth in the form of food, medicine and other commercially important substances.

EDWARD O. WILSON was one of the first to call attention to the global decline in biological diversity and to sound the alarm on the consequences of its loss. His interest in living organisms, especially ants, stems back to his childhood, which was devoted to the exploration and collection of living things, and to his undergraduate studies in evolutionary biology at the University of Alabama. He received his Ph.D. in biology from Harvard University, where he is now Frank B. Baird, Jr., Professor of Science and Curator in Entomology. Wilson has made major contributions to a number of fields, including the behavior and evolution of social insects, chemical communication and the evolution of social behavior. He has been awarded the National Medal of Science, the Pulitzer Prize in general nonfiction for his book *On Human Nature* and the Tyler Prize for environmental achievement.

It is a remarkable fact, given the interdependence of human beings and the other species that inhabit the planet, that the task of studying biodiversity is still in an early stage. Although systematics is one of the two oldest formal disciplines of biology (the other is anatomy), we do not even know to the nearest order of magnitude the number of species of organisms on the earth. With the help of other specialists, I have estimated the number of species that have been formally described (given a Latinized scientific name) to be about 1.4 million. Even conservative guesses place the actual number of species at four million or greater, more than twice the number described to date.

Terry L. Erwin of the Smithsonian's National Museum of Natural History believes the number of species to be even greater. With the help of co-workers, he applied an insecticidal fog to the forest canopy at localities in Brazil and Peru in order to obtain an estimate of the total number of insect and other arthropod species in this rich but still relatively unexplored habitat. By extrapolating his findings to moist tropical forests around the world and by including a rough estimate of the number of ground-dwelling species in his calculations, Erwin arrived at a global total of 30 million species. Even if this number proves to be a considerable overestimate, the amount of biodiversity in the world is certain to be projected sharply upward in other, compensatory ways.

Groups such as the mites and fungi, for example, are extremely rich and also very underexplored, and habitats such as the floors of the deep sea are thought to harbor hundreds of thousands of species, most of which remain undescribed. Even the number of bacterial species on the earth is expected to be many times greater than the 3,000 that have been characterized to date. To take one example, an entirely new flora of bacteria has recently been discovered living at depths of 350 meters or more beneath the ground near Hilton Head, South Carolina. Even new species of birds continue to turn up at an average rate of two per year.

Systematists are in wide agreement that whatever the absolute numbers, more than half of the species on the earth live in moist tropical forests, popularly referred to as rain forests. Occupying only 6 percent of the land surface, these ecosystems are found in warm areas where the rainfall is 200 centimeters or more per year, which allows broad-leaved evergreen trees to flourish. The trees typically sort into three or more horizontal layers, the canopy of the tallest being 30 meters (about 100 feet) or more from the ground. Together the tree crowns of the several layers admit little sunlight to the forest floor, inhibiting the development of undergrowth and leaving large spaces through which it is relatively easy to walk.

The belief that a majority of the

TROPICAL RAIN FORESTS, such as this one in northern Costa Rica, are among the most species-rich habitats on the earth. The enormous biological diversity found in these forests can be explained by the fact that the most species-rich groups on the planet, the invertebrates and flowering plants, are concentrated there. The vegetation, much of it broad-leaved evergreens, is extremely lush; the tallest trees tower as much as 30 meters (100 feet) above the rain-forest floor.

DEFORESTATION IS OCCURRING at a rapid rate around the world. In Costa Rica (*top*), as well as in parts of South America, rain forest is often cut and the land fenced in and converted to pasture. Unlike temperate forests, where nutrients accumulate in the soil, tropical forests typically have poor-quality soil. Consequently, within two or three years after being cleared, soil that once supported dense vegetation becomes too nutrient-poor to provide much grass for grazing cattle. In the U.S. (*bottom*), the impact of large-scale logging operations can be clearly seen in this photograph of a mountain range in the state of Washington. The scattered logs in the foreground are trees that have been cut and stripped of their branches and are waiting to be collected.

planet's species live in tropical rain-forest habitats is not based on an exact and comprehensive census but on the fact that the two overwhelmingly species-rich groups, the arthropods (especially insects) and the flowering plants, are concentrated there. Other extremely species-rich environments exist, including the coral reefs and abyssal plains of the oceans and the heathlands of South Africa and southwestern Australia, but these appear to be outranked substantially by the rain forests.

Every tropical biologist has stories of the prodigious variety in this one habitat type. From a single leguminous tree in Peru, I once retrieved 43 ant species belonging to 26 genera, approximately equal to the ant diversity of all of the British Isles. In 10 selected one-hectare plots in Kalimantan in Indonesia, Peter S. Ashton of Harvard University found more than 700 tree species, about equal to the number of tree species native to all North America. The current world record at this writing (certain to be broken) was established in 1988 by Alwyn H. Gentry of the Missouri Botanical Garden, who identified approximately 300 tree species in each of two one-hectare plots near Iquitos, Peru.

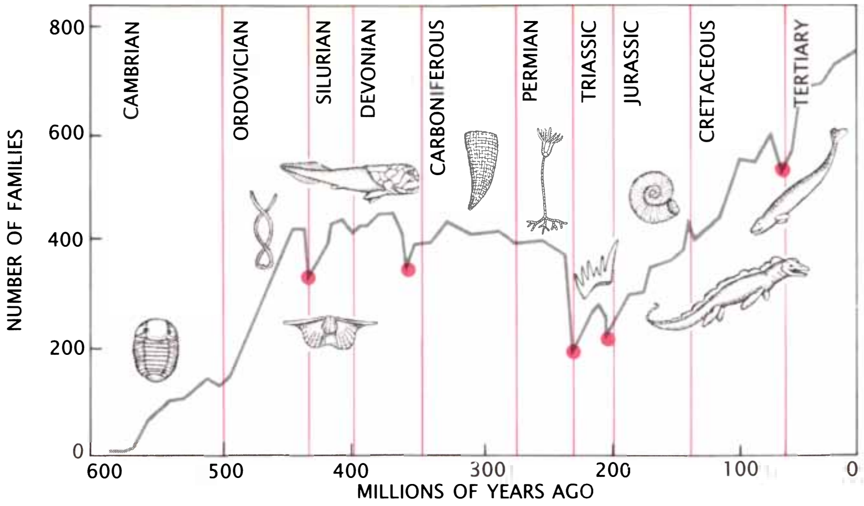
Why has life multiplied so prodigiously in a few limited places such as tropical forests and coral reefs? It was once widely believed that when large numbers of species coexist, their life cycles and food webs lock together in a way that makes the ecosystem more robust. This diversity-stability hypothesis has given way during the past 20 years to a reversed cause-and-effect scenario that might be called the stability-diversity hypothesis: fragile superstructures of species build up when the environment remains stable enough to support their evolution during long periods of time. Biologists now know that biotas, like houses of cards, can be brought tumbling down by relatively small perturbations in the physical environment. They are not robust at all.

The history of global diversity is reflected in the standing diversity of marine animals, the group best represented in the fossil record. The trajectory can be summarized as follows: after the initial "experimental" flowering of multicellular animals, there was a swift rise in species number in early Paleozoic times (some 600 million years ago), then plateaulike stagnation for the remaining 200 million years of the Paleozoic era and finally a slow but steady climb through the Mesozoic and Cenozoic eras to diversity's present all-time high [*see illustration at right*].

The overall impression gained from examining these and comparable sets of data for other groups of organisms is that biological diversity was hard won and a long time in coming. Furthermore, the procession of life was set back by five massive extinction episodes during the Ordovician, Devonian, Permian, Triassic and Cretaceous periods. The last of these is by far the most famous, because it ended the age of dinosaurs, conferred hegemony on the mammals and ultimately, for better or worse, made possible the origin of our own species. But the Cretaceous crisis was minor compared with the great Permian crash some 240 million years ago, which extinguished between 77 and 96 percent of all marine animal species. As David M. Raup of the University of Chicago has observed, "If these estimates are even reasonably accurate, global biology (for higher organisms, at least) had an extremely close call." It took five million years, well into Mesozoic times, for species diversity to begin a significant recovery.

What lessons can be drawn from these extinction episodes of the past? It is clear that recovery, given sufficient time, is sometimes possible. It is also true that in some cases new species can be created rapidly. A large minority of flowering-plant species have originated in a single generation by polyploidy—a multiplication of chromosome sets, either within a single individual or following the hybridization of two previously distinct species. Even geographic speciation, in which populations diverge genetically after being separated by a barrier such as a strait or desert, can in extreme cases lead to the evolution of new species in as few as from 10 to 100 generations. Hence, it might be argued that when a mass extinction occurs the deficit can be made up in a relatively short time. But under such circumstances pure *numbers* of species mean little. What matters more, in terms of the spread of genetic codes and the multiple ways of life they prescribe, is diversity at the higher taxonomic levels: the number of genera, families and so on.

A species is most interesting when its traits are sufficiently unique to warrant its placement in a distinct genus or even a higher-level taxon, such as a family. A concrete example helps to illustrate my point. In western China a new species of muntjac deer was recently discovered, which appears to differ from the typical muntjac of Asia only in chromosome number and in a few relatively minor anatomical traits. Human beings intuitively value this slightly differentiated species, of course, but not nearly so much as they value the giant panda, which is so distinctive as to be placed in its own genus (*Ailuropoda*) and family (Ailuropodidae).



BIOLOGICAL DIVERSITY has increased slowly over time, set back occasionally by mass extinctions. There have been five mass-extinction events so far: at the close of the Ordovician, Devonian, Permian, Triassic and Cretaceous periods, when the number of families of marine organisms declined by 12, 14, 52, 12 and 11 percent, respectively. The extinction event at the end of the Permian was by far the most severe; since then diversity has slowly increased to its present all-time high. It is now declining at an unprecedented rate, however, as a result of human activity.

Within the past 10,000 years biological diversity has entered a wholly new era in the turbulent history of life on the earth. Human activity has had a devastating effect on species diversity, and the rate of human-induced extinctions is accelerating. The heaviest pressure has hitherto been exerted on islands, lakes and other isolated and strongly circumscribed environments. Fully one half of the bird species of Polynesia have been eliminated through hunting and the destruction of native forests. In the 1800's most of the unique flora of trees and shrubs on St. Helena, a tiny island in the South Atlantic, was lost forever when the island was completely deforested. Hundreds of fish species that are endemic to Lake Victoria, formerly of great commercial value as food and aquarium fish, are now threatened with extinction as the result of the careless introduction of one species of fish, the Nile perch. The list of such biogeographic disasters is extensive.

Serious as the episodes of pinpoint destruction are, they are minor compared with the species hecatomb caused by the clearing and burning of tropical rain forests. Already the forest has been reduced to approximately 55 percent of its original cover (as inferred from soil and climate profiles of the land surface), and it is being further reduced at a rate in excess of 100,000 square kilometers a year. This amount is 1 percent of the total cover, or more than the area of Switzerland and the Netherlands combined.

What is the effect of such habitat reduction on species diversity? In archipelago systems such as the West Indies and Polynesia, the number of species found on an individual island corresponds roughly to the island's area: the number of species usually increases with the size of the island, by somewhere between the fifth and the third root of the area. Many fall close to the central value of the fourth root. The same relation holds for "habitat islands," such as patches of forest surrounded by a sea of grassland. As a rough rule of thumb, a tenfold increase in area results in a doubling of the number of species. Put the other way, if the island area is diminished tenfold, the number of species will be cut in half.

The theory of island biogeography, which has been substantiated at least in broad outline by experimental alterations of island biotas and other field studies, holds that species number usually fluctuates around an equilibrium. The number remains more or less constant over time because the rate of immigration of new species to the island balances the extinction rate of species already there, and so diversity remains fairly constant. The relation between the theory of island biogeography and global diversity is an important one: if the area of a particular habitat, such as a patch of rain forest, is reduced by a given amount, the number of species living in it will subside to a new, lower equilibrium. The rich forest along the Atlantic coast of Brazil, for example, has been cleared to less than 1 percent of its original cover; even in the unlikely event that no more trees are cut, the forest biota can be expected to decline by perhaps 75 percent, or to one quarter of its original number of species.

I have conservatively estimated that on a worldwide basis the ultimate loss attributable to rain-forest clearing alone (at the present 1 percent rate) is from .2 to .3 percent of all species in the forests per year. Taking a very conservative figure of two million species confined to the forests, the global loss that results from deforestation could be as much as from 4,000 to 6,000 species a year. That in turn is on the order of 10,000 times greater than the naturally occurring background extinction rate that existed prior to the appearance of human beings.

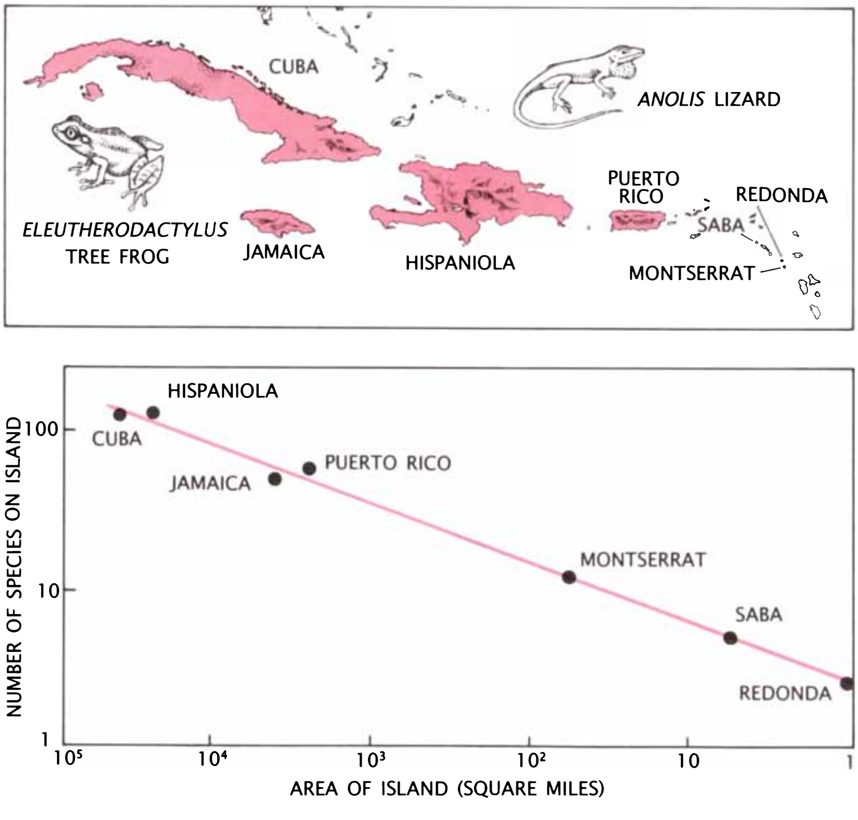
Although the impact of habitat destruction is most severely felt in tropical rain forests, where species diversity is so high, it is also felt in other regions of the planet, particularly where extensive forest clearing is taking place. In the U.S. alone, some 60,000 acres of ancient forests are being cut per year, mostly for lumber that is then exported to Japan and other countries in the Pacific rim. Most severely affected are the national forests of the Pacific Northwest, from which some 5.5 billion board-feet of timber were harvested in 1987, and Alaska's Tongass National Forest, where as much as 50 percent of the most productive forestland has been logged since 1950. Although reforestation in these areas is possible, the process of regrowth may last 100 years or more.

How long does it take, once a habitat is reduced or destroyed, for the species that live in it to actually become extinct? The rate of extinction depends on the size of the habitat patch left undisturbed and the group of organisms concerned. In one ingenious study, Jared M. Diamond of the University of California at Los Angeles and John W. Terborgh of Duke University counted the number of bird species on several continental-shelf islands, which until about 10,000 years ago had been part of the mainland but then became isolated when the sea level rose. By comparing the number of species per island with the number of species on the adjacent mainland, Diamond and Terborgh were able to estimate the number of species each island had lost and to correlate the rate of species loss with island size.

Their model has been reasonably well confirmed by empirical studies of local bird faunas, and the results are sobering: in patches of between one and 20 square kilometers, a common size for reserves and parks in the tropics and elsewhere, 20 percent or more of the species disappear within 50 years. Some of the birds vanish quickly. Others linger for a while as the "living dead." In regions where the natural habitat is highly fragmented, the rate of species loss is even greater.

These extinction rates are probably underestimates, because they are based on the assumption that the species are distributed more or less evenly throughout the forests being cut. But biological surveys indicate that large numbers of species are confined to very limited ranges; if the small fraction of the forest habitat occupied by a species is destroyed, the species is eliminated immediately. When a single ridge top in Peru was cleared recently, more than 90 plant species known only from that locality were lost forever.

Ecologists have begun to identify "hot spots" around the world—habitats that are rich in species and also in imminent danger of destruction. Norman Myers, an environmental consultant with wide experience in the tropics, has compiled a list of threatened rain-forest habitats from 10 places: the Chocó of western Colombia, the uplands of western Amazonia, the



NUMBER OF SPECIES on an island corresponds to its size. As a general rule, when the area of an island increases tenfold, the number of species on it doubles. This is easily demonstrated for an island archipelago, such as the West Indies (*top*), where there are numerous islands of different sizes. The numbers of species of reptiles and amphibians on five islands, including *Anolis* lizards and *Eleutherodactylus* tree frogs, were counted and the combined total plotted against the area of each island. As the curve shows (*bottom*), a large island, such as Cuba, has more than twice as many species as, say, the smaller island of Saba. These findings have important implications for conservation biology because the data can be used to predict species loss from habitat destruction and to determine the optimal size of wildlife preserves.

SATELLITE IMAGE of the northern tip of Prince of Wales Island in Tongass National Forest, Alaska, shows the extent to which the region has been clear cut. Areas that have recently been cleared and are barren of tree cover are indicated in pink; those that have been cut but have started to recover are light green; areas where the forest has not yet been disturbed are dark green. The image covers about 400 square miles.

Atlantic coast of Brazil, Madagascar, the eastern Himalayas, the Philippines, Malaysia, northwestern Borneo, Queensland and New Caledonia. Other biologists have similarly classified certain temperate forest patches, heathlands, coral reefs, drainage systems and ancient lakes. One of the more surprising examples is Lake Baikal in Siberia, where large numbers of endemic crustaceans and other invertebrates are endangered by rising levels of pollution.

The world biota is trapped as though in a vise. On one side it is being swiftly reduced by deforestation. On the other it is threatened by climatic warming brought on by the greenhouse effect. Whereas habitat loss is most destructive to tropical biotas, climatic warming is expected to have a greater impact on the biotas of the cold temperate regions and polar regions. A poleward shift of climate at the rate of 100 kilometers or more per century, which is considered at least a possibility, would leave wildlife preserves and entire species ranges behind, and many kinds of plants and animals could not migrate fast enough to keep up.

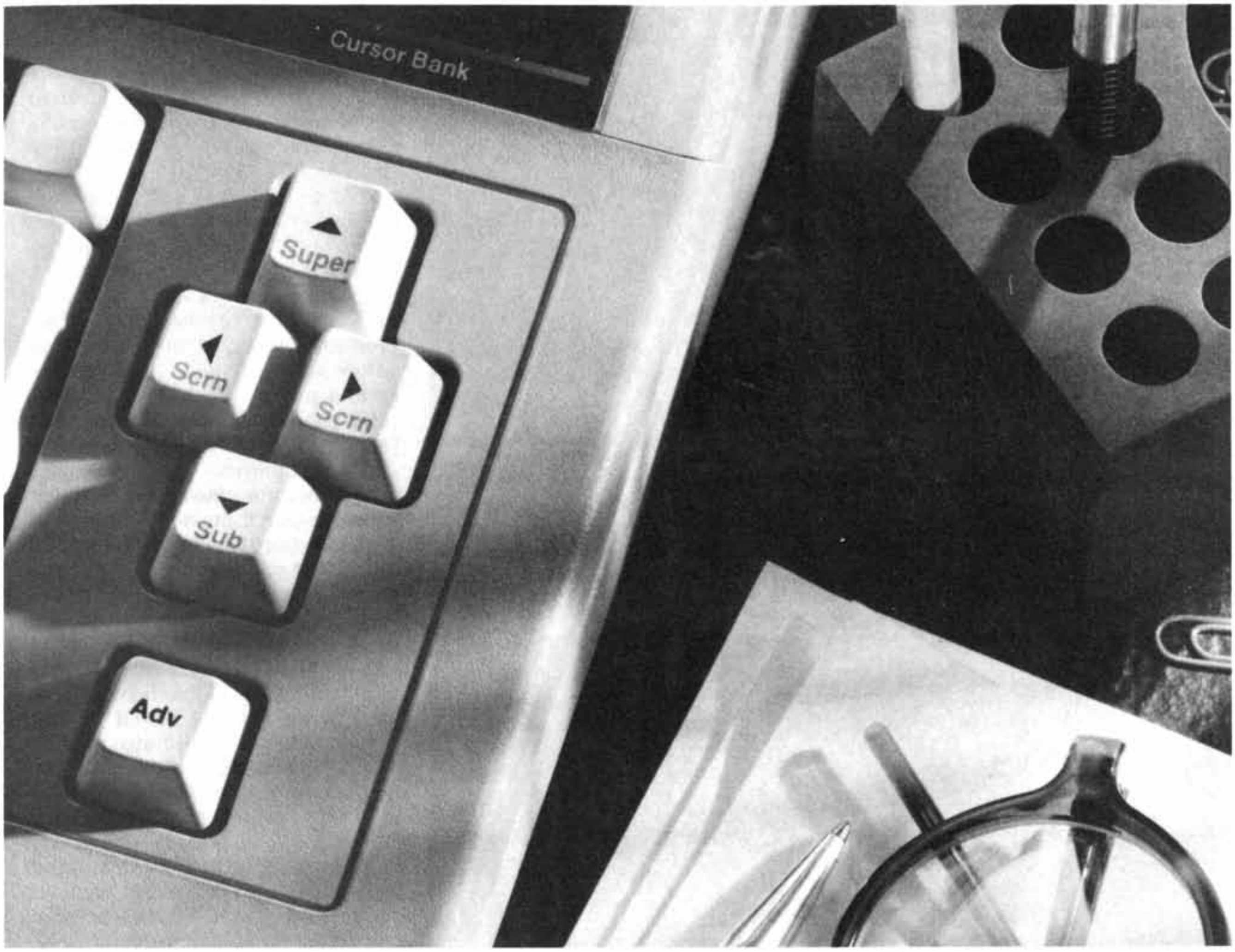
The problem would be particularly acute for plants, which are relatively immobile and do not disperse as readily as animals. The Engelmann spruce, for example, has an estimated natural dispersal capacity of from one to 20 kilometers per century, so that massive new plantings would be required to sustain the size of the range it currently occupies. Margaret Davis and Catherine Zabinski of the University of Minnesota predict that in response to global warming four North American trees—yellow birch, sugar maple, beech and hemlock—will be displaced northward by from 500 to 1,000 kilometers. Hundreds of thousands of species are likely to be similarly displaced; how many will adapt to the changing climate, not having migrated, and how many will become extinct is, of course, unknown.

Virtually all ecologists, and I include myself among them, would argue that every species extinction diminishes humanity. Every microorganism, animal and plant contains on the order of from one million to 10 billion bits of information in its genetic code, hammered into existence by an astronomical number of mutations and episodes of natural selection over the course of thousands or millions of years of evolution. Biologists may eventually come to read the entire genetic codes of some individual strains of a few of the vanishing species, but I doubt that they can hope to measure, let alone replace, the natural species and the great array of genetic strains composing them. The power of evolution by natural selection may be too great even to conceive, let alone duplicate. Without diversity there can be no selection (either natural or artificial) for organisms adapted to a particular habitat that then undergoes change. Species diversity—the world's available gene pool—is one of our planet's most important and irreplaceable resources. No artificially selected genetic strain has, to my knowledge, ever outcompeted wild variants of the same species in the natural environment.

It would be naive to think that humanity need only wait while natural speciation refills the diversity void created by mass extinctions. Following the great Cretaceous extinction (the latest such episode), from five to 10 million years passed before diversity was restored to its original levels. As species are exterminated, largely as a result of habitat destruction, the capacity for natural genetic regeneration is greatly reduced. In Norman Myers's phrase, we are causing the death of birth.

Wild species in tropical forests and other natural habitats are among the most important resources available to humankind, and so far they are the least utilized. At present, less than one tenth of 1 percent of naturally occurring species are exploited by human beings, while the rest remain untested and fallow. In the course of history people have utilized about 7,000 plant species for food, but today they rely heavily on about 20 species, such as wheat, rye, millet and rice—plants for the most part that Neolithic man encountered haphazardly at the dawn of agriculture. Yet at least 75,000 plant species have edible parts, and at least some of them are demonstrably superior to crop species in prevalent use. For example, the winged bean, *Psophocarpus tetragonolobus,* which grows in New Guinea, has been called a one-species supermarket: the entire plant—roots, seeds, leaves, stems and flowers—is edible, and a coffeelike beverage can be made from its juice. It grows rapidly, reaching a height of 15 feet in a few weeks, and has a nutritional value equal to that of soybeans.

Wild plant and animal species also represent vast reservoirs of such potentially valuable products as fibers and petroleum substitutes. One example is the babassú palm, *Orbignya phalerata,* from the Amazon basin; a stand of 500 trees produces about 125 barrels of oil a year. Another striking example is the rosy periwinkle, *Catharanthus roseus,* an inconspicuous little plant that originated in Madagascar. It yields two alkaloids, vinblastine and vincristine, that are extremely



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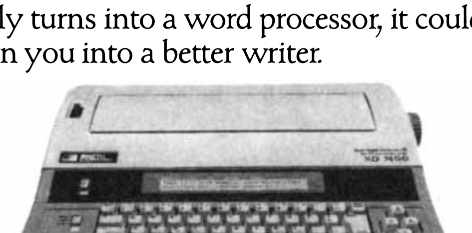

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PLANTS FROM TROPICAL RAIN FORESTS are the source of food, medicine and other commercially valuable products. The rosy periwinkle, *Catharanthus roseus* (*left*), contains substances that are effective against some cancers, and the babassú palm, *Orbignya phalerata* (*right*), produces bunches of fruit (each one weighing about 200 pounds), from which oil (for cooking and other purposes) can be extracted.

INSECT DIVERSITY is extraordinarily high in tropical rain forests, where millions of species, including this ant from the island of Sulawesi in Indonesia, have yet to be inventoried. The ant, which is unusual for its large eyes and robotlike movements, belongs to the genus *Opisthopsis* but has not yet been given a species name.

effective against Hodgkin's disease and acute lymphocytic leukemia. The income from these two substances alone exceeds $100 million a year. Five other species of *Catharanthus* occur on Madagascar, none of which have been carefully studied. At this moment one of the five is close to extinction due to habitat destruction.

Biological diversity is eroding at a swift pace, and massive losses can be expected if present rates continue. Can steps be taken to slow the extinction process and eventually bring it to a halt? The answer is a guarded "yes." Both developed and developing (mostly tropical) countries need to expand their taxonomic inventories and reference libraries in order to map the world's species and identify hot spots for priority in conservation. At the same time, conservation must be closely coupled with economic development, especially in countries where poverty and high population densities threaten the last of the retreating wildlands. Biologists and economic planners now understand that merely setting aside reserves, without regard for the needs of the local population, is but a short-term solution to the biodiversity crisis.

Recent studies indicate that even with a limited knowledge of wild species and only a modest effort, more income can often be extracted from sustained harvesting of natural forest products than from clear-cutting for timber and agriculture. The irony of cutting down tropical forests in order to grow crops or graze cattle is that after two or three years the nutrient-poor topsoil can no longer support the agricultural activity for which it was cleared in the first place.

Thomas Eisner of Cornell University has suggested that in addition to the compilation of biological inventories, programs should be established to promote chemical prospecting around the world as part of the search for new products. The U.S. National Cancer Institute has begun to do just that: their natural products branch is currently screening some 10,000 substances a year for activity against cancer cells and the AIDS virus.

It has become equally clear that biological research must be tied to zoning and regional land-use planning designed not only to conserve and promote the use of wild species but also to make more efficient use of land previously converted to agriculture and monoculture timber. More efficient land use includes choosing commercial species well suited to local climatic and soil conditions, planting mixtures of species with yields higher than those of monocultures and rotating crops on a regular basis. These methods relieve pressure on natural lands without reducing their overall productivity. No less important are social studies and educational programs that focus directly on the needs of the people who live on the land.

I have enough faith in human nature to believe that when people are both economically secure and aware of the value of biological wealth they will take the necessary measures to protect their environment. Out of that commitment will grow new knowledge and an enrichment of the human spirit beyond our present imagination.

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PEPSI

The Growing Human Population

Development will stabilize populations, but will development come before population growth and harsh technologies do irremediable damage to the planet's life-support capacity?

by Nathan Keyfitz

The human life we know is set in a small space and in a small slice of time. If the earth were represented as a globe two feet in diameter, most life would be contained within the paint marking its surface, and the habitat of the five billion humans would be a thin layer within that. As recently as 10,000 years ago, people gathered into small Neolithic settlements. There were from five to 10 million human beings then—not enough to exercise much influence on the ecosystem within which they lived and worked. That situation prevailed for most of the next 10,000 years. Only in the past few decades have humans brought about changes comparable in magnitude to those wrought by nature during long epochs of geological time. Forests that grew over centuries and soils that took millions of years to develop are now being used up in a single human lifetime.

The population of the world at mid-century was 2.5 billion; some time in 1987 it passed five billion. The increase in the past 40 years has equaled the total increase over the millions of years from when the human species emerged until 1950. According to projections by the United Nations Population Division, the next 35 years (to 2025) will see a further increase to 8.5 billion. Of the projected increase of some 3.2 billion, the United Nations finds that less than 200 million will be in the developed countries; at least three billion—that is, 95 percent—will be in the less developed countries.

Should we be worrying about the absolute increase of 3.2 billion people, or should we take satisfaction in the fact that the rate of increase is slowing? Between 1980 and 1985 total population increased by 9 percent; between 2020 and 2025 the increase is projected to be only 4 percent. Yet because the rate of increase applies to an ever larger base, the absolute population curve will continue upward. It will be well into the second quarter of the 21st century before the absolute number of births will come down even to the high levels of today. The population curve, of course, will continue to slope upward well beyond that time.

Is this progress or retrogression? Can one take satisfaction from the fact that the hungry will represent a declining fraction of the total population when their absolute number is increasing? Can one be glad that the rate of increase is slowing when it is not rates that wreak ecological destruction but absolute numbers of people?

The exponential growth of population and its attendant assault on the environment is so recent that it is difficult for people to appreciate how much damage is being done. Through long ages, many societies wanted more people; people added to the strength of the family and of the kingdom in which they labored. Death rates were so high that populations did not increase by much. The human population was viewed as a fragile entity in constant danger of extinction, locally if not globally. People were precious to their ruler, in much the same way as slaves were to their owners.

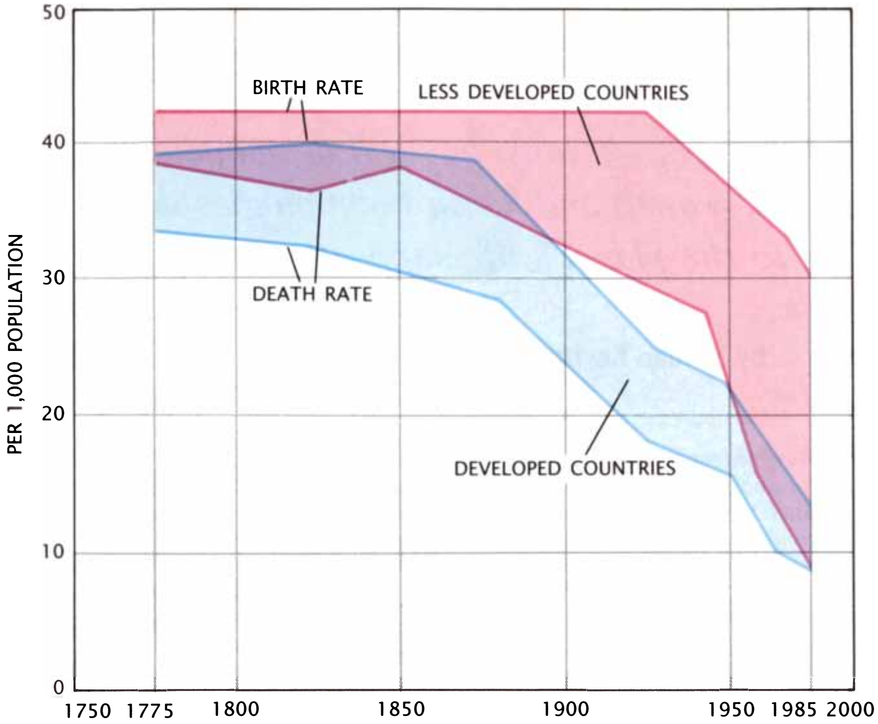
In 17th-century Europe the land could provide food for more people than were needed to work it. Hence, a ruler could put surplus laborers to work at the labor-intensive task of weaving cloth. The cloth could then be sold abroad in exchange for gold. That system was mercantilism, as practiced for example by Jean-Baptiste Colbert, finance minister to Louis XIV of France. Similar economic ideas were accepted throughout Europe. Even with the advent of machine production, large numbers of laborers could be employed, because although productivity per worker certainly increased, the demand for products increased even faster. Hence, labor remained a valued commodity.

Today rapid population growth is occurring simultaneously with improvements in production methods. In addition, an egalitarian ethos has spread in less developed countries as well as in industrialized ones. And so the conditions that prevailed until the 19th century—low population density on fertile land, labor-intensive technology and regard for the welfare of rulers rather than of workers—apply much less now. Labor-saving technology makes it more difficult to turn unequipped workers into gold. On the contrary, the less developed countries borrow capital to buy equipment in order to create employment for their people. Yet the equipment, designed in highly developed countries, requires relatively few hands to run it, and so even when borrowing by the less developed countries was at its height in the 1970's, unemployment kept increasing.

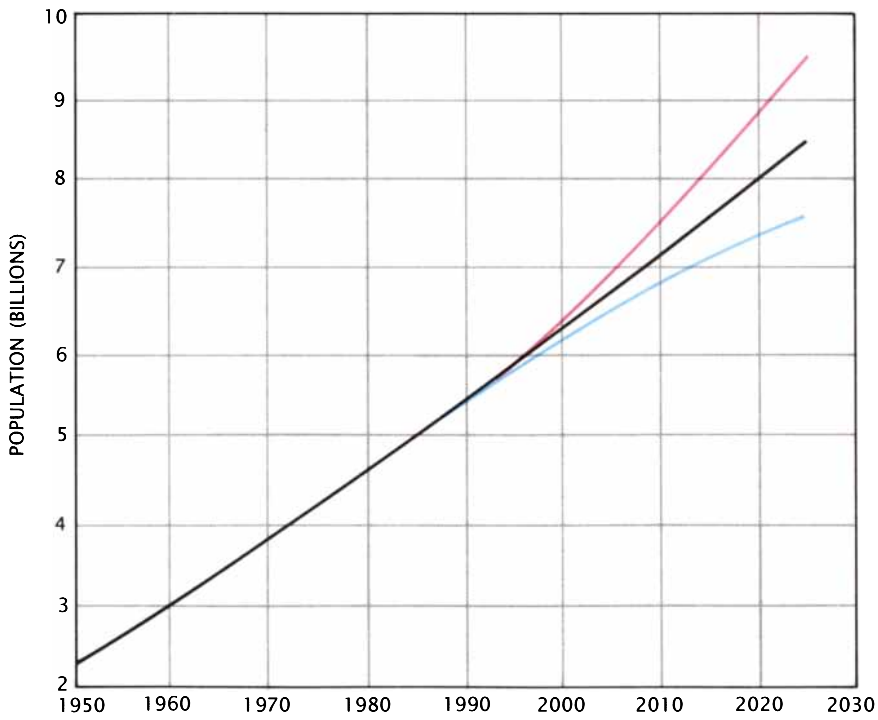
Are the unemployed evidence of

EXTREME CROWDING in Mexico City, the largest city in the world, forces millions of poor people to live in slums such as this one, where sewage disposal, adequate water supplies and other services do not exist. The city's population of 19.4 million is expected to swell to 24.4 million by the end of the century.

NATHAN KEYFITZ was born in Montreal. He received his B.Sc. in 1934 from McGill University and his Ph.D. in sociology from the University of Chicago in 1952. He has held appointments at the University of Toronto, University of Chicago, University of California at Berkeley, Harvard University and Ohio State University. He is currently Andelot Professor Emeritus at Harvard, Lazarus Professor Emeritus at Ohio State, head of the Population Program at the International Institute of Applied Systems Analysis in Austria and a consultant to the government of Indonesia.



INDUSTRIALIZATION in the developed regions led to a fall in death rates, followed by a drop in birth rates that began a little over a century ago. Having passed through this "demographic transition," the developed regions now have a net growth (*shaded area*) of only about .4 percent. In contrast, the decline in death rates in the less developed countries has not yet been compensated by the decline in birth rates.



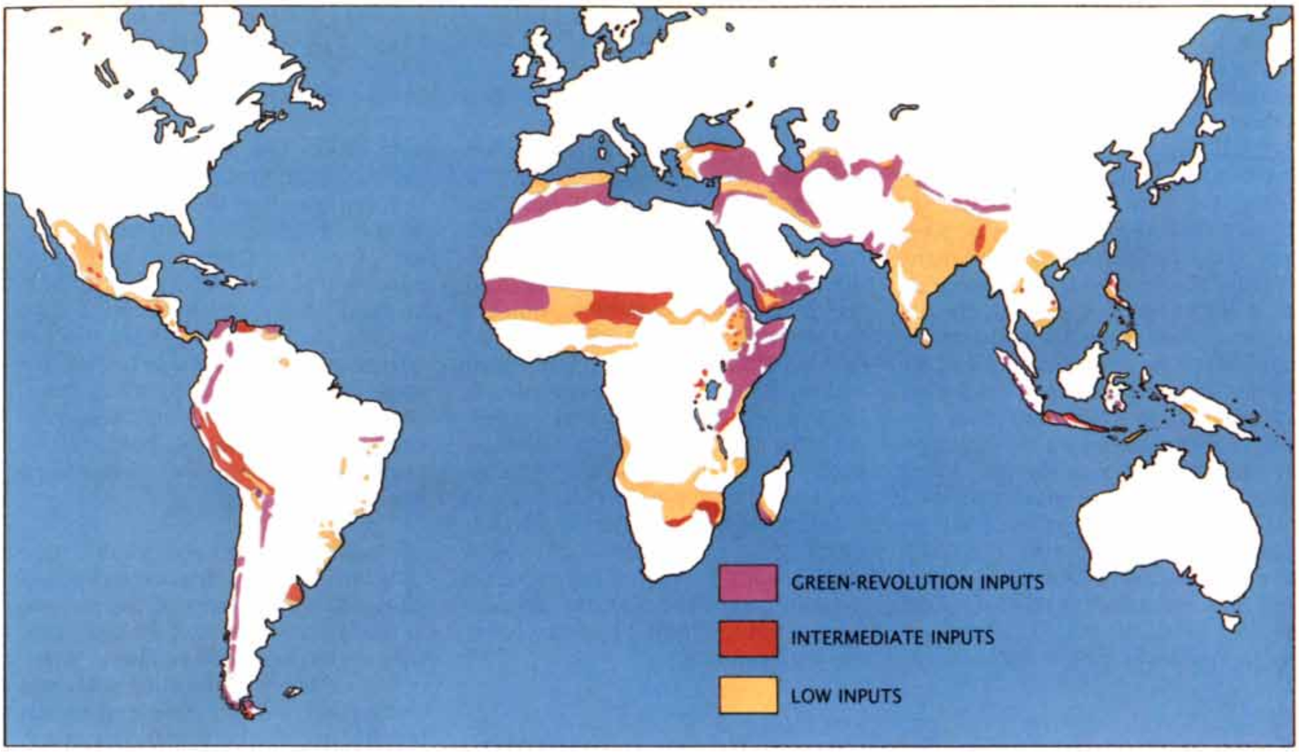
THREE PROJECTIONS of the growing human population are shown here. If the growth rate were to remain near the current 1.74 percent a year until the year 2000 and decline thereafter to .98 percent in 2025, the world population will reach almost 8.5 billion in 2025 (*black*). If the growth rate were to decline at a faster rate and reach .59 percent by 2025, the population in 2025 will be around 7.6 billion (*blue*). If the growth rate were to climb to 1.9 percent at the end of the century before declining, the population in 2025 will be more than 9.4 billion (*red*). The data were supplied by the United Nations Department of International Economic and Social Affairs.

overpopulation? Or are they not, rather, evidence of a badly run economy, in which the wages of those who do have jobs are kept artificially high? Anything, including labor, will remain unused if its price is maintained above what buyers can afford to pay for it. National leaders who see that it is politically impossible to free their labor markets at least want to add as few more people as possible, knowing that one birth prevented now is one unemployed person fewer in 2010. And since the same political forces are promoting the rapid spread of education, that unemployed person is likely to be a high school or college graduate and therefore especially dangerous to political stability.

Population increases, then, abetted by various aspects of technology and political structure, threaten social and political stability in the less developed countries. In addition, environmental issues are now emerging in the less developed as well as in the developed regions. One such issue is the flooding caused by deforestation; overlogging is directly related to the demand from ever-expanding populations for building material, firewood, additional farmland and foreign capital. Heavy floods caused by deforestation have recently led Thailand to ban all logging, and Malaysia is considering doing the same—even though both countries depend on timber and its products as an important source of employment and foreign exchange.

High birth rates in the countryside have forced many subsistence farmers onto marginal lands. In the Indian state of Rajasthan, arid soils are being rapidly depleted by intensive cultivation. The children of Javanese peasants, unable to make a living on subdivided plots of inherited land, have cleared mountainous terrain to grow crops, at the cost of much wasted labor and ecological damage. In Brazil peasants from overpopulated regions have destroyed millions of acres of rain forest in an attempt to eke out a living from soil that is essentially unsuitable for farming.

Meanwhile, more and more people are moving to cities, causing extraordinary urban concentration around the world. Before the advent of modern transport and the international grain trade, the size of a city was determined by its ability to command the agricultural surplus of farmland, usually in neighboring areas. All that has changed now: Mexico City and Caracas have grown by exchanging oil



LOCAL FOOD PRODUCTION is outstripped by population in the shaded regions on this map. The assessments are based on local agricultural technology, where only traditional, low-input (low-capital) methods are available (*yellow*); where intermediate inputs are being employed (*red*); and even where high, green-revolution inputs are being employed (*purple*).

for food, New Delhi has grown by virtue of its political dominance and India's rail network, and Calcutta has grown by virtue of water transport. In cities that have nothing to exchange, foreign aid has intervened to mitigate hunger and so, incidentally, to increase population further.

No longer dependent on local products to trade for food and other necessities, cities around the world are expanding rapidly. A sixfold increase in urban population was foreseen for the world as a whole between 1950 and 2020. What is more, the growth of cities no longer has much relation to the level of development. Whereas only 17 percent of the population of the less developed countries was urban in 1950, well over 50 percent is expected to be urban in 2020.

From some points of view the concentration of people in cities has much to be said for it. To be sure, the air above Mexico City is scarcely breathable—but this is a local effect. In spite of the bad air, city dwellers probably live longer than their country cousins. Certainly health care, education and other amenities are more easily provided to urban populations than to rural ones. When people are concentrated in cities, they would seem to have less direct effect on the forests, the wildlife, the oceans—on the biosphere in general.

A case might therefore be made for the ecological innocuousness of cities—were it not for one feature of modern urban dwellers: their unprecedented mobility. People in the middle class or higher, whether they live in developed or less developed countries, are mostly urban, and they are on the move incessantly—as commuters, as vacationers, for business or for pleasure, by car, bus and plane. And much of the damage to the ecosphere is related to movement and travel. A middle-class American eats somewhat more than an Asian peasant, owns more clothes and has more varied entertainment, but none of these advantages requires extravagant amounts of resources. From an ecological perspective, it is the amount and mode of movement that principally distinguishes the American town dweller from the Asian peasant.

There are currently 500 million registered automobiles on the planet, and on the average they burn up nearly two gallons of fuel a day. Filling their tanks consumes about one third of the world's production of oil. Most of this feverish movement occurs among the 1.2 billion people in developed countries, but in the future most net growth in use of motor vehicles will take place in the less developed countries. Indeed, the number of automobiles is increasing more quickly than the population. At current rates of increase, by 2025 there will be four times as many automobiles as there are today.

The absolute increase in population, coupled with such trends as urbanization and greater mobility, clearly presents serious threats, especially for the less developed countries. Yet surely the absolute growth cannot continue forever. There must be some natural limit, some ultimate constraint. The 3.4 percent annual growth rate of Nigeria, for example, translates into a doubling of its population in 22 years. If Nigeria were to continue at this rate for the next 140 years, its population would be equal to that of the whole world today. Needless to say, this will not happen. Either its birth rate will fall or its death rate will rise. Because migration on a scale large enough to alleviate the pressure is out of the question, there are no other possibilities.

It is certain, then, that sooner or later growth has to stop. What are the natural limits, and what do they imply? Malthus assumed that the limit was food, but agricultural progress during the past two centuries has thrown that assumption into question. Food surpluses exist in many nations, and even when famines do occur the cause is much less the absence of food than its maldistribution—which is often accentuated by politics and civil war, as in the Sudan. Yet progress in agriculture does not exorcise other limits set by, for example, the availability of suitable living space, constraints on production and the limited capacity of the environment to absorb insults to it. To wait for natural constraints to intervene to limit population size is to accept famine, low living standards, unemployment, political instability and ecological destruction. Society finds these options unacceptable. It must seek ways to curb population growth and to modify human activity so that it is environmentally more benign.

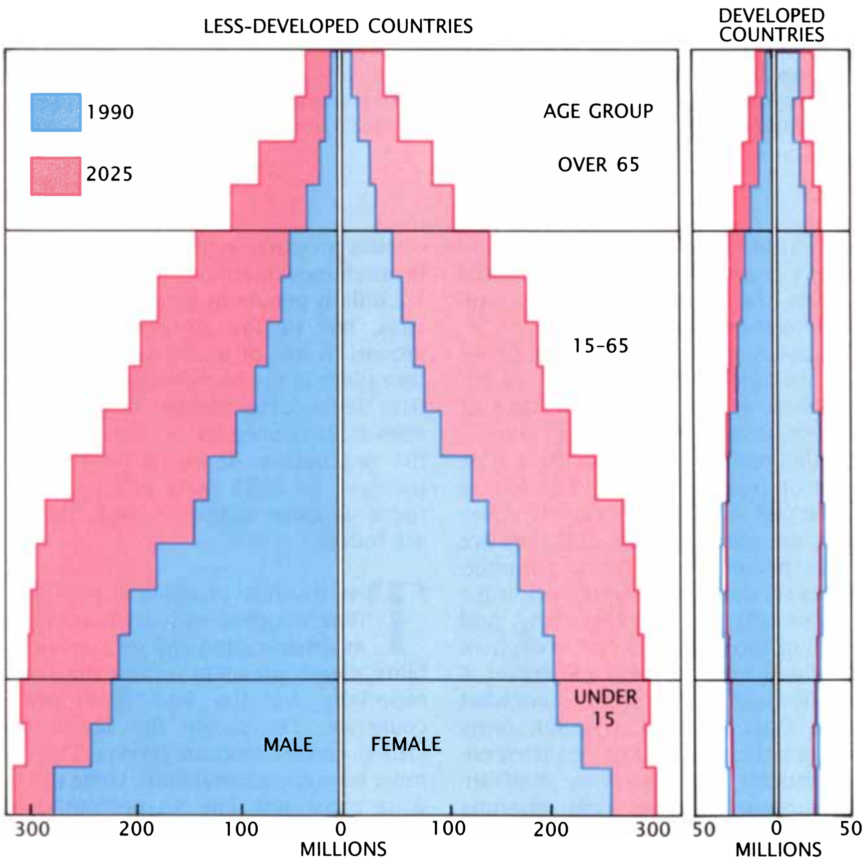
The first question, then, is two-pronged: How does a decline in growth come about, and how can progress toward this goal be accelerated? One of the most universally observed and least readily explained social phenomena of modern times is the demographic transition: the fact that with industrialization both death and birth rates fall to new low levels. Medical advances are partly responsible for the fall in death rates; improvements in nutrition and other aspects of the way of life also play a considerable role. Because death rates drop first, populations experience large growth during the course of the transition: for example, Great Britain's population multiplied by four during the 19th century.

Sooner or later after the fall of death rates, birth rates also start to decline. Indeed, birth rates do not merely drop to the point where they just offset the number of deaths (the condition that applied on the average throughout most of history); they fall below that, to the point where they fail to counterbalance deaths. The European countries, the U.S. and Japan have a disproportionately large number of people of childbearing age because of high fertility in the recent past. Consequently, they will continue to grow for some time. Once the current generation has passed, however, the populations of these countries could fall by anywhere from one tenth to one third in each generation.

In analyzing the demographic transition, what requires explanation—the low birth rates of the present or the high birth rates of the past? One view is that people have always wanted to be relieved of the burden of child rearing but did not have convenient (or effective) methods of birth control. Another is that children were desired because they provided security in old age, as well as extra hands and marriage ties to other families. Wives were subordinate to husbands, and whatever else the wife was doing, the husband could set her to childbearing as well. This behavior pattern was inculcated into boys and girls from earliest childhood, and the whole structure was supported by pronatalist doctrine, in particular of religion.

Yet religious doctrine by itself is less than decisive for determining fertility: witness the recent decline in birth rates in some of the most developed Catholic societies, such as Italy, Austria and the province of Quebec. Apparently some other elements of culture offset religious influence on birth rates as countries develop. One prominent social factor is the improved status of women. For example, in regions such as Java, where women enjoy greater rights and better education than they do in other Muslim regions, birth rates are falling, whereas in Muslim regions such as Pakistan, Bangladesh and certain Arab countries, where women have low status, birth rates remain high.

Modern industry and commerce make it possible for women to earn their own income and become financially independent of their husbands. Similarly, children enter the work force and become independent of their parents, and parents become independent of their children to the



AGE DISTRIBUTION of the populations of the less developed and the developed countries in 1990 is compared with that projected for 2025. In less developed countries 37 percent of the population is younger than 15 years. Even if growth rates in these countries decline, their populations will continue to grow rapidly when these young people reach childbearing age. The labor force will expand even faster than the total population of these countries; indeed, the number of working-age people in the world will triple between now and 2050. The data were furnished by the United Nations Department of International Economic and Social Affairs.

SOCIO-ECONOMIC SETTING	1982 FAMILY-PLANNING PROGRAM STRENGTH: STRONG — COUNTRY	PERCENT	MODERATE — COUNTRY	PERCENT	WEAK — COUNTRY	PERCENT	VERY WEAK OR NONE — COUNTRY	PERCENT	MEAN
HIGH	HONG KONG SINGAPORE TAIWAN KOREA COLOMBIA MEXICO	80 71 70 58 51 40	CUBA PANAMA JAMAICA TRINIDAD/TOBAGO FIJI	79 63 55 54 38	COSTA RICA BRAZIL VENEZUELA PERU CHILE	66 50 49 43 43	PARAGUAY	36	
MEAN		60		58		50		36	55
UPPER MIDDLE	CHINA SRI LANKA	69 57	THAILAND PHILIPPINES DOMINICAN REPUBLIC MALAYSIA EL SALVADOR TUNISIA	58 45 43 42 34 31	ECUADOR TURKEY HONDURAS EGY T MOROCCO GUATEMALA ALGERIA	40 40 27 24 19 18 7	IRAN SYRIA GHANA NICARAGUA ZAIRE ZAMBIA	23 20 10 9 3 1	
MEAN		63		42		25		11	30
LOWER MIDDLE	INDONESIA	48	INDIA VIETNAM	32 21	HAITI ZIMBABWE KENYA PAKISTAN PAPUA NEW GUINEA SENEGAL LIBERIA	19 14 7 6 5 4 1	BOLIVIA NIGERIA LESOTHO BURMA CAMEROON UGANDA KAMPUCHEA	24 6 6 7 2 1 0	
MEAN		48		27		8		6	12
LOW			BANGLADESH	19	NEPAL TANZANIA	7 1	BENIN SUDAN SIERRA LEONE ETHIOPIA SOMALIA YEMEN BURUNDI CHAD GUINEA MALAWI MALI NIGER BURKINA FASO MAURITANIA	18 5 4 2 2 1 1 1 1 1 1 1 1 1	
MEAN				19		4		3	4
MEAN		59		44		23		7	26

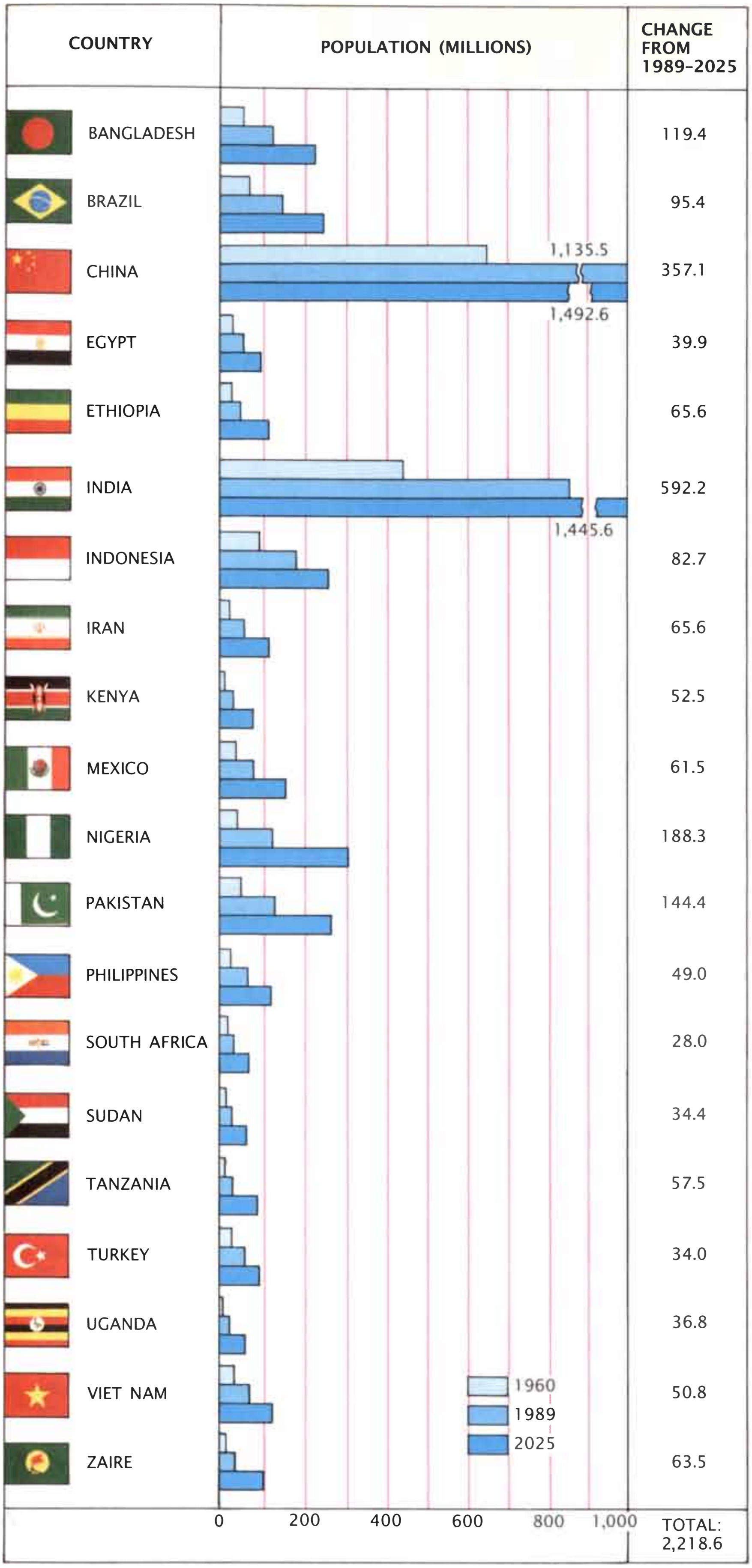
EFFECTIVENESS of family-planning programs is shown by measuring the percentage of couples who use contraceptives in less developed countries. Given comparable socioeconomic settings, the percentage of couples who use contraceptives is higher in countries that have stronger programs than in countries with weaker programs. The study was carried out by the late Robert J. Lapham of Demographic and Health Surveys and W. Parker Mauldin of the Rockefeller Foundation.

extent that they can rely on social security and private savings. If a child is no longer a source of economic support, will the effort of raising children seem worthwhile? If one knew what mechanisms led to the drop in birth rates, the industrialized nations could check their failure to reproduce and the poor nations would know how to bring their birth rates down.

Whatever the mechanisms, it is certain that birth rates in the less developed countries will decline as the countries develop. Their economic development is hindered by large and growing populations, however, and so the scale of development will have to be enormous in order for the benefits to reach everyone. The strain on the environment will therefore be unprecedented. Brazil says it cannot develop without cutting down Amazon forests, and it resents foreign demands for restraint. Population growth in some areas is now so great that the limits of materials and the environment have already been reached; this strain has slowed the economic development that would check births. In the face of such a danger, the urgency of birth-control programs cannot be stressed enough.

Regardless of the deeper origins of low birth rates, abundant evidence shows that information about birth control and access to contraceptives have been major causes of declining fertility in all countries. In Asian nations that established family-planning programs in the 1960's—China, Indonesia, Thailand and South Korea—crude birth rates declined by from 25 to 60 percent over two decades. In Tunisia birth rates dropped about twice as fast in the decade after the program began as in the previous seven years. The birth rate in Mauritius was nearly 40 per 1,000 before 1965, when a birth-control program was initiated, and it dropped to below 25 per 1,000 during the first eight years of the program. Mexico set up a program in 1973, and its birth rate fell within about four years from some 45 per 1,000 to some 38; the rate is currently about 31 per 1,000.

Policymakers would like to know how much of these declines can be attributed to the programs and how much would have occurred in any case because of general socioeconomic improvements. Using data from 19 developing countries, Timothy King of the World Bank has calculated that family-planning programs account for 39 percent of the decline and overall socioeconomic improvement for 54 percent. Other investigators, who used different data but applied essentially the same method, report that family-planning programs account for from 10 to 40 percent of observed declines in birth rates; no serious study has failed to find some effect. It is worth noting that the first stages of modernization often lead to temporary increases in fertility, because tradition-



al methods of birth control—extended breast-feeding and postpartum abstinence—are typically abandoned. Hence, the actual effect of family-planning programs is considerably greater than the initial figures indicate.

Indonesia's family-planning program began officially in 1970. By 1980 the National Family Planning Coordinating Board had established more than 40,000 village distribution centers for contraceptive devices and information, mostly in Java and Bali. These centers are often linked to agricultural cooperatives and health services and so become intrinsic aspects of the country's development efforts. They provide social centers where people receive free contraceptives. Educational programs promote the notion that a family should be "small, happy and prosperous." The barrage of public messages about family planning is relentless: the national family-planning jingle plays when a train passes a railway crossing, religious leaders give lectures on contraception at the local mosque (Islam accepts birth control, with the exception of permanent sterilization), and at five o'clock every afternoon sirens wail to remind women to take their pill.

Indonesia's campaign has met with notable success. Since 1972 the fertility rate has fallen from 5.6 to 3.4 children per woman; whereas 400,000 couples practiced birth control in 1972, in 1989 more than 18.6 million couples did so. Infant mortality meanwhile has fallen by 40 percent. It is interesting that abortion is illegal in Indonesia; the lowering of the birth rate was brought about by strong government and community support, education—and the dissemination of free contraceptives to any couple who wanted them. The country's family-planning strategists hope eventually to get couples—those who can afford it—to pay for their contraceptives: they want people to take responsibility for family planning and to consider contraceptives a commodity worth paying for.

It is especially important to give couples the widest possible choice of contraceptive methods. The contraceptive pill and condoms require effective distribution systems to ensure

SEVENTY PERCENT of the projected increase in world population by the year 2025 will occur in these 20 less developed countries. The data are from the United Nations Department of International Economic and Social Affairs.

that couples have a constant supply. Intrauterine devices and injections of Depo-Provera (a synthetic hormone) are more convenient in that they only require occasional visits to health clinics. All these methods have possible side effects, however, ranging from irregular menstrual bleeding to pelvic infections, which can discourage women from adopting a method and sticking to it. Among the more recent and most promising developments are contraceptives such as Norplant that can be implanted under the skin and are effective for up to five years. Still, there remains a great need for safer, more convenient and inexpensive birth-control methods.

For some of the countries of Asia and especially of Africa, the pronatalist culture is too strong for family-planning programs to have much effect. Programs set up in Pakistan, Nepal and Kenya have had little success. Family-planning programs can work only if countries are economically and socially ready to accept them. Based on a series of surveys conducted under the auspices of the World Fertility Survey, most of the less developed countries are now at the point where sizable portions of their populations want smaller families than has traditionally been the norm. This finding, at least, is cause for optimism.

KENYAN WOMAN receives an injection of the contraceptive Depo-Provera at a health clinic. She and her husband already have four children; the youngest lies on the table. "If we have more, how can we send them to school, how can we feed them?" she asks. The Kenyan government has recently begun to discuss instituting family-planning programs, a major change from past policy. At its current annual growth rate of more than 4 percent, Kenya's population of 25.1 million will double in 17 years.

The impact of people depends not only on their number but also on their setting in the biosphere and on their economic activities. Can changes in economic practices rather than in population growth mitigate the harmful effects on the environment? In Europe, North America and much of Asia, the traditional culture has usually taken a long-range perspective on its impact on the environment: good traditional farming and forestry practices entailed maintaining the land in such condition that it would keep producing indefinitely.

But tradition is not everywhere a protection: the loggers of Nepal and the cattle raisers of the Sahel have traditions that—under the pressure of growing populations—are improvident. One could say of them, as of many other societies, that if they were fewer in number, they would destroy less; if they had better practices, they would destroy less. If there were fewer people to drive automobiles, less fuel would be consumed and less smog generated; if people relied on public transport, the results would be similarly beneficial.

A purely cultural feature underlies the economics. One can demonstrate this by noting that an Austrian town may have its own swimming pool and that hundreds of people walk to it on weekends, doing essentially the same thing as their American counterparts do by driving 100 miles or so to go to a beach. For affluent people everywhere, the urge to get into one's car and drive 100 miles or to board a jet and fly across the country to swim and sunbathe is strong. Will the culture shift in a direction that will spare the biosphere? That question is as hard to answer for American sunbathers as it is for African cattle herders.

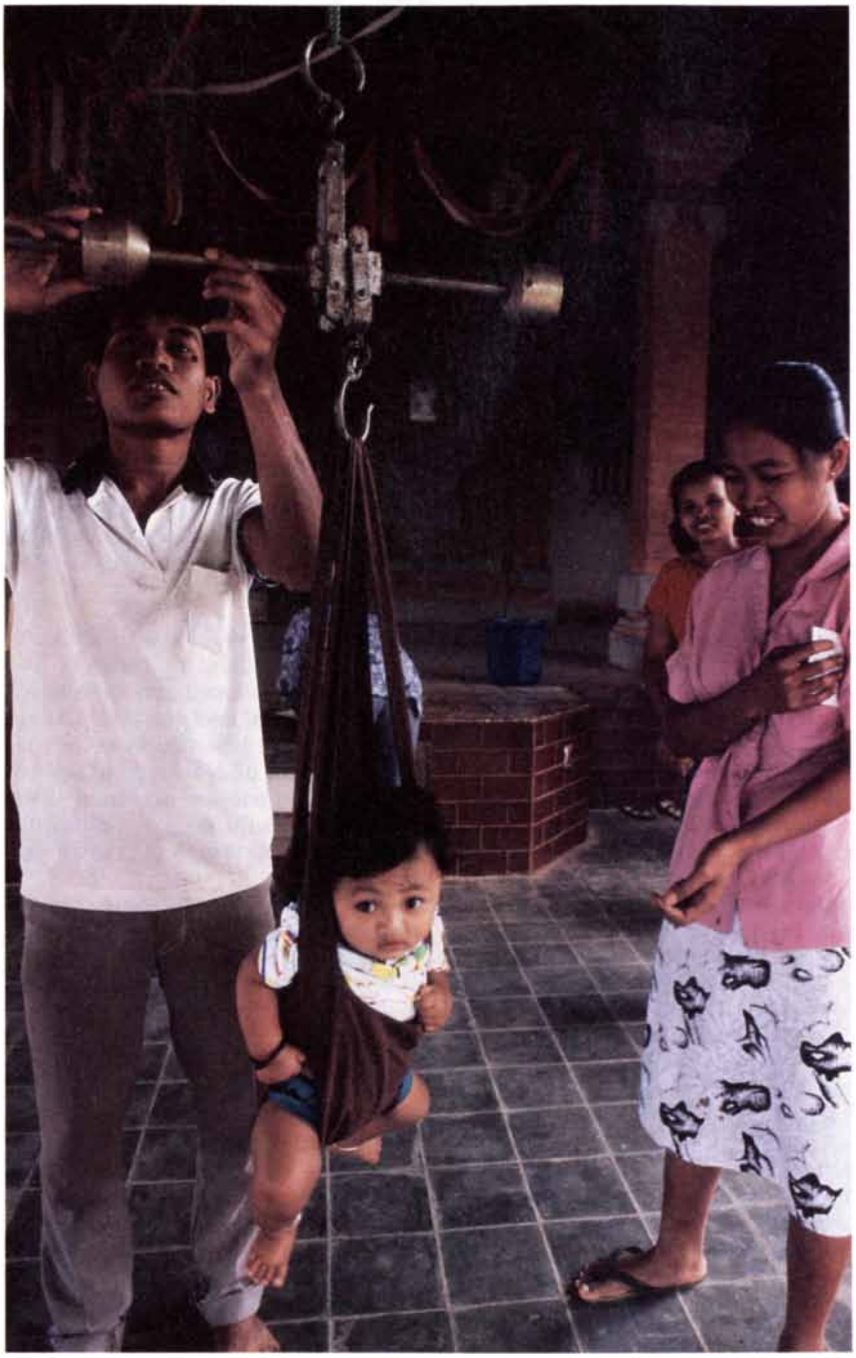
Everywhere there is this symmetry between numbers of people on the one hand and harmful practices on the other. Hence, the endless debate on appropriate policies. Some argue that the number of people does little harm in itself but only exacerbates the effect of bad practices; others argue that bad practices should of course be rectified but meanwhile the size of the population should be controlled.

What are the population-policy questions regarding the assault on the planet? They will involve the relation between population and agricultural and industrial technology and will have to be dealt with in the context of conflicts between less developed and developed countries and of civil and international wars in the less developed countries. The path of development will be rough for the people concerned—and in many places the degree of difficulty will be in proportion to the size of the population.

People ultimately will become aware of how their own childbearing affects the future ecological stability of their country and of the planet. If the ecological base of an economy is undermined by overpopulation, this cannot but depress economic growth. People will come to understand that it is preferable to have a few children of high quality rather than to have many children who will be uneducated and unemployed. Good policies will make expensive to citizens that which is expensive to the nation. The ecological (and other) costs of children to the community must be transmitted to the individual parents. Yet no one wants to tax excessive childbearing in such a way as to harm the children who are already born. This concern makes it much more difficult to fashion effective family policy than it is to, say, develop commodity-consumption policies.

All these concerns apply particularly to the less developed countries, where almost all the future increases in world population will occur. Some experts are concerned that population growth in the developed nations will soon cease entirely and urge action to counter this possibility. Stimulating growth in the more developed countries, however, would set a bad example and, worse, would seem to carry a racist message: there are too many of you and not enough of us.

But the developed nations can do more for the planet and for economic development than merely set a good example on population control. They can become more aware of how their policies affect the less developed countries. They cannot expect to collect debts from developing nations without accepting their exports. By imposing tariffs against export items in the less developed regions and insisting on debt repayment, the developed nations undermine the ability of the less developed regions to sustain their populations.



INDONESIAN INFANT is weighed as his mother looks on. The country's infant-health program sponsors monthly weighings, which enable mothers to monitor the development of their children. The program subtly promotes the idea that parents with small families are better able to care for their children.

Certain agricultural and forestry goods, such as Senegal's peanuts and Thailand's plywood, are important means by which these countries earn foreign exchange, but these products can exact a high ecological cost. The subsidies that stimulate European and American farmers to produce surplus food have an unnecessarily deleterious effect on the environment. Shipping excess wheat and corn to the less developed countries is a desirable form of charity to relieve a food emergency, but not when the foreign grains discourage local agriculture.

Even with some care in management, industrial development pollutes air and water and is destructive in other ways. Education will increase awareness of these destructive effects and lower the birth rate; hence, it will ultimately lessen the stress on the environment. A sufficient level of economic development should bring a corresponding mastery of all problems, including ecological ones. Yet if the environment is mishandled badly enough, that in itself will slow down or even prevent further development.

The question each country must face, then, is how to attain a sufficient pace of economic development without destroying the environment: that eventuality would make any future economic advances impossible. Most less developed nations are aware that the pace of development would be faster and the destruction of the environment slower if their populations were to increase more slowly than they do today. Not all of them have the same capacity to formulate and implement policies that will put that knowledge to use.

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Strategies for Agriculture

Agricultural research will probably yield many new technologies for expanding food production while preserving land, water and genetic diversity. The real trick will be getting farmers to use them

by Pierre R. Crosson and Norman J. Rosenberg

One hundred years from now the earth may have 10 billion inhabitants, about twice as many as it has now. If projections made by demographers at the World Bank are correct, the human population will by then be approaching a stable level, as the populations of many industrialized countries already have. Will our species be able to feed itself when this steady state is reached? The short answer is probably yes. World food production could grow significantly more slowly than the current rate, and there would still be enough food for 10 billion mouths by the time they arrive.

The long answer is not quite as simple. Not only must the food supply expand, it must expand in a way that does not destroy the natural environment. For that to happen, a steady stream of new technologies that minimize erosion, desertification, salinization of the soil and other environmental damage must be introduced. We are confident that if the strong system of agricultural-research organizations already in place is provided with enough financial support and leadership, it will develop these techniques. But we also believe that developing new technology is not the most difficult problem facing the world's agriculture; society is.

In order for new, less damaging techniques to have an effect, they must be used. For them to be introduced at the level of the individual farm, they must benefit the farmer. In a market system, such benefit generally takes the form of profit. Yet markets are not well equipped to protect resources such as water and genetic diversity, in which it is difficult to establish property rights. In our view the most challenging problem for agricultural policy is to devise institutional mechanisms that will reward individual farmers for valuing these precious resources at their true social worth.

The pressure to develop new agricultural technologies will be roughly proportional to the rate of depletion of natural resources employed in agriculture. Of these resources, three—land, water and genetic diversity—are critical, and those are the three we shall focus on in this article.

In many parts of the world the supply of agricultural land is threatened by various kinds of degradation. Among the most important forms are erosion by wind and water and the consequent loss of soil productivity; degradation of rangelands in the arid, semiarid and subhumid regions; and waterlogging and salinization of irrigated lands. All these processes can be considered under the general heading of desertification (even though that term in the popular imagination suggests only the expansion of desert onto adjacent rangeland or farmland), and that is the rubric under which they will be treated here.

Data compiled by the United Nations Environment Program (UNEP) indicate that about 60 percent of the 3.3 billion hectares of agricultural land that are not in humid regions is affected to some degree by desertification as broadly defined above. (One hectare is 2.47 acres.) Such a large fraction suggests desertification is a major problem in the world today.

Yet all such global estimates must be taken with more than a few grains of salt. For one thing, they depend on the definition of desertification, which may vary. For another, in most of the world's regions accurate estimates of degradative processes are not available. Take the case of erosion. The U.S. is the only country in the world that has reasonably accurate and comprehensive estimates of soil erosion and its effect on productivity. Those estimates suggest that if current rates of cropland erosion prevail for 100 years, crop yields will be from 3 to 10 percent lower than they would be otherwise. Yield increases (resulting from technology) that are modest by historical standards would much more than compensate for such a loss.

Estimates of erosion have been made for other parts of the world—some showing very large losses. But experts who have examined these estimates closely, including a review carried out for the United Nations Food and Agriculture Organization in 1984, concluded that these evaluations have little scientific merit. There is no question that erosion and the resulting loss of productivity is significant in some regions, including Nepal, parts of India, the highlands of East Africa and parts of the Andes. The importance of these losses in relation to the world's total output of food, however, is quite uncertain, and apocalyptic scenarios ought to be evaluated skeptically.

Even areas that have been subject to desertification are not necessarily lost to agriculture forever. The overwhelming share of the land reported to the UNEP as desertified is rangeland. Rangeland is subject to degradation around the world, but events in the Sahelian zone of Africa provide a striking example. Rapid growth of population in the Sahel and the Horn of Africa

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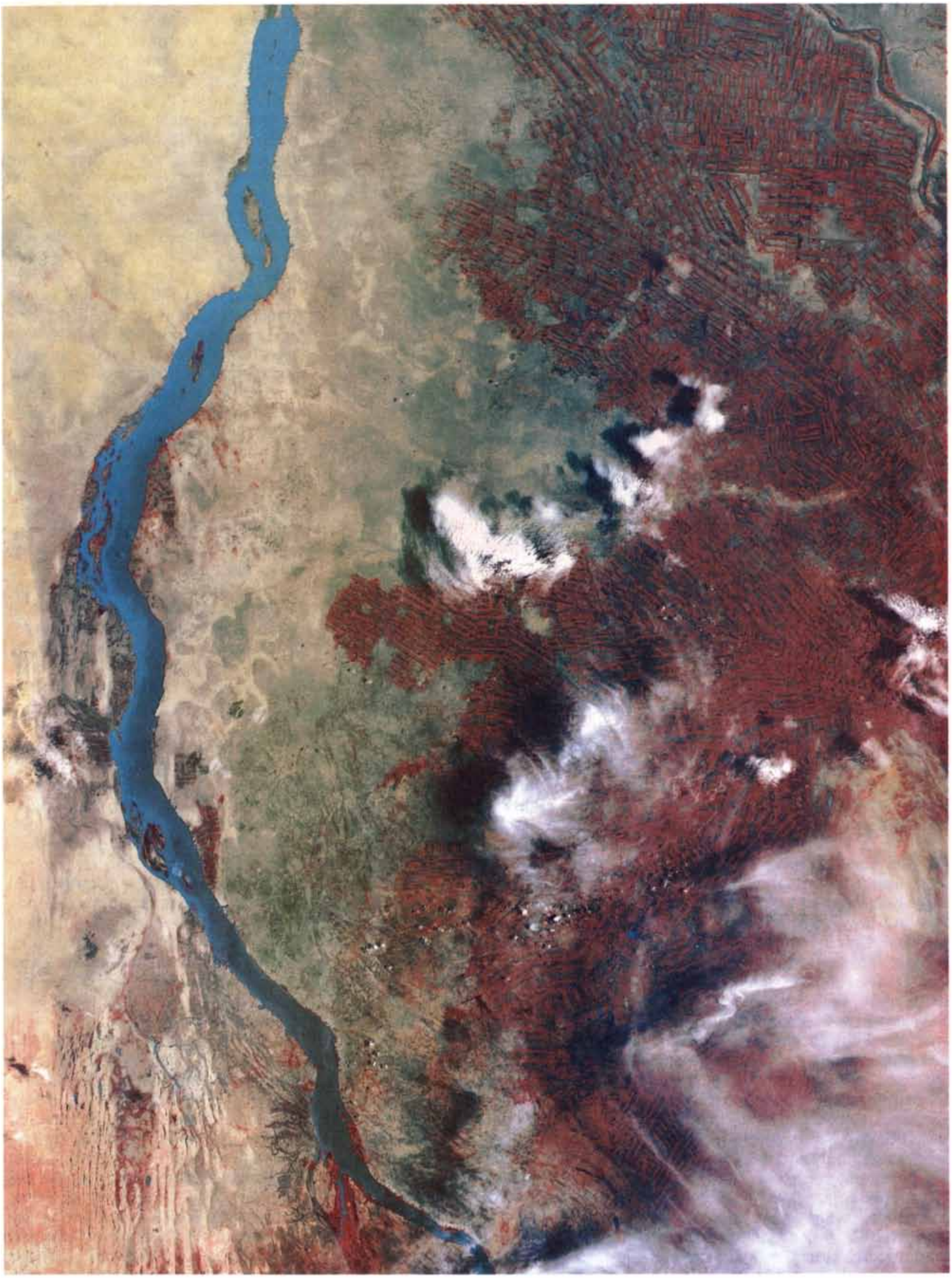
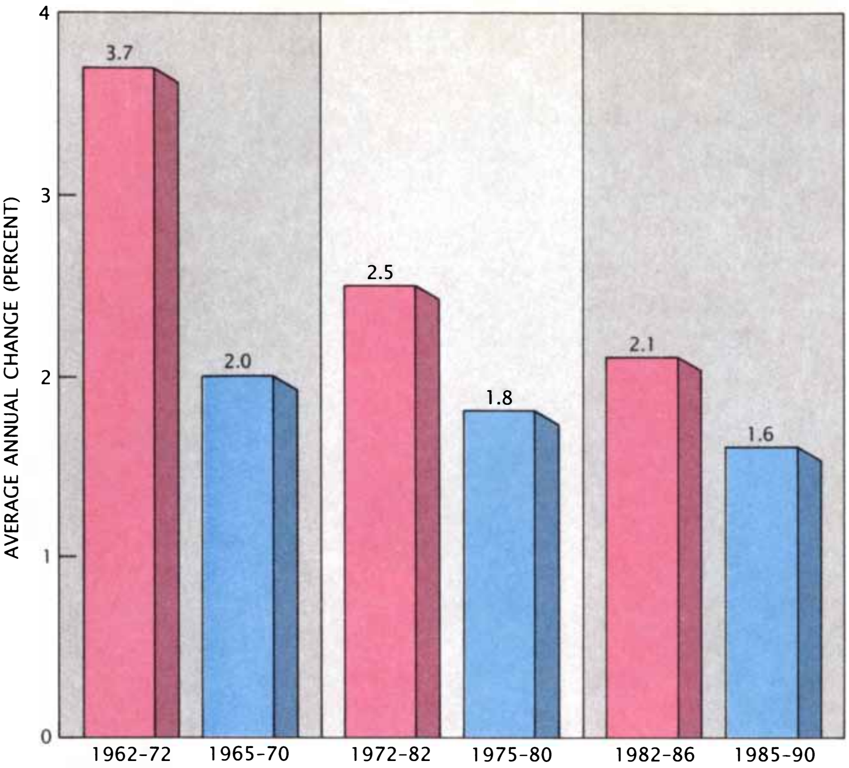


IRRIGATED CROPLAND appears red in this satellite photograph made over the Nile where it flows through the Sudan. In the past 70 years, a variety of irrigation projects have increased the agricultural productivity of this dry region. More than half of the increase in the world's agricultural productivity during the past few decades has come from irrigation.



WORLD FOOD PRODUCTION is growing faster than population. The chart shows the annual increase in total production of cereals (*red*) and in the world's population (*blue*). If the food supply can be increased at the current pace (or even a slower one), there will be enough food for a stable world population of 10 billion in 100 years.

after World War II led to an increase in grazing pressure that would by itself have led to a decline in range productivity. The process of degradation was intensified by a severe drought that began in the 1960's and has continued intermittently since.

Yet satellite images show that even the depleted Sahelian rangeland and farmland can recuperate. In years of good rainfall the so-called Green Wave of vegetation extends farther north into the Sahel than it does during dry years. It is likely that high-quality vegetation does not return immediately to the overgrazed areas, but it does seem that with carefully controlled grazing programs in place much apparently desertified land could recover. The problem, of course, is to maintain "careful control" where the population is growing rapidly and there is a tradition of unhindered access to the land. As we shall argue later on, the chief difficulties facing world agriculture stem from the lack of institutions for handling such situations and not from inexorable natural processes.

Another aspect of desertification, broadly defined, is salinization. In areas where irrigation water contains large quantities of dissolved salts, improper irrigation practices and lack of drainage often lead to salt buildup in the soil and direct damage to growing plants. According to James D. Rhoades of the U.S. Salinity Laboratory in Riverside, Calif., irrigation water can contain as much as 3.5 tons of salt per 1,000 cubic meters. Since crops often require from 6,000 to 9,500 cubic meters of water per hectare each year, that amount of land may receive up to 33 tons of salt. Little of the salt is taken up by plants; most of it is left behind in the soil as the water evaporates.

Technical means for dealing with salinization are known: the salt must be flushed out of the root zone by applying excess water. Yet when this is done, the problem is often only moved on. If drainage water reenters the supplying canal, the salt content of the irrigation water is increased for all users farther downstream. The key problem in reducing salinization is the absence of institutions and policies that require the upstream farmer to take account of the consequences of his actions for those downstream.

The conversion of rural land to urban uses is an inevitable part of economic development; sometimes it is seen as a threat to the supply of land for agricultural production. In the 1970's a study by the U.S. Department of Agriculture and the Council on Environmental Quality concluded that by the 1990's the conversion of agricultural land could present the nation with a resource-scarcity problem as serious as the then prevailing energy crisis. Subsequent analysis has greatly diminished such concern, and the issue is no longer much discussed in the U.S.

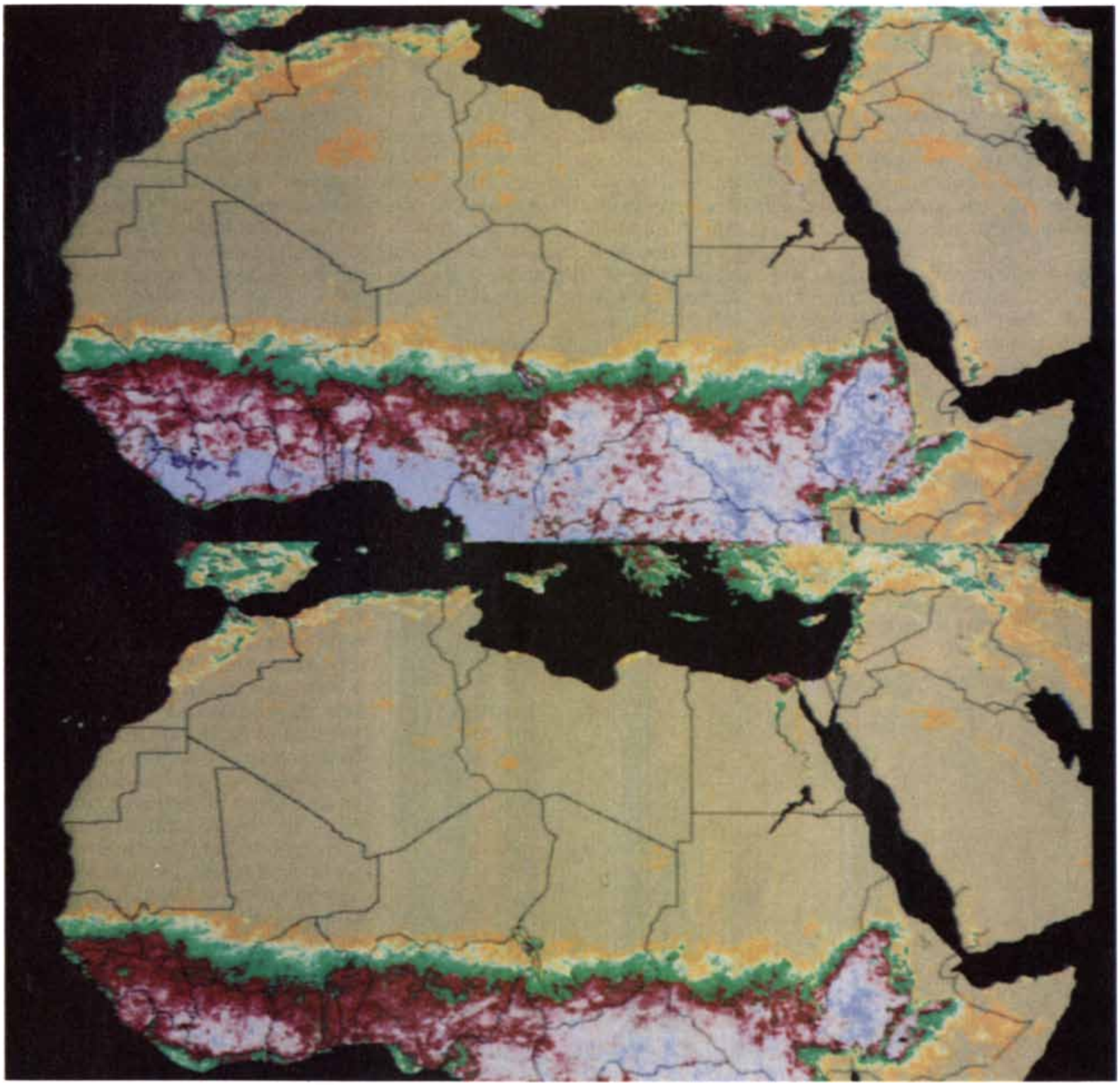
In countries where farmland is less abundant than it is in the U.S. (in Asia, for example), urbanization may be a larger threat. Yet some data suggest that even in Asia the problem is not yet very imposing. In northern India (where about half of the country's people live) and in Bangladesh, both cropland and urban land increased from 1950 to 1980. (The reason both can increase is that areas in neither category, such as forested regions, may be converted to urban or agricultural purposes.) In India in 1980 urban land included about a tenth as much area as cropland did; in Bangladesh the fraction was about an eighth. Hence, even in these crowded countries, a rapid increase in the amount of urban land would reduce the amount of cropland by relatively little.

In addition to land, the other natural resources central to agriculture are water and genetic diversity. Water is particularly important: data gathered by the World Bank indicate that the spread of irrigation contributed between 50 and 60 percent of the massive increase in agricultural output of the developing countries from 1960 to 1980. Although there is still potential for expanded irrigation, such expansion will be more expensive than it has been in the past, because low-cost sources of water were exploited first.

Furthermore, demographic and economic growth steadily increase the competition for water—a competition in which agriculture does not fare well, since the return on investments in water is generally lower in agriculture than in urban or industrial uses. In addition, in some parts of the developing world, the supply of water for irrigation is also threatened by the buildup of silt in reservoirs. Reservoirs are designed to accept a certain amount of silt, but in some areas deforestation, overgrazing and erosive cropping practices are causing reservoirs to be filled much faster than at the designed rate. Although the evidence is anecdotal, it suggests that siltation is not a trivial threat.

The threat to genetic diversity in agriculture is somewhat more difficult to determine. Since World War II there has been a worldwide trend away from crop rotation and toward continuous raising of a single crop, such as corn. Monocropping can lead to sharp reductions in genetic diversity, with ominous results. A striking example occurred in the U.S. in 1970, when corn production was reduced 15 percent by a fungus well matched to the "*T*-cytoplasm" that had been incorporated in most of the hybrid seed corn planted in the U.S. corn belt. By the following year seed producers had stopped relying on the *T*-cytoplasm, and a more variable genetic basis was reestablished.

Up to this point we have considered the natural resources that are crucial for the continuing growth of agricultural production. But it is also clear that agricultural growth has potent consequences for the environment in general. Some of these processes are taken up in greater detail elsewhere in this issue of *Scientific American*. Clearing forestland to plant crops reduces the variety of vegetation and has adverse effects on animal habitat. In tropical rain forests such effects may be severe [see "Threats to Biodiversity," by Edward O. Wilson, page 108]. Several radiatively active trace gases released by agricultural processes, including carbon dioxide, methane and nitrous oxide, contribute to the greenhouse effect [see "The



"GREEN WAVE" appears each year as vegetation is revived by seasonal rains moving north into the Sahelian zone south of the Sahara. These maps were generated by computer treatment of satellite data. Vegetation is shown on a scale extending from tan (little or no vegetation) through purple (heavy vegetation). In 1980 (*upper map*), a year of "ordinary" rainfall, the Green Wave extended farther than in 1984 (*lower map*), when the rains were disastrously low. An extended drought and overgrazing have made the Sahel a heavily "desertified" region, but even there the process is reversible, as the maps suggest.

Changing Climate," by Stephen H. Schneider, page 70].

Of course, the greenhouse effect and the loss of animal habitat are not the result of agriculture alone. Some threats to the environment, however, are specific to agriculture, and among these is the increasing burden of pesticides and fertilizers. Pesticides and fertilizers are, along with irrigation and higher-yielding crop varieties, responsible for much of the remarkable increase in agricultural productivity that has taken place in the past few decades. But these substances can also have unfortunate side effects. Fertilizers and pesticides in groundwater may cause ailments ranging from cancer to methemoglobinemia ("blue baby syndrome"), which results from excess concentrations of nitrates in drinking water. Although good data are lacking, the rapid increase in the use of these agents around the world undoubtedly has some fairly serious health implications.

As the preceding paragraphs suggest, the challenge to agriculture is not only to provide food for the 10 billion people who will probably be living a century from now but also to achieve that level of production with less environmental damage than is apparent today. This twofold goal is often discussed under the heading of "sustainable agriculture." Achieving sustainability will clearly require continued long-term support for nationally based agricultural-research establishments and for the 13 institutes in the Consultative Group on International Agricultural Research (CGIAR), headquartered at the World Bank in Washington, D.C.

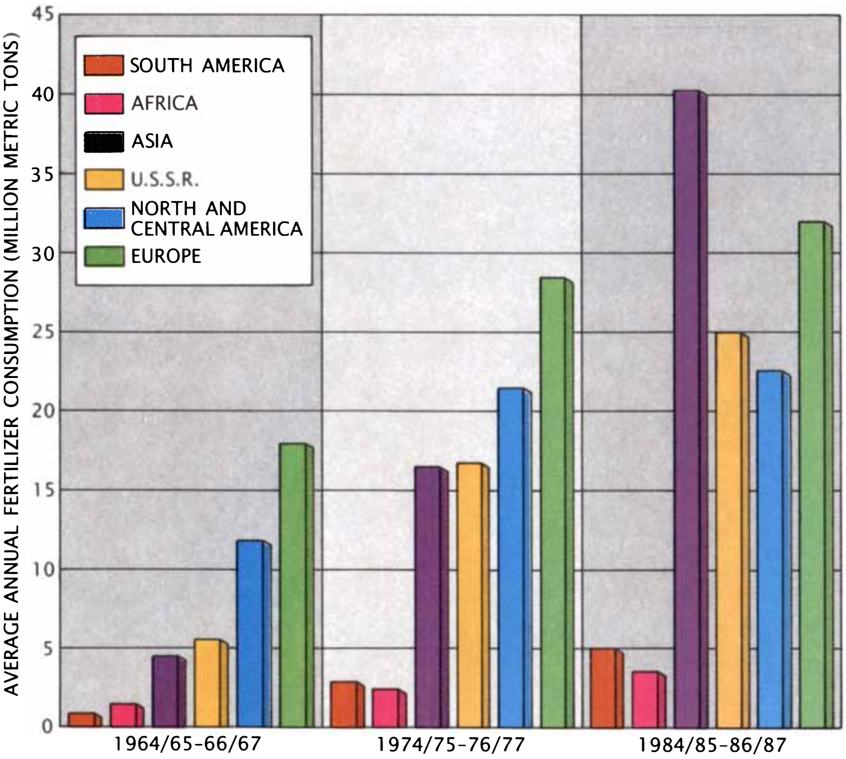
The CGIAR system is a major resource for research on new agricultural technologies for developing countries. Indeed, the Green Revolution of the 1960's was largely the result of varieties of rice and wheat developed by research workers at CGIAR institutes in the Philippines and in Mexico. The Green Revolution in turn was a major component of the increase in world food production that has taken place in recent decades. The World Resources Institute has estimated that from the mid-1960's to the mid-1980's world food production increased at an annual rate of 2.4 percent. Grain production grew even faster: at an annual rate of 2.9 percent.

These substantial increases, combined with the fact that the growth rate of the world's population has recently slowed to less than 2 percent [see "The Growing Human Population," by Nathan Keyfitz, page 118], provide the basis for our optimism that food production will keep pace with population growth. Meeting that goal sustainably, however, will necessitate a steady stream of new agricultural technologies that can only come from the CGIAR system and national research institutions in both the developed and the developing countries. What technologies are needed? Although one might point to any number of innovations, three categories seem of particular importance: those that reduce the environmental burden of pesticides and fertilizers, those that reduce the demand for irrigation water and those that continue to improve crop production per hectare.

One of the main components of fertilizer is nitrogen. If plants other than legumes could be biologically engineered so as to "fix" nitrogen in the soil, the demand for fertilizer would be greatly reduced. A prime candidate for such a transformation is corn. The job will clearly require the resources of biotechnology, which make it possible to manipulate the genetic material of an organism directly. Biotechnology has already proved its worth in a number of applications related to animal production, and the engineering of a nitrogen-fixing corn is by no means out of reach. Indeed, Frederick Ausubel of the Harvard Medical School noted recently that "it is simply an extremely complex engineering job" that will almost certainly be accomplished within 50 years.

Both old and new techniques are now being put to the task of saving irrigation water. "Water harvesting," a technique employed in the Middle East in pre-Christian times, calls for the land to be shaped to permit rain to run off large upland areas into collection devices or to spread out over smaller areas in sufficient quantities to wet the root zone fully. The efficiency of gravity-flow irrigation systems made up of basins and furrows, probably the most widely used type, can be improved by a high-tech method: laser leveling. Lasers can be employed to guide machines that level growing fields, making it possible to flood them quickly and uniformly.

Another system—trickle, or drip, irrigation—depends on a higher overall level of technology than gravity-fed systems. Trickle irrigation gained wide acceptance in Israel, the U.S. and other countries in the 1970's and is now being introduced around



USE OF FERTILIZER serves as one measure of the burden agriculture places on the environment. The chart shows the total quantity of fertilizer that is employed in the world's major regions. In most regions fertilizer use has increased sharply in recent years. Comprehensive data on the remainder of the global environmental burden from agriculture (including pesticide production) are not available.

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the world. Trickle systems deliver water directly to a small area adjacent to an individual plant. The water is carried by tubing, generally plastic, that may be either buried or placed on the surface; usually a nozzle called an "emitter" releases the water at the appropriate location.

Trickle systems, along with some others, not only increase efficiency in the use of irrigation water but also offer new approaches to preventing salinization. One new strategy emphasizes keeping salts (and other pollutants such as pesticides) on the land rather than passing them back into the water supply. This is done by cycling wastewater back into the farm's irrigation system and strategically reapplying it to the fields at times and in ways that minimize the effects of the salts carried in it.

Trickle irrigation is particularly helpful in this regard. Much of the damage to crops from salt comes from the salt left behind after water is supplied and then evaporates repeatedly. High concentrations of salt outside the roots of plants lower the osmotic pressure and make it more difficult for the plant to take water in from the surrounding soil. In trickle systems, however, plant roots are continuously supplied with water, and the salts do not build up enough to make water uptake difficult.

TALL WHEATGRASS, a perennial plant, protects winter wheat in an experiment carried out by the U.S. Department of Agriculture Agricultural Research Service near Sidney, Mont. In winter (*upper photograph*) wheatgrass barriers capture snow, forming a uniform layer. Snow insulates dormant plants from the effects of extremely low temperatures. In spring the snow melts, providing the moisture that is needed by wheat plants for early growth. Later the wheat breaks dormancy and begins to grow (*lower photograph*), and at that time the wheatgrass serves as a wind barrier.

Another group of agricultural innovations entails not specific high-tech solutions but the application of (sometimes ancient) principles of integration to crops. The concept of multiple cropping takes in crop rotations, intercropping (sometimes with trees and annual crops sharing the same field), overseeding legumes into cereals and also double cropping—growing two or more crops simultaneously in a single field. Multiple cropping is an old tradition. For example, a system employed in Central America since pre-Columbian times calls for growing maize, beans and squash together. The maize provides a trellis for the beans; the beans enrich the soil with nitrogen; the squash provides ground cover, reducing erosion, soil compaction and weed growth.

Trees can be used in multiple cropping systems. In Europe, North Africa, the U.S.S.R. and the Great Plains regions of Canada and the U.S., windbreaks made up of trees protect growing crops from mechanical damage and the drying effect of wind. Elsewhere, shade trees grow in combination with shade-loving plants such as coffee, annual crops such as maize or beans, or pasture. The trees provide fodder, erosion control and fuel. In West Africa leaf litter from *Acacia alba* trees enriches the soil for the benefit of various grain and vegetable crops grown between them.

In addition to its ecological advantages, multiple cropping can sharply increase crop yields. In the American Midwest farmers are experimentally growing corn with other, low-growing plants. In one experiment in an irrigated field in western Nebraska, two-row corn windbreaks were spaced every 15 rows throughout a field of sugar beets. The wind shelter provided by the corn increased the yield of sugar by 11 percent. The greater sunlight penetration and more rapid replenishment of carbon dioxide to the corn's leaves increased the yield of corn by 150 percent.

Multiple cropping has another important advantage. In fields where crops are rotated regularly, pests, including weeds, insects and pathogens, cannot adapt themselves to a single set of environmental conditions and therefore do not increase as quickly. Where two types of crops are grown in a single field, the pests in one type are sometimes kept down by predators that inhabit the other. Such beneficial interactions can be consciously employed to form the basis of a method called integrated pest management (IPM).

IPM includes the use of a wide range of techniques—chemical pest control, mechanical manipulation of the soil and many biological strategies—to control pests while minimizing the environmental burden of chemicals and frequent passages of tillage and pest-control machinery through the fields. A good example comes from the cotton-growing regions of Texas. IPM in Texas has several aspects: choice of cotton varieties that mature early (throwing them out of synchrony with the typical cotton pests), encouragement of the predators that consume pests such as the boll weevil and the bollworm, and the burning of all plant residues after the harvest, a practice that destroys many larvae. This system works well on cotton in Texas. Yet it should be noted that it has not been equally successful on the same crop in the Mississippi delta,

Center	Year Established	Location	Mandate
Centro Internacional de Agricultura Tropical	1966	Cali, Colombia	Improve production of beans, cassava, rice, and beef in the Tropics of the Western Hemisphere
Centro Internacional de la Papa	1971	Lima, Peru	Improve the potato in the Andes and develop new varieties for lower tropics
Centro Internacional de Mejoramiento de Maiz y Trigo	1943 1966	Mexico City	Improve maize, wheat, barley, and triticale
International Board for Plant Genetic Resources	1974	Rome, Italy	Promote an international network of genetic-re ources (germplasm) centers
International Center for Agricultural Research in the Dry Areas	1977	Aleppo, Syria	Focus on rainfed agriculture in arid and semiarid regions in North Africa and West Asia
International Crops Research Institute for the Semi-Arid Tropics	1972	Andhra Pradesh, India	Improve quantity and reliability of food production in the semiarid tropics
International Food Policy Research Institute	1974	Washington, D.C.	Address issues arising from governmental and international agency intervention in national, regional, and global food problems
International Institute of Tropical Agriculture	1967	Ibadan, Nigeria	Be responsible for improvement of worldwide cowpea, yarn, cocoyam, and sweet potato, and for cassava, rice, maize, beans, among others
International Laboratory for Research on Animal Disease	1974	Nairobi, Kenya	Help develop controls for trypanosomiasis (transmitted by the tsetse fly) and theileriosis (transmitted by ticks)
International Livestock Centre for Africa	1974	Addis Ababa, Ethiopia	Conduct research and development on improved livestock production and marketing systems, train livestock specialists, and gather documentation for livestock industry
International Rice Research Institute	1960	Los Banos, Philippines	Select and breed improved rice varieties, maintain a germplasm collection bank
International Service for National Agricultural Research	1980	The Hague, The Netherlands	Strengthen national agricultural research systems
West Africa Development Association	1971	Monrovia, Liberia	Promote self-sufficiency in rice in West Africa and improve varieties suitable for the area's agroclimate and socioeconomic conditions

CGIAR SYSTEM, the Consultative Group on International Agricultural Research, consists of 13 agricultural-research institutions. Each has a specific mandate. New strains of rice and wheat developed in the CGIAR system were largely responsible for the "Green Revolution" that greatly boosted agricultural productivity in the developing countries during the 1960's.

NEW STRAINS OF RICE grow on a Philippine hillside near the International Rice Research Institute (IRRI) at Los Banos. High-yielding, pest-resistant varieties of rice developed at IRRI have greatly increased the yield in rice-producing regions of Asia.

suggesting that integrated pest management must be carefully adapted to local circumstances.

These examples show that many new (and some old) agricultural methods are now finding their way into widespread use. To offset increasing scarcities of land, water and environmental resources, a steady supply of comparable improvements will be needed in the future. If the agricultural-research establishment gets the support it needs (and the record is moderately encouraging), such improvements will in all probability be forthcoming. The much more difficult task, in our judgment, is to create the policies and institutions that will induce farmers to adopt the new technologies and management practices.

Why should that be a problem? After all, conserving scarce resources is good for everyone. Why shouldn't farmers be eager to adopt practices leading to that desirable end? The answer is that the social scarcity of resources is not always communicated faithfully to the level of the individual farm. The underlying reason for that failure is the lack of adequate mechanisms for conveying the signals of scarcity.

A free market, for example, is a mechanism for communicating information about scarcity: the price of a commodity rises as the commodity becomes scarcer. In a market system a resource that is expensive because it is scarce will be treated with the proper regard by the farmer-businessman.

Markets do not function effectively, however, unless clear property rights can be established in the resources that are to be exchanged. This is easier to do for land than for water or for genetic resources, partly because parcels of land can be readily identified and stay in place. As a result, land markets operate in many regions of the world. When land is sold in those regions, landowners reap the benefits of good land management in higher prices or pay the penalty of bad management in lower prices. In this way markets signal conditions of land scarcity and give farmers the incentive to adopt land-conserving technologies.

Markets in water and in genetic diversity are much more difficult to establish. Water is a fugitive resource that moves across hundreds or thousands of miles. As it moves, the same water can be used repeatedly by different individuals or institutions, none of them having exclusive rights to it. Since the essence of a property right is exclusive use, markets for water are poorly developed. Most of the world's irrigation water, both in the developed and in the developing world, is distributed by publicly administered systems. Because these systems are subsidized, the price farmers pay for water (when they pay at all) is usually much less than the value of the water measured according to its social scarcity.

This is a signaling failure. One of its consequences is that farmers have little incentive to adopt water-saving technologies, because they often cost more to install than the (artificially low) amount the farmer saves. That situation is changing in some regions. In the western U.S., water markets have been set up in which various parties, including farmers and municipalities, bid for water rights. In areas where such markets operate, the price of water has generally gone up, indicating that the system is conveying more accurate information about water's scarcity.

There is, however, another side of the question. Water subsidies are deeply rooted in social and political traditions of long standing. Their removal would encounter fierce resistance. It will be of little benefit if policies aimed at saving water evoke social turmoil. The challenge to policymakers is to design policies that carry the needed signal without provoking unacceptably high levels of conflict.

If the concept of a market in water is problematic, that of one in genetic diversity is even less plausible. Who owns diversity? How can it be bought and sold? Yet even here alternatives are available that might imitate the signal-carrying function of markets. There are millions of people around the world who put a high value on the tropical rain forest, which is the basis of much genetic diversity. Such people could form coalitions to pay owners of tropical forests for protecting them. There are formidable obstacles to this idea, but some realization of it has already been seen in the proposal to swap developing-country debt for agreements to protect the rain forest.

The examples of water and genetic diversity suggest it is possible to foster marketlike mechanisms even in areas where that approach would seem intrinsically implausible. But markets do have limits. The difficulty of establishing property rights in environmental resources has encouraged the regulatory approach, in which governmental authorities set limits on particular threats to the environment. The clearest instance in agriculture is the regulation of pesticide production and use, which forces manufacturers and farmers to give more weight to the social scarcity of a pesticide-free environment than they would without regulations.

If marketlike mechanisms rooted in economics cannot be created, then regulations become a necessary tool of social policy. Regulations carry a heavy social cost, however, because they require people to act against their own economic self-interest. This is true by definition; no regulations are needed to get people to act in the direction of economic self-interest. As a result, regulations foster political conflict and must be enforced by some form of bureaucratic apparatus. If the two interests that are on a collision course (society's interest in protecting the environment and the self-interest of the individual farmer) are large, as they are in the case of pesticide use, the social costs of a regulatory approach can be high.

It is our view that in the long run the most successful approaches will rest on merging individual and societal interests rather than on enforcing the one over the other. This is essentially an institutional, not a technological, problem. What is lacking are forms of communication that connect the overarching interest of society in a sustainable agricultural system with the well-being of the individual farmer. Specifically, institutional mechanisms must be devised that correctly signal the emerging social scarcities of land, water and genetic diversity. Finding these mechanisms is the most important policy challenge for the world's agricultural development.

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Strategies for Energy Use

Energy efficiency can reconcile environmental concerns with economic development for all nations. It can stretch energy supplies, slow climatic changes and buy time to develop alternative energy resources

by John H. Gibbons, Peter D. Blair and Holly L. Gwin

Energy fosters human activity. It cooks our food, fuels our transportation system, heats and cools our buildings and powers our industries. Energy helps to sustain a way of life that includes good health, rewarding employment and leisure time. The standard of living enjoyed by the U.S., Japan, West Germany and other industrialized nations results in large part from energy access: one fifth of the world's population consumes more than 70 percent of the world's commercial energy. Yet the industrialized world's energy intensity—the amount of energy used to produce a unit of gross national product—fell by one fifth between 1973 and 1985. In the U.S. the gross national product grew 40 percent while energy consumption remained constant.

The most rapid growth in energy consumption now occurs in developing countries. As they seek to industrialize, raise standards of living and accommodate population growth, the less developed countries, such as China, Mexico and India, must expend more energy. Between 1980 and 1985, population in less developed countries grew by 11 percent and energy consumption grew by 22 percent; corresponding numbers for the industrialized world were 3 and 5 percent. Even so, less developed countries still consume four to seven times less energy per person than do the industrialized countries.

JOHN H. GIBBONS, PETER D. BLAIR and HOLLY L. GWIN explore energy-policy options at the Congressional Office of Technology Assessment. Gibbons has been the director of the agency for the past decade. He was educated at Randolph-Macon College and Duke University, where he got his Ph.D. in nuclear physics. Gibbons joined the Oak Ridge National Laboratory in 1954 and later directed its environmental program. Blair is manager of the energy and materials program at the agency. He earned his B.S. in engineering from Swarthmore College and his Ph.D. from the University of Pennsylvania, where he now holds an adjunct faculty appointment. Gwin is the agency's general counsel. Her undergraduate and law degrees are from the University of Tennessee.

Worldwide energy demand increases even as knowledge of how energy use threatens the global environment grows. Coal and oil combustion produces acid rain, which damages lakes, forests, structures and crops in Europe and North America. Nuclear fission produces long-lived radioactive wastes. Automobiles fill the air with smog, which threatens health and property throughout the industrialized world. Energy consumption dumps more than five billion tons of carbon into the atmosphere each year. The resulting accumulation of carbon dioxide, coupled with other greenhouse gases, could warm the globe several degrees by the middle of the next century, altering the earth's climate at a rate from 10 to 100 times faster than the rate of climatic change at the end of the last ice age.

We seem to be playing out an ancient myth. Prometheus stole fire and wound up chained to a rock, lashed by the seas and burned by the sun. We have captured the power of fossil fuels, and our penalty is the loss of personal and environmental health.

We can change the story. Technological ingenuity can dramatically reduce the amount of energy required to provide a given level of goods and services, simultaneously cutting down on energy-driven problems. Investments in energy efficiency can help us reduce fossil-fuel demand without sacrificing economic growth. Application of existing efficiency technologies can save investment capital, buy time for the development of new supply technologies and ultimately make it possible to provide a higher level of goods and services at a given level of energy consumption. In the following discussion we consider the possibilities for new energy resources and increased efficiency. We emphasize efficiency as our best hope.

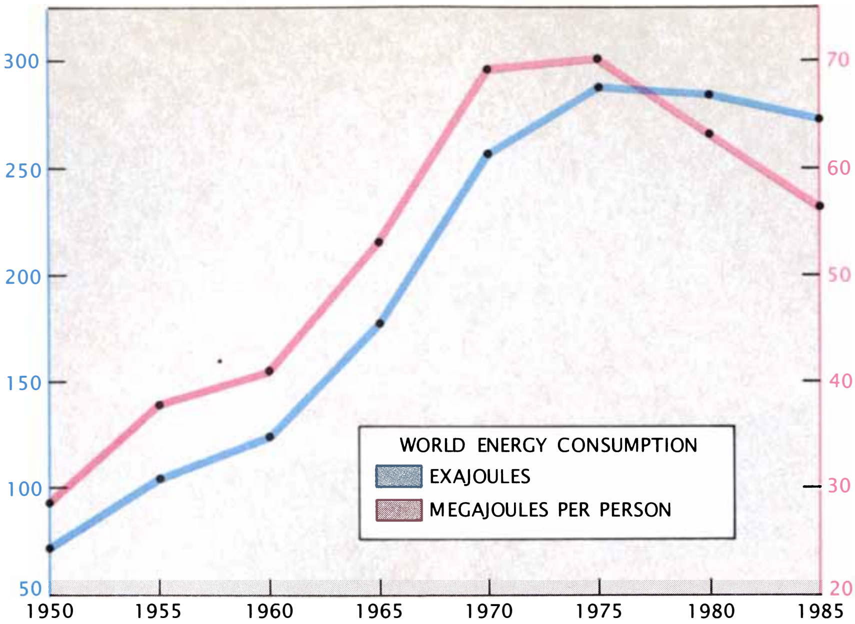
Humankind expends in one year an amount of fossil fuel that it took nature roughly a million years to produce. Global energy consumption rose from 21 exajoules in 1900 to 318 exajoules in 1988. (An exajoule is 10^{18} joules, approximately one quadrillion British thermal units, or the heat that would be released by burning 170 million barrels of crude oil.) Coal, oil and natural gas supply 88 percent of global energy, and nuclear energy provides most of the rest. Many less developed countries still depend heavily on noncommercial fuels, such as wood, dung and crop wastes, but as their economies develop, they rely increasingly on fossil fuels for commerce and industry.

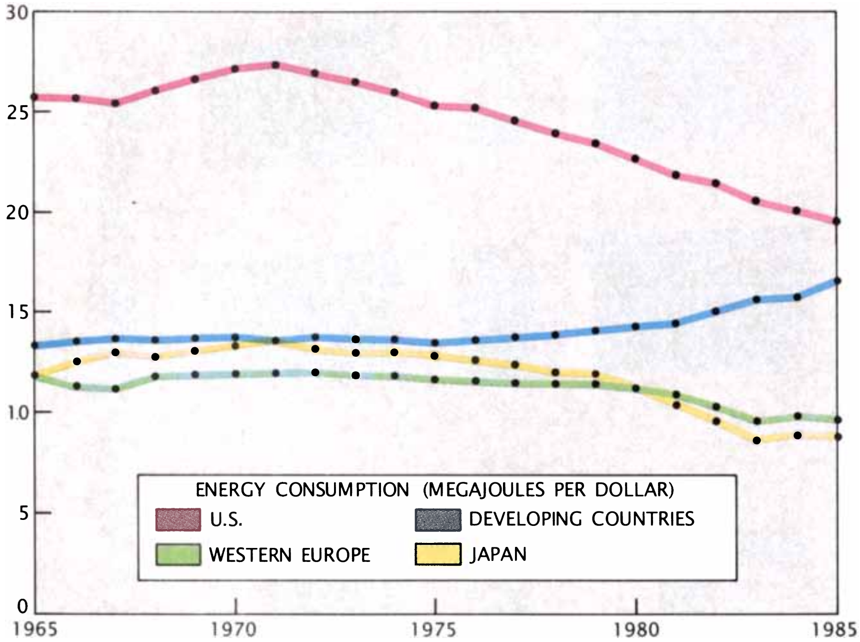
Oil dominates energy markets, accounting for 38 percent of commercial energy consumption. The Organization of Petroleum Exporting Countries (OPEC) controls three quarters of proved crude-oil reserves, including all recent additions. Reserve estimates have been revised downward for non-OPEC nations, including the Soviet Union, which consumes 15 percent of world oil and has been increasing its production rates.

Dependence on Middle East oil strains the economies of both the less developed and the industrialized world. Expenditures for oil imports have hampered the developing world's efforts to gain hard currency and repay debts. In 1987 the U.S. imported $40 billion worth of oil, an amount equal to one third of the country's trade deficit. During the same year, the Pentagon spent $15 billion to protect oil supplies. As the Soviet Union, the U.S. and other non-OPEC nations deplete their oil reserves, the geopolitics of energy will once again focus on the Middle East.

Natural gas provides a fifth of all

ENERGY-EFFICIENT BUILDINGS, such as this bank in St. Cloud, Minn., and efficiency technologies for transportation and industry can help provide energy services—shelter, mobility and goods—at lower environmental costs. The building's insulating windows saved the bank $59,000 in heating equipment. A low-emissivity coating blocks heat flow through the windows.





WORLD ENERGY CONSUMPTION (*top*) is shown from 1950 to 1985 (*blue*). The red line traces world energy consumption per capita. Energy intensity—consumption divided by gross national product—is shown by region in 1985 dollars (*bottom*). In less developed countries the rise in intensity can be attributed to growth in population and economic activity. Although the U.S. has reduced its intensity by growing economically without consuming more energy, it lags far behind Europe and Japan.

commercial energy. It is clean-burning, efficient and flexible enough for use in industry, transportation and power generation. It generates fewer pollutants than any other fossil fuel and less carbon dioxide as well: natural gas releases 14 kilograms of carbon dioxide for every billion joules, whereas oil and coal release 20 and 24 kilograms, respectively. Many industry experts expect conventional sources of natural gas to last four or more decades, and many electric utilities consider natural gas to be the best near-term substitute for oil as a fuel for some power plants. Yet known conventional gas supplies, too, are controlled by only a few nations. The Middle East and the Soviet Union hold nearly 70 percent of these reserves. As conventional supplies dwindle and costs rise, however, large and widely distributed sources of "unconventional" gas such as coal-seam gas may become economical.

World coal reserves total about 950 billion metric tons, and roughly half of them are of high quality. Reserves could last more than 275 years at today's production rates. The U.S. and the Soviet Union each control a quarter of global coal reserves; the rest are spread across Africa, Australia, Europe and Asia (mostly in China). Industrialized countries generate between 20 and 30 percent of their energy from coal. China gets almost three quarters of its total energy from coal.

Coal is a dirty fuel: mining it can ravage the land, and burning it can generate large amounts of carbon dioxide and other pollutants. Environmental concerns could limit coal consumption worldwide, unless technologies to burn it more efficiently or convert it to alternative fuels are adopted. Devices known as precipitators and scrubbers, which can filter out some pollutants, may not be adequate to their task. In the past decade engineers have developed a number of "clean coal" technologies, such as an electric generator that first transforms the coal into natural gas and then burns the gas to drive a turbine. These technologies offer great promise for reducing most pollutants, but they would not reduce coal's carbon dioxide emissions. Continued heavy reliance on coal may require technologies that can trap carbon dioxide, which will compromise efficiency.

Environmental, geopolitical and economic pressures on fossil-fuel use prompt a search for energy alternatives. Many energy planners favor increased reliance on nuclear power, which today generates about 17 percent of the world's electricity, since its use does not emit carbon dioxide or the pollutants that cause acid rain. Light-water reactors (the dominant design), however, are increasingly expensive to build and operate. France obtains about 70 percent of its electricity from nuclear power, but the accidents at Three Mile Island and Chernobyl have tarnished public perception of reactor safety and reliability. Much of the public doubts that adequate radioactive-management techniques exist or can be developed or that a remedy for proliferation of weapons-grade nuclear materials has been found. As a consequence of these handicaps and the growing attractiveness of other energy sources, U.S. utilities have not ordered a new nuclear plant since 1978.

Advanced reactor designs could help restore the promise of nuclear energy. "Passively stable" reactors could be built that would prevent runaway chain reactions without relying on an external control system. Standardized designs could reduce construction costs, licensing complexities and downtime. Perhaps most important, successful demonstration of radioactive waste-disposal capabilities will be critical to widespread public acceptance of nuclear power.

The potential of wresting energy from the fusion of light nuclei is a fond hope for future generations. Fusion, graced with limitless fuel supplies (deuterium) and less troublesome radioactive by-products, avoids many of the frustrations and limitations of nuclear fission. Still, demonstration and commercialization of fusion power will require billions of dollars and is likely to take decades. The scale of the required effort indicates a need not only for government funding but also for international collaboration. Yet few technologies promise more attractive returns on investment.

Solar-energy markets continue to expand, and unlike nuclear power, the price of solar energy continues to drop. Electricity produced by photovoltaic cells, which directly convert sunlight to electricity, now costs 30 cents per kilowatt-hour and is already a common power source for calculators, watches and satellites. These small-scale applications help to sustain the industry as the technology develops, but photovoltaic cells remain more expensive than conventional electricity generation for most applications. Further advances in microelectronics and semiconductors promise to increase efficiency and further reduce costs.

Solar-power generation is taking place on a larger scale at plants that convert solar energy to heat. In these solar-central-thermal systems, mirrors or lenses focus sunlight onto a receiver containing a fluid that then conducts heat to a conventional electric generator. In February, a company in California opened a solar-thermal plant that is expected to produce power for less than eight cents per kilowatt-hour. (At today's fossil-fuel prices, combustion turbines generate electricity for about three cents per kilowatt-hour.) Research on advanced, lightweight mirrors and better heat-transfer fluids, such as molten salts, may improve these results.

Solar technologies are not sufficiently advanced to supply base electric loads but could boost energy supplies during periods of peak daytime energy consumption in areas like the American Southwest, where sunshine is plentiful and dependable. Solar plants can also be used as part of a pumped storage system, wherein solar-powered pumps raise water to reservoirs, which later feed hydroelectric generators. Solar power is a natural partner for other types of energy storage as well, such as compressed air, batteries or (conceivably) current-storing superconducting coils.

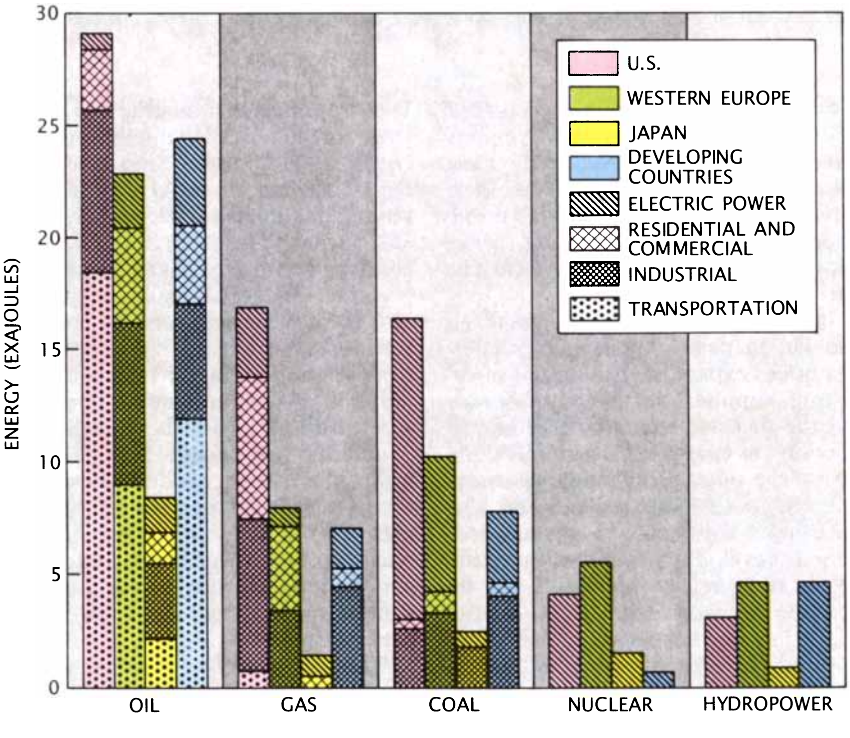
Hydroelectric power, a mature technology, carries high capital and environmental costs: new dams often result in the destruction of farmlands and the dislocation of population. Although sites are limited in the industrialized world, small-scale hydroelectric power may prove to be a valuable energy source in developing nations.

Biomass, which consists of wood and organic waste, provides energy for much of the world. Conversion of biomass to more useful products, such as methane or alcohol transportation fuels, will increase the value of this energy source. Power plants fueled by urban solid waste may become a modest but economical energy source as garbage-disposal problems worsen, but methods to separate combustible from noncombustible materials and devices to control emissions must be perfected. The carbon dioxide emissions associated with burning biomass can be offset by regrowing the plants or trees, thereby renewing the "carbon sink" they initially provided.

Some energy planners view wind power as a promising source of energy. Sweden is considering the replacement of its nuclear reactors with wind turbines anchored to the sea floor. Before wind power can be viewed as a dependable energy source, however, a system must be designed to operate reliably at variable rotor speeds.

Geothermal production of energy, which extracts heat from underground masses of hot rock, and ocean-thermal energy conversion, which exploits the temperature difference between the ocean's warm surface waters and its cold depths, can also contribute substantial amounts of energy in certain regions. For example, more than 2,000 megawatts of geothermal power has been tapped in northern California. In the next several decades, low-temperature applications (for example, for heating greenhouses) could develop into significant markets in some areas.

The conjuncture of the Arab oil embargo and a U.S. coal miners' strike in 1973 heightened concern about the immediate shortage of energy supplies and their ultimate depletion. Analysts of the time fair-



ENERGY HABITS differ among nations, but fossil fuels still feed most energy production. The U.S. transportation system alone consumes enough oil to provide for all of Japan's energy needs. Developing nations devote most of their energy to industry.

GENERATION OF ELECTRICITY at plants fueled by oil, coal or gas, like this coal-burning plant in San Juan, N.M., accounts for 23 percent of carbon dioxide emissions from energy production as well as for pollutants that cause acid rain. Although emission-control devices can remove the pollutants, an effective method has not yet been devised to capture carbon dioxide.

ly consistently projected two things. First, the high rate of growth in energy demand would continue, since a nation's energy consumption was inextricably linked to its economic development. Second, a continuing rise in energy consumption would have disastrous consequences.

Neither projection has been realized so far, in part because higher energy prices expanded the amount of existing supplies but largely because of the massive, unanticipated contributions of energy-efficiency technologies. The most promising opportunities for both industrialized and less developed countries to sustain economic development without the many costs of increased fossil-fuel use lie on the demand side of the energy equation. Improvements in energy efficiency can be implemented much more economically than new supplies of energy can be developed.

The buildings sector of the global economy holds many opportunities for improved energy efficiency. In 1985 buildings in industrialized countries consumed 37 exajoules, almost equal to OPEC's production. New condensing furnaces could significantly reduce this demand. Because they reabsorb much heat from exhaust gases, condensing furnaces need 28 percent less fuel and emit fewer pollutants into the atmosphere than do conventional gas furnaces. Systems for controlling the indoor environment can monitor outdoor and indoor temperatures, sunlight and the location of people and then provide light and conditioned air where needed. These systems typically can provide energy savings of from 10 to 20 percent. A combination of improved lamps, reflectors and daytime lighting can cut the consumption of energy for lighting by 75 percent or more.

Advanced building materials can sharply reduce loss of heat through windows, doors and walls. In "superinsulated" homes, where normal insulation is doubled and a liner forms an airtight seal in walls, heat radiating from people, light, stoves and other appliances alone can warm the house. In comparison with the average home built in the U.S., some superinsulated homes in Minnesota require 68 percent less heat; for some residences in Sweden, the saving is 89 percent.

In industry, sensors and controls, advanced heat-recovery systems and friction-reducing technologies can decrease energy consumption. A great opportunity for improving efficiency is cogeneration—the combined production of heat and electricity. Only a third of the energy from the steam produced by a boiler in a conventional electric-power plant is converted to electricity; in a cogeneration plant, much of the energy remaining in the used steam serves as a heat source for other industrial processes.

Other efficiency measures are specific to each industry. In the paper industry, automated process control, greater process speeds and high-pressure rollers can boost efficiencies significantly. Advanced processes in the steel industry offer energy savings of at least 40 percent in U.S. plants. In developing nations, efficiencies could be improved still further: China and India use four times as much energy to make a ton of steel as Japan does.

New electric-generation technologies promise greater efficiency around the globe. Fluidized-bed combustion, in which burning coal is suspended (fluidized) in a stream of air, can increase efficiency and reduce emission of pollutants. Some analysts feel that the most promising future option for electric-power generation is the aeroderivative turbine, which is based on jet engine designs and burns natural gas. With additional refinement, this technology could raise conversion efficiency from its present value, 33 percent, to more than 45 percent.

Transportation in industrialized and less developed countries constitutes the largest and most rapidly growing drain on the world's oil reserves and is a major threat to the environment. Cars and light trucks consume more than one out of every three barrels of oil and contribute 15 percent of carbon dioxide emissions in the U.S. During the past 15 years, new cars and trucks have become markedly more efficient through strategies such as increased use of light materials, the installation of radial tires to reduce rolling resistance and the redesign of exteriors to decrease aerodynamic drag. Further gains in vehicle efficiency could come from a variety of technologies such as continuously variable transmissions and direct-injection diesel engines.

The technical potential exists to push automobile fuel economy over 65 miles per gallon. If the price of gasoline were to increase in the U.S. to reflect its full costs—economic, environmental and geopolitical—as it has in other nations, U.S. consumers might demand more fuel-efficient cars, and regulations for increased efficiency would make more sense. Even now, U.S. new-car fuel economy could be increased to 33 miles per gallon with existing technology at little cost to consumers. Yet manufacturers resist these steps, fearing consumer backlash, since in many instances lower fuel efficiency can be traded for improved performance. Alternatively, the fuel economy of new cars could be increased from its current level of about 22 miles per gallon to 38 by improving technologies at a cost equal to the value of the gasoline saved over a car's lifetime (calculated at the current average price per gallon of $1.10).

Transportation, communication, manufacturing—all those things we associate with economic development and higher standards of living require energy services. Many technologies exist, however, to supply both necessities and amenities with far less fuel than we currently use. Planning for future energy needs and deciding how much to invest in new supplies or in technologies for efficient use requires a sense of what we can or would like to achieve. Decreasing oil consumption in the U.S., for instance, could significantly protect its economy and increase geopolitical and planetary stability.

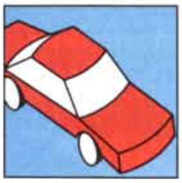
Yet even dramatic improvements in energy efficiency will not be sufficient to protect the environment if they are confined to the industrialized world. Economic projections show that if nothing is done to hasten energy-technology development and to move existing efficiency technologies into the market in developing countries, global climatic change and other major environmental problems will escalate beyond acceptable bounds. Even if industrialized countries managed to halve their carbon dioxide emissions (currently 1,800 kilograms per person per year), population growth and economic development in the less developed countries would most likely drive up their carbon dioxide emissions from 450 to 900 kilograms per person per year by 2030. Annual worldwide emissions of carbon dioxide would then be 2.5 times what they are today.

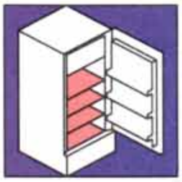
The industrialized world uses the lion's share of commercial energy, but it has the tools at hand to increase efficiency and decrease fossil-fuel use. One place to start is application of the market rule—"energy prices matter"—to the U.S. transportation system.

The cost of a gallon of gas in the U.S. has reached its lowest level ever. It does not reflect the cost of defense for the Middle East, smog, global warming or the trade imbalance caused by oil imports. Gasoline prices in Europe and Japan are double or triple the U.S. price because governments there impose levies that force consumers to consider and internalize the full costs of their behavior. If Americans want to hold down oil consumption and attendant carbon dioxide emissions and play a world leadership role, a revision of transportation policy to reflect all energy-related costs would be a good place to start.

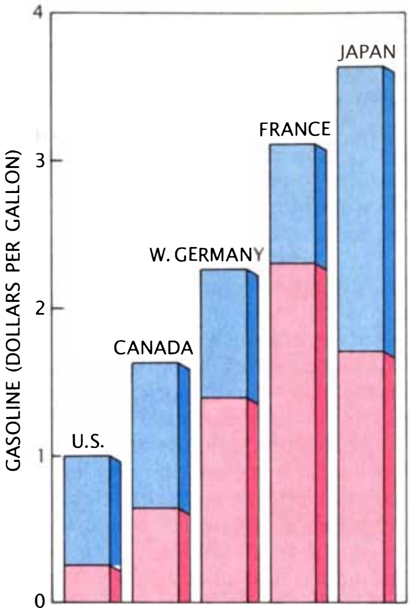
Policies designed to speed the market penetration of new technologies are also essential. For example, research done at the Lawrence Berkeley Center for Building Science in California indicates that an $8-million investment in manufacturing and installing low-emissivity windows could eliminate the need for 36 million barrels of oil, which would cost $300 million to produce. Governments may want to take steps to create a preference for investment in efficiency technologies over production. The U.S. Congress did recently pass legislation imposing minimum efficiency standards on all new appliances. This measure was

OPPORTUNITIES FOR EFFICIENCY





	CAR MILES PER GALLON	HOME THOUSAND JOULES PER SQUARE METER	REFRIGERATOR KILOWATT-HOURS PER DAY	GAS FURNACE MILLION JOULES PER DAY	AIR CONDITIONER KILOWATT-HOURS PER DAY
MODEL AVERAGE	18	190	4	210	10
NEW MODEL AVERAGE	27	110	3	180	7
BEST MODEL	50	68	2	140	5
BEST PROTOTYPE	77	11	1	110	3



GASOLINE PRICES in the U.S. do not reflect the full costs of protecting oil supplies and cleaning the environment. Other nations impose heavy taxes (*red*) on gasoline that force consumers to consider the full impact of their energy habits.

necessary because builders, who seek to minimize initial costs, were eschewing cost-effective technologies to the detriment of building occupants, who are more interested in life-cycle costs.

Efficient lighting, another big energy saver, may also require policy intervention to succeed because of the inherent imperfections of the marketplace. In one promising approach, utilities subsidize customers to replace existing lighting with more efficient equipment; both parties share the savings. Ironically, the same utilities that gave away light bulbs in the 1950's to build electricity demand may now find it in their interest to give away high-efficiency light bulbs to decrease demand in the 1990's.

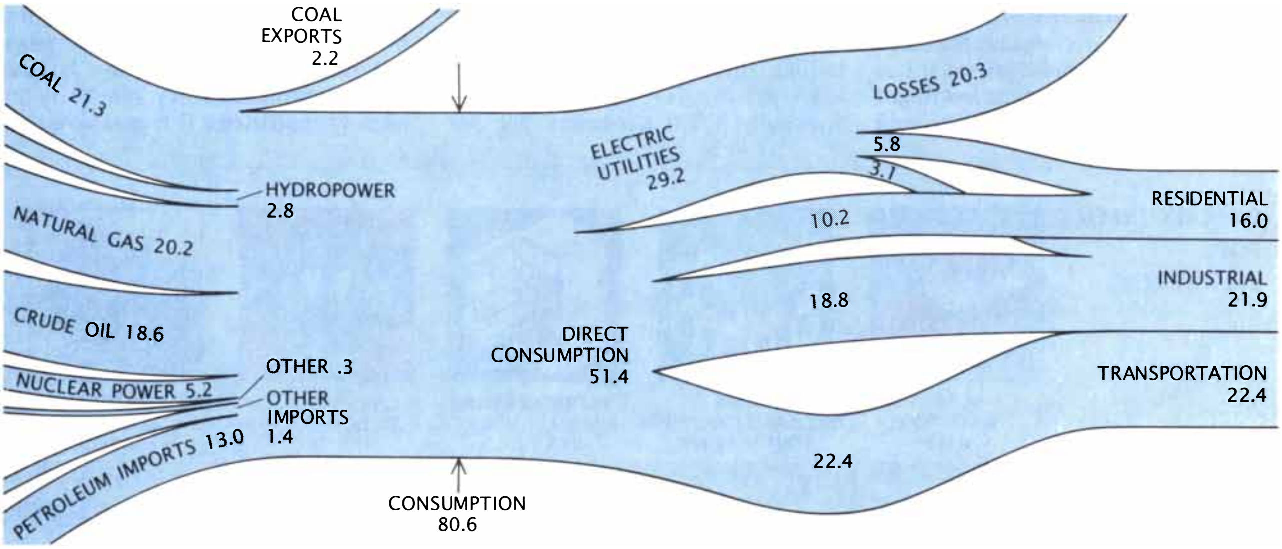
The developing world's share of energy consumption is small but inefficient, and demand is rapidly growing. With the help of the industrialized world, however, developing countries could apply technical solutions that would promote economic growth while keeping energy-demand growth relatively low. One important analysis shows that application of the best energy technology available today could provide a developing nation with a mid-1970's European level of energy services while increasing energy consumption by only 20 percent over the average consumption of a developing country in 1980. This model also confirms that industrialized countries could continue economic growth but consume less energy than they do today.

Why should less developed countries worry at all about saving energy when their prime concern is generating economic growth, which includes increasing the availability of energy services? The answer is that energy efficiency reconciles the simultaneous goals of development and environmental protection. Efficiency saves capital and decreases the production of carbon dioxide, sulfates (which cause acid rain), hydrocarbons and nuclear waste.

The less developed countries face some hard choices. The path of industrial development in China, for instance, could have a greater effect on the atmospheric accumulation of carbon dioxide than that of any other nation. China's critical role stems from its large and growing population, its tendency toward energy-intensive processes, its poor energy efficiency and its massive reliance on coal. Between 1980 and 1986 China's manufacturing sector grew by 12 percent a year, the fastest growth in any large nation in the world. The average energy intensity of China's industrial sector has dropped, but it remains higher than the intensity of any other developing nation. Indeed, the potential for improved efficiency is China's chief future energy resource.

Achieving that potential will require large transfers of technology and capital from the industrialized world, but it will also require reform of China's energy-pricing policy. Coal in China is priced at one quarter the international level. Folk wisdom has it that "one ton of coal could not even buy a ton of sand; one barrel of oil could not even buy a bottle of liquor."

Industrialized countries with aging infrastructure will also have a major impact on future energy consumption and carbon emissions. Energy intensity in the Soviet Union is twice the average of nations belonging to the Organization for Economic Cooperation and Development and shows no sign of improvement. The new policies of *perestroika* and *glasnost*, which encourage efficiency, market-oriented systems and global cooperation, therefore hold great promise for the global economy and environment. As the U.S.S.R., China and other centrally planned economies move toward a



ENERGY FLOW shows that in 1987 the U.S. consumed 12.2 exajoules more than it produced. The balance was maintained largely through petroleum imports. Alternative energy resources accounted for only 12 percent of total energy production.

more rational price system, they will soon recognize, however, that market prices still do not reflect major external costs. Because we now realize that these costs may include extraordinary global environmental problems, it may be up to more industrialized countries to encourage—through technology transfer, subsidies or loans—policies or technologies that take developing countries beyond the levels of efficiency justifiable on the basis of free-market prices. Such policies would require unprecedented levels of international cooperation.

SIGN OF THE TIMES on a mountain highway has lights powered by photovoltaic cells. The price of the cells has dropped rapidly, thereby expanding their market. Time can be gained to research and develop such innovative technologies, which increase energy supplies, by consuming existing energy resources more efficiently.

Capital and ingenuity can substitute for energy throughout the world, but it will take technical sophistication, political will, enlightened economic thinking and time. Much of the technical sophistication needed to guarantee significant increases in the efficiency of energy conversion and use already exists, and efficiency is often cheap compared with the real costs of fossil fuels and the capital costs of new supplies. But research and development, funded both privately and by the government, is necessary to push beyond existing limits. We also need to continue investigating new supplies, especially nuclear energy and renewable energy sources, so that they can complement and ultimately replace fossil fuels. In the meantime, efficiency improvements will hold down fossil-fuel demand, lessen environmental problems, save investment capital and ultimately enable a given level of amenities to be provided for less energy.

Political will is another matter, as is enlightened economic thinking. Who wants to raise the apparent cost of fuel to the poor, in the U.S. or in India? We may know, rationally, that subsidizing fuel costs imposes far greater burdens on a nation than encouraging and perhaps subsidizing purchases of efficient cars or home appliances, but policy adjustments to foster efficiency will require that we plow through some new emotional territory. Political will is also crucial for exploiting some alternative-energy technologies. Most scientists believe that safe and reliable nuclear waste-disposal technologies are at hand, but the not-in-my-backyard sentiment prevails among the wider populace. What combination of technical, educational and political skills will enable us to reach accord on this issue, which will be critical to any future deployment of nuclear power?

The fact that one country acting alone cannot "cure" global problems compounds the political burden. Yet the sheer magnitude of U.S. energy consumption indicates that the U.S. could have a significant impact on global carbon emissions by instituting savings within the cost-effective ranges established by existing technology. And the U.S., because of its energy-intensive past and present and its great technological ingenuity and capability, can be charged with great responsibility in effecting the transition to an era beyond fossil fuels. To do so, it must increase its own efficiency, develop a new array of energy sources and expand the energy possibilities for other countries. The U.S. might consider a twofold goal: first, increase the fraction of useful energy produced from nonfossil resources (by fuel substitution and more efficient combustion) by 20 percent by the end of this century; second, increase the output of goods and services provided per unit of energy consumed by at least 2.5 percent a year for at least two decades. Such goals are challenging but achievable and could be a useful focus for the U.S. to assume leadership on this truly global issue.

But it is the collective response of developing countries to opportunities for efficient resource use in their economies that will determine humanity's ultimate success in slowing the deterioration of the global environment. New technology can help less developed countries to leap over the undesirable practices of the past and follow new energy paths for development. The industrialized world and developing countries must work together to ensure that opportunities are available and, when sensible, are accepted. Investment in energy-efficiency technologies, which often cost the same as the fuels they displace, represents the most sensible energy path available today. The challenges are great, but so are the opportunities.

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Strategies for Manufacturing

Wastes from one industrial process can serve as the raw materials for another, thereby reducing the impact of industry on the environment

by Robert A. Frosch and Nicholas E. Gallopoulos

People create new technologies and industries to meet human needs more effectively and at lower cost. Innovation is a major agent of progress, and yet innovators' incomplete knowledge sometimes leads to undesirable side effects. Such unforeseen consequences of new inventions are not unique to the feverish industrialization of the 19th and 20th centuries. The ancient Greek myths tell of Pandora and the box full of plagues, of Prometheus punished for stealing fire from the gods and of Icarus, who plummeted from the sky when the sun's heat melted the wax of his wings. In historical times the shift from rawhide to tanned leather, although it made for garments and tools that lasted much longer and were more comfortable to wear and use, brought stenches and disease, so that tanneries had to be segregated from the communities they served.

Today such inadvertent effects can have a global impact. Consider, for example, the invention of chlorinated fluorocarbons. Before CFC's were developed in the 1930's, refrigerator compressors contained ammonia or sulfur dioxide; either chemical was toxic, and leaks killed or injured many people. CFC's saved lives, saved money and provided such elements of modern life as air-conditioned buildings and untainted food. Only later did atmospheric scientists determine that CFC's contribute to global warming and affect the chemistry of the upper atmosphere, where they destroy ozone.

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Such failures should not diminish the fact that technology has improved the lot of people everywhere. Standards of living in many parts of the world are better today than they were 20 or 30 years ago. Many of the adverse effects of industrialization have been brought under control by further applications of technology. Yet as the world's population and standard of living increase, some of the old solutions to industrial pollution and everyday wastes no longer work. There is often no "other side of town" where the modern equivalents of tanneries can be put, no open space beyond the village gates where garbage can be dumped and do no harm.

By the year 2030, 10 billion people are likely to live on this planet; ideally, all would enjoy standards of living equivalent to those of industrial democracies such as the U.S. or Japan. If they consume critical natural resources such as copper, cobalt, molybdenum, nickel and petroleum at current U.S. rates, and if new resources are not discovered or substitutes developed, such an ideal would last a decade or less. On the waste side of the ledger, at current U.S. rates 10 billion people would generate 400 billion tons of solid waste every year—enough to bury greater Los Angeles 100 meters deep.

These calculations are not meant to be forecasts of a grim future. Instead they emphasize the incentives for recycling, conservation and a switch to alternative materials. They lead to the recognition that the traditional model of industrial activity—in which individual manufacturing processes take in raw materials and generate products to be sold plus waste to be disposed of—should be transformed into a more integrated model: an industrial ecosystem. In such a system the consumption of energy and materials is optimized, waste generation is minimized and the effluents of one process—whether they are spent catalysts from petroleum refining, fly and bottom ash from electric-power generation or discarded plastic containers from consumer products—serve as the raw material for another process.

The industrial ecosystem would function as an analogue of biological ecosystems. (Plants synthesize nutrients that feed herbivores, which in turn feed a chain of carnivores whose wastes and bodies eventually feed further generations of plants.) An ideal industrial ecosystem may never be attained in practice, but both manufacturers and consumers must change their habits to approach it more closely if the industrialized world is to maintain its standard of living—and the developing nations are to raise theirs to a similar level—without adversely affecting the environment.

If both industrialized and developing nations embrace changes, it will be possible to develop a more closed industrial ecosystem, one that is more sustainable in the face of decreasing supplies of raw materials and increas-

INDUSTRIAL PLANTS such as this oil refinery in New Jersey make the products and materials that sustain modern life. They also emit pollutants that are difficult to dispose of and that may have long-lasting adverse effects on the environment. Meeting environmental needs calls for manufacturing plants that not only produce goods more efficiently but also fit together into a more harmonious industrial ecosystem. At the same time, consumers must learn to use those products less wastefully.

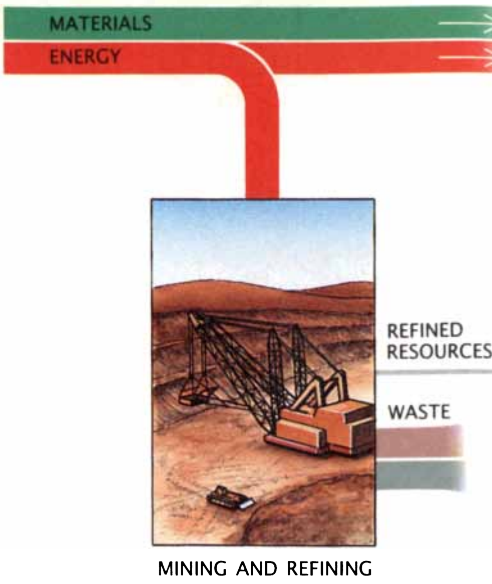
ing problems of waste and pollution. Industrialized nations will have to make major and minor changes in their current practices. Developing nations will have to leapfrog older, less ecologically sound technologies and adopt new methods more compatible with the ecosystem approach.

Materials in an ideal industrial ecosystem are not depleted any more than those in a biological one are; a chunk of steel could potentially show up one year in a tin can, the next year in an automobile and 10 years later in the skeleton of a building. Manufacturing processes in an industrial ecosystem simply transform circulating stocks of materials from one shape to another; the circulating stock decreases when some material is unavoidably lost, and it increases to meet the needs of a growing population. Such recycling still requires the expenditure of energy and the unavoidable generation of wastes and harmful by-products, but at much lower levels than are typical today.

Today's industrial operations do not form an ideal industrial ecosystem, and many subsystems and processes are less than perfect. Yet there are developments that could be cause for optimism. Some manufacturers are already making use of "designed offal," or "engineered scrap," in the manufacture of metals and some plastics: tailoring the production of waste from a manufacturing process so that the waste can be fed directly back into that process or into a related one. Other manufacturers are designing packaging to incorporate recycled materials wherever possible or are finding innovative uses for materials that were formerly considered wastes.

Three examples delineate some of the issues involved in developing self-sustaining industrial process systems: the conversion of petroleum derivatives to plastics, the conversion of iron ore to steel, and the refining and use of platinum-group metals as catalysts. We have picked these examples because each represents a different stage in the evolution of a closed cycle. Examining their workings and shortcomings should provide insight into how subsystems can be improved so as to develop an industrial ecosystem.

The iron cycle, in which recycling is well established, is a very mature process with a history dating back thousands of years, even though extensive production of steel did not begin until the 19th century. The plastics cycle, in which reuse is just beginning to make its mark, is less than 100 years old; the first completely synthetic plastic, Bakelite, was introduced shortly after the turn of the century. The platinum-group-metals cycle—in which reuse is common because of the high cost of the materials involved—is even younger: industrial noble-metal catalysts became widely used only in the early 1950's, and the widespread use of noble metals to reduce pollution from automotive exhaust dates back less than 15 years.



INDUSTRIAL-ECOSYSTEM CYCLE starts with resources and progresses to a finished product that can be recycled (*blue*)

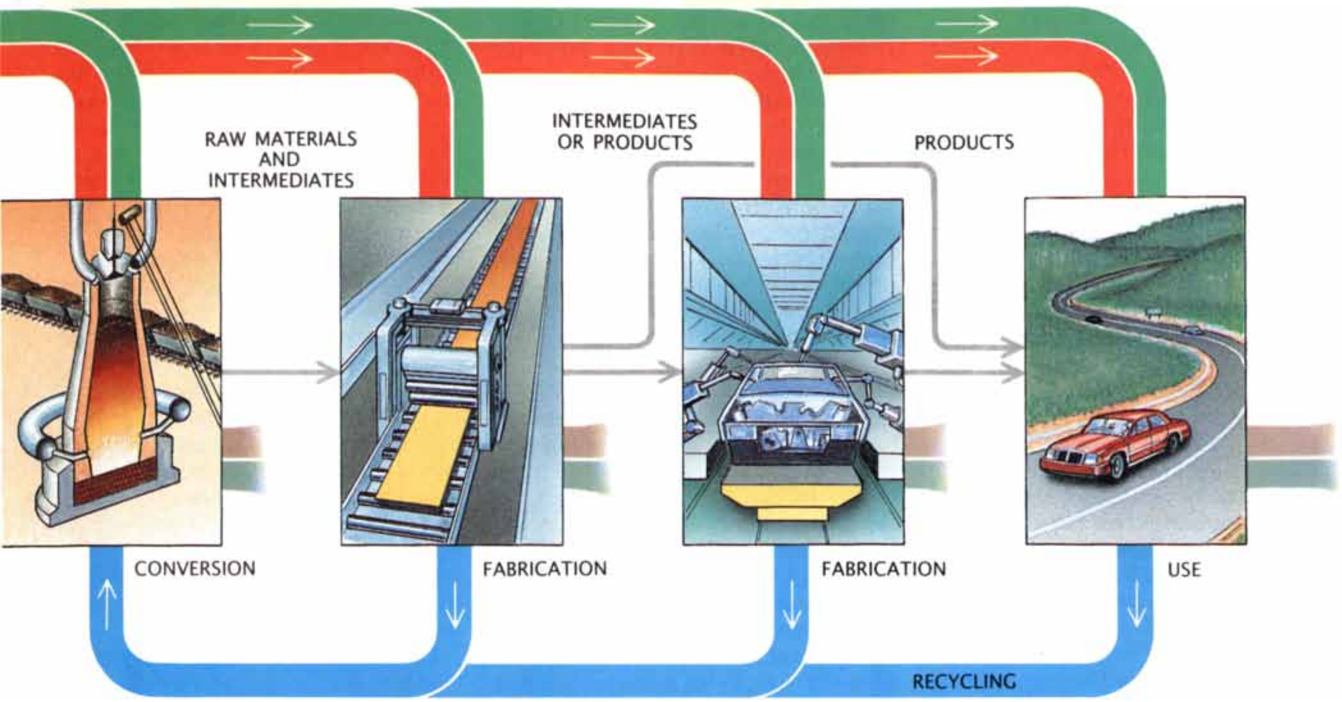
The plastics system is potentially highly efficient, but realizing that potential poses challenges that have yet to be met. Plastics are a diverse group of chemically complex compounds whose use has grown explosively, so that they now present a growing disposal problem. Plastics are formed into any number of products, and different plastic resins are difficult to distinguish. This difficulty leads to problems in collection, separation and recycling. Moreover, breaking plastics down to their original chemical constituents is often technologically infeasible or economically unattractive.

The drawbacks of plastics must nonetheless be weighed against their benefits. Plastic containers, for example, are safer than the glass containers they replace. Countless injuries, from minor cuts to severe lacerations, have been prevented by the substitution of plastic for glass in milk bottles and containers for bathroom products such as shampoo. Plastic containers are generally lighter than glass or metal ones, so that less energy is required to transport them; they also require less energy to make than glass or metal containers, especially if they are

ESTIMATED LIFETIMES OF SOME GLOBAL RESOURCES

	CURRENT CONSUMPTION RATES		2030 RATES	
	RESERVES	RESOURCES	RESERVES	RESOURCES
ALUMINUM	256	805	124	407
COPPER	41	277	4	26
COBALT	109	429	10	40
MOLYBDENUM	67	256	8	33
NICKEL	66	163	7	16
PLATINUM GROUP	225	413	21	39
COAL	206	3226	29	457
PETROLEUM	35	83	3	7

WORLD STOCKS of some essential raw materials will drop perilously low if less developed countries increase their consumption to match that of the industrialized world. Figures show reserves (quantities that can be profitably extracted with current technology) and resources (total quantities thought to exist). Estimates of years left until depletion are based on current global consumption (*left*) or on the assumption that in 2030 a population of 10 billion will consume at current U.S. rates (*right*).



after use to enter the cycle again as a raw material. (The iron and steel cycle is shown here.) At each stage in the manufacturing process, energy (*red*) and additional raw materials (*green*) are added, and waste heat and by-products are generated. In an optimal cycle, wastes are captured and reused either in the same manufacturing process or in a different one.

recycled. The Midwest Research Institute in Kansas City, Mo., determined that compared with glass containers, half-gallon polyvinyl chloride (PVC) containers require less than half the energy to produce and transport and consume one twentieth the mass of raw materials and less than one third as much water in their manufacture. They also generate less than half of the waste of glass manufacturing.

Each kind of plastic poses different problems depending on its particular composition and use. PVC, of which almost four million tons are produced every year in the U.S., is a particularly dramatic example of the complex threats plastics pose to the environment. PVC, which accounts for about one sixth of total plastic production, is made into products ranging from pipes to automobile parts to shampoo bottles. Its production requires both hydrocarbons and chlorine. (The chlorine makes the plastic's impact on the environment greater than it would be if only hydrocarbons were required—as is the case for polyethylene, for example.) Natural gas is the most commonly used feedstock for PVC in the U.S.; elsewhere it is naphtha, a petroleum fraction. In either case the feedstock is converted to ethylene, which is chlorinated to form vinyl chloride monomer; the monomer molecules are then linked to form PVC.

The efficiency of the production process has already been improved. For example, manufacturers have developed more efficient membrane cells for the electrolysis of sodium chloride to produce the required chlorine. (The sodium chloride, common table salt, is dissolved in cells through which a current flows; sodium ions migrate to one electrode, and chlorine ions migrate to the other. A membrane separates the two electrodes.) The membrane cells also eliminate the asbestos and mercury required in older electrolysis cells, thus reducing hazardous wastes.

Even so, the PVC production process exemplifies classic "end of pipe" control measures for reducing pollutants. Emissions of vinyl chloride monomer during manufacturing are tightly controlled, a practice instituted when it became known that the monomer is both toxic and carcinogenic. Unreacted vinyl chloride is generally stripped from the finished PVC by low-pressure steam. Most of the monomer is recovered and recycled, but some of it is present at concentrations too low for easy recovery and recycling; instead it is sent to an incinerator to be broken down. Scrubbers remove hydrochloric acid from the exhaust.

Recycling of PVC during manufacturing is fairly straightforward. Plants that make PVC products typically recycle almost all of their in-house scrap. At General Motors, for example, scrap generated in the manufacture of PVC parts such as decorative trim, seat covers and dashboards is segregated by color, reground, melted and used along with virgin PVC.

Once plastic enters the consumer market, however, recycling becomes considerably more complicated. Only about 1 percent of the PVC discarded by consumers is recycled. The wide range of products in which PVC is found makes collection and recovery more difficult, but it also creates interesting opportunities. For example, potential health hazards and liability concerns prevent recycled plastics from being incorporated into containers where the plastic touches food; recycled bottles may find their way into drainage pipes instead.

Other vinyl products that cannot easily be recycled can be burned to produce heat or electricity. PVC contains roughly as much energy as wood or paper, but its chlorine content poses problems: incinerators that burn PVC must have scrubbers to prevent emissions of hydrochloric acid, which contribute to acid rain. During combustion the chlorine can also form small amounts of dioxins, which are believed to be potent carcinogens. As a result, the incineration of discarded PVC is discouraged. Although recent tests by the New York State Energy Research and Development Authority have shown that properly designed and operated incinerators do not emit significant quantities of hydrochloric acid or dioxins, environmentalists and regulators are not convinced that incinerators would achieve such low emission levels in practice.

Because of its chlorine content, PVC is a worst-case example of the problems plastics pose. Other polymers such as polypropylene and polyethylene present fewer environmental hazards. They have physical properties similar to those of PVC, but they contain no chlorine. Polyethylene terephthalate (PET), the material used in carbonated beverage bottles, is recycled in nine states that have mandatory deposit laws: California, Connecticut, Delaware, Maine, Massachusetts, Michigan, New York, Oregon and Vermont. Bottles collected in these states account for 150 million of the 750 million pounds of PET resin produced every year. Recyclers pay from $100 to $140 per ton of PET, making it the second most valuable component of municipal solid waste after aluminum. The PET is reconstituted into resins for injection molding to produce products ranging from automobile parts to electronic devices or is spun into polyester fibers that go into pillows, stuffed furniture, insulated clothing and carpeting.

BEVERAGE CONTAINERS, seen here bound into bales at a major recycling center in New Jersey, can be reprocessed into plastic products such as polyester fiber and molded parts. Some 150 million pounds of bottles made from polyethylene terephthalate (PET) were collected last year from the nine U.S. states that have mandatory deposit laws; 750 million pounds are produced nationwide.

As the infrastructure for collecting and sorting PET and other consumer plastics grows, recycling rates should increase significantly. According to recyclers such as Wellman Inc., of Shrewsbury, N.J., which currently processes about 100 million pounds of PET a year, the market for recycled plastics is limited by collection efficiency rather than by demand.

The industrial system for iron presents a different picture. Techniques for recycling are well established, and there is a strong infrastructure for collecting scrap. Yet discarded metal continues to pile up in scrapyards and across the U.S. because there is not enough demand for it. Elemental iron, the predominant component of both steel and cast iron, is the backbone of modern life: it is used in roads, in the automobiles that pass over the roads and in buildings. In the U.S. iron production begins when ore is mined in huge open pits as deep as 100 meters or more. The ore is concentrated and formed into pellets at the mine and then converted into pig iron in a blast furnace, where it is heated with coke, limestone and air. The coke adds carbon to the mix, and the limestone and the oxygen in the air react with impurities in the ore to form slag, which is then removed. Small admixtures of other elements yield steel to be cast, rolled or forged into billets, slabs, beams or sheets.

Once iron has been formed into products, which are eventually discarded, its properties (especially its ferromagnetism) facilitate identification and separation. The enormous amount of iron in circulation makes recycling relatively easy and economically attractive. It is not surprising, therefore, that every year millions of tons of scrap join iron ore to produce steel products. The scrap generated by stamping steel parts for automobiles, for example, is recycled into engine blocks and other castings. All four foundries that GM operates rely entirely on scrap steel obtained from other GM operations and on scrap iron generated during the casting process.

Although iron recycling is a relatively simple process, the system is not a closed loop. Much of the scrap from discarded consumer products is not recovered but is scattered around the countryside, where it corrodes away a little every year and is considered a blight rather than an asset. In 1982 recoverable iron scrap amounted to 610 million tons; at the end of 1987 the figure had risen to more than 750 million. A major reason for the increase is that U.S. production of iron and steel during this period was the lowest it had been since the end of World War II. The demand for scrap to make steel decreased while iron and steel products continued to be scrapped at the previous rate.

Shifting patterns of steel manufacturing, both in the U.S. and around the globe, are responsible for the increase in scrap. One subtle culprit is a technology shift from open-hearth furnaces to basic oxygen furnaces for producing steel. Basic oxygen furnaces (so called because they make steel in a large closed vessel supplied with pressurized oxygen) require only 25 tons of scrap steel to be mixed with every 100 tons of pig iron from the blast furnace, as opposed to a nearly equal mix for the open hearth.

The shift to basic oxygen furnaces began in the U.S. about 1958, and today open-hearth furnaces account for less than 3 percent of total production. Open-hearth furnaces were replaced to improve manufacturing efficiency and reduce air pollution, but their disappearance led to a decline in iron recycling. In making these changes, steelmakers had no economic mechanism for taking account of the adverse environmental impacts of scrap accumulation or the possible long-term effects of consuming more iron ore for each unit of steel.

More recently minimills have been built that rely on electric-arc furnaces and consume scrap steel almost exclusively. These low-volume mills have increased their share of U.S. steel production, but not enough to compensate for the lost demand for scrap to feed open-hearth furnaces. Furthermore, minimills produce only a limited range of steel products, and many of those products must be made from scrap containing very low levels of impurities. Scrap that contains excess copper, for example, is not suitable for making sheet steel, because the resulting sheet is too brittle to form into products. If electric-arc furnaces are to make significant inroads into the U.S. stock of scrap iron, they must be coupled to production facilities that produce a wider range of products, and better techniques must be developed for dealing with impure scrap.

Platinum-group metals (platinum, palladium, rhodium, ruthenium, iridium and osmium) were, until the mid-1970's, part of a very efficient industrial system. These metals were once recycled with efficiencies of 85 percent or better, but the advent of catalytic converters for automobiles dealt this system a shock from which recycling rates are only now beginning to recover.

Recycling of platinum-group metals is dictated not so much by the environmental effects of their disposal as by their limited supply and the difficulties of mining and refining them. Ores contain only about seven parts per million of mixed platinum-group metals, so that about 20 million metric tons a year must be refined to produce 143 tons of purified metals—an amount that could fit into a cube roughly two meters on a side.

About 60 percent of the platinum-group metals mined is formed into metal products such as jewelry, ingots for investors and chemical-reaction vessels; these products are eventually recycled with almost complete efficiency. The remainder is used to make chemicals and catalysts for chemical plants, petroleum refineries and automobiles. Catalysts adsorb molecules on their surfaces and promote chemical reactions that either join the molecules together or break them into smaller ones. Catalytic converters for automobiles, which reduce exhaust emissions of hydrocarbons, carbon monoxide and oxides of nitrogen, are the most rapidly growing use of platinum-group metals; consumption rose from about 11.5 metric tons in 1975 to about 40 in 1988. Automobiles currently account for most of the yearly permanent consumption of platinum-group metals.

Platinum-group metals in industrial applications are recycled quite efficiently. Each plant uses large amounts of catalyst, so that the payoffs from recycling are clear. Used catalysts are generally recycled every few months, providing a large, continuing stream of materials for reclaimers to process. In chemical and pharmaceutical plants, for example, catalysts are typically recycled in less than a year, and about 85 percent of the platinum-group metals in them are recovered. Some petroleum refineries are even more successful, recovering up to 97 percent of their noble metals.

The automotive pattern of noble-metal use stands in sharp contrast to that of the process industries: there are tens of millions of catalytic converters, each of which contains only a few grams of platinum-group metals (less than two grams of platinum, for example), and the lifespan of about 10 years for an average car makes for a much slower turnover of recyclable materials. As a result, only about 12 percent of the platinum-group metals in catalytic converters is currently recycled.

SCRAP METAL from the casting and machining of engine parts awaits recycling at a General Motors foundry in Defiance, Ohio. The company operates four foundries; they are supplied entirely by scrap from sheet-metal stamping, iron casting and machining operations. Despite the relative ease with which scrap can be recycled, millions of tons pile up every year in U.S. scrapyards for lack of ready markets.

Poor recycling rates for automotive catalysts can be blamed almost entirely on the lack of an effective means for collecting discarded converters. The technology for recovering platinum-group metals from the converters is quite well understood; a plant opened by Texasgulf Minerals & Metals, Inc., in Ala. in 1984 recovers 90 percent of the platinum, 90 percent of the palladium and 80 percent of the rhodium from used converters. Millions of individual converters, however, are dispersed among thousands of scrapyards and almost 2,000 automotive scrap recyclers. The cost of locating, collecting and emptying the converters and then transporting the catalyst to a reprocessing plant is sufficiently high so that recycling is not profitable for most refining operations unless the price of platinum exceeds $500 an ounce.

The outlook for catalytic-converter recycling is improving. Now that most of the first-generation of cars built with catalytic converters have found their way to U.S. scrapyards, there is a large, continuing flow of raw materials for recyclers. More important, an infrastructure for collecting spent converters is being established. Even Japanese companies such as Nippon Engelhard have set up collecting organizations in the U.S. to acquire automotive catalysts for reprocessing in Japan. In addition the introduction of more stringent emissions controls in Europe, where catalytic converters have not been required, will increase the demand for platinum-group metals, making recycling more profitable.

The life cycles of plastics, iron and the platinum-group metals illustrate some of the issues involved in creating sustainable industrial systems. Equally important is the way in which the inputs and outputs of individual processes are linked within the overall industrial ecosystem. This linkage is crucial for building a closed or nearly closed system.

Like their biological counterparts, individual manufacturing processes in an effective industrial ecosystem contribute to the optimal function of the entire system. Processes are required that minimize the generation of unrecyclable wastes (including waste heat) as well as minimize the permanent consumption of scarce material and energy resources. Individual manufacturing processes cannot be considered in isolation. A process that produces relatively large quantities of waste that can be used in another process may be preferable to one that produces smaller amounts of waste for which there is no use.

A good example of the subtleties involved is the dematerialization of manufactured goods—the use of plastics, composites and high-strength alloys to reduce the mass of products. The trend toward dematerialization has drawn increasing attention in recent years. The mass of a typical automobile, for example, has decreased by more than 400 kilograms since 1975; about 100 kilograms of the decrease are due to the substitution of aluminum and plastics for steel. Lighter cars burn less gasoline. Steel, however, is easy to recycle, whereas the composite plastics that have replaced it resist reuse. The net result may be an immediate drop in fuel consumption but an overall increase in the amount of permanent waste created and in the resources consumed.

Waste-minimization activities in U.S. industries have been aided by regulations developed in the late 1970's to control hazardous-waste disposal. The regulations, reflecting long-term environmental costs, have increased the cost of landfill disposal from less than $20 a ton to $200 a ton or more, making alternatives to disposal profitable. Many companies find it profitable to sell their wastes as raw materials. For example, Meridian National in Ohio, a midwestern steel-processing company, reprocesses the sulfuric acid with which it removes scale from steel sheets and slabs, reuses the acid and sells ferrous sulfate compounds to magnetic-tape manufacturers.

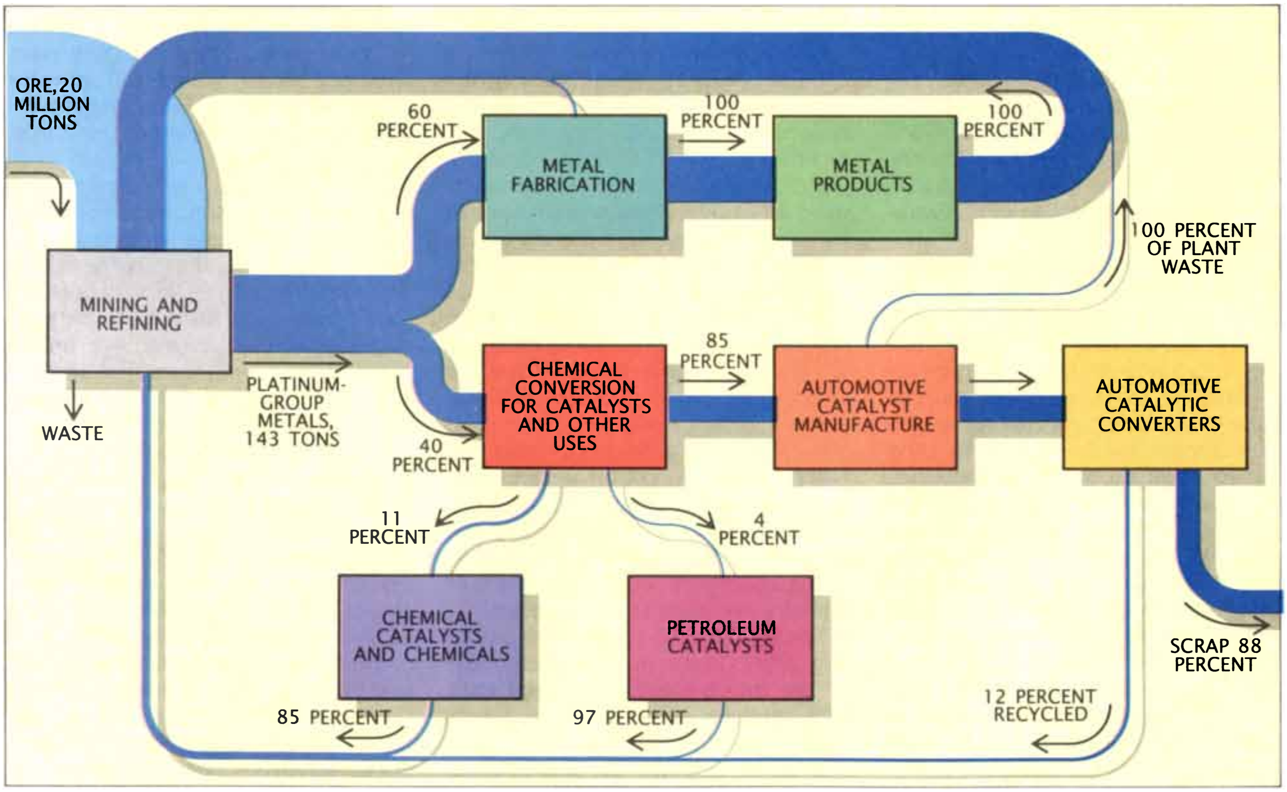
If the production of unrecyclable wastes is to be eliminated, similar steps must be taken for each of the low-level by-products in large streams of process effluents. Although emissions at each stage of such manufacturing processes may be relatively small, taken together they can cause serious pollution problems. Minimizing each of these myriad smaller emissions one at a time is a complex and potentially costly challenge.

The challenge can be met in part by implementing a multitude of relatively small changes. Some chemical plants and oil refineries, for example, have significantly reduced their hazardous-waste output by simply changing their procedures for buying and storing cleaning solutions and other low-volume chemicals. By doing so, they have been able to eliminate the need to dispose of leftover amounts.

At ARCO's Los Angeles refinery complex, a series of relatively low-cost changes have reduced waste volumes from about 12,000 tons a year during the early 1980's to about 3,400 today, generating revenue and saving roughly $2 million a year in disposal costs. The company sells its spent alumina catalysts to Allied Chemical and its spent silica catalysts to cement makers. Previously these materials were classified as hazardous wastes and had to be disposed of in landfills at a cost of perhaps $300 a ton.

Alkaline carbonate sludge from a water-softening operation at the refinery goes to a sulfuric acid manufacturer a few miles away, where it neutralizes acidic wastewater. (The acid manufacturer previously purchased pure sodium hydroxide for the same purpose.) A few outflow pipes have been rerouted to improve access for loading, and plant personnel must track the *p*H of their sludge, but the total investment has been minimal.

The ARCO refinery has also started to recover oil from internal spills and



PLATINUM-GROUP METALS are recovered efficiently from jewelry and other fabricated objects, two uses that constitute about 60 percent of consumption. Industrial catalysts and chemicals, also efficiently recycled, account for another 6 percent. The fastest-growing use for the metals is in automotive catalytic converters, an application marked by low recycling rates. The infrastructure is only now being set up to collect the millions of converters that enter automotive scrapyards each year and to recover the approximately two grams of platinum (worth about $32 in mid-1989) in each converter.

other wastes in a new $1-million recycling facility. When the recycler is fully operational next year, it is expected to reduce wastes by another 2,000 tons. Off-site treatment or landfilling will still be needed for miscellaneous wastes such as solvents, spray cans and the several hundred tons of asbestos insulation being removed from the plant each year.

ARCO's situation is not unique; other major refiners and chemical manufacturers are engaged in similar efforts. For example, investments of $300,000 in process changes and recovery equipment at Ciba-Geigy's Toms River plant in New Jersey reduced disposal costs by more than $1.8 million between 1985 and 1988. Dow Chemical established a separate unit to recover excess hydrochloric acid, which it then either recycles to acid-using processes or sells on the open market. The operation recovers a million tons of acid a year at a profit of $20 million.

CONSUMER WASTES strain the capacity of landfills such as this one in Deptford, N.J. The environmental problems posed could be avoided by changes in disposal habits. Sorting trash to facilitate the recycling of paper, glass and plastics could simultaneously slow the filling of landfills and reduce the consumption of scarce resources.

By-products and effluents created during manufacturing represent only the supply side of the industrial ecosystem. The demand side is the consumer, who takes in manufactured goods and produces scrap that could be the raw materials for the next cycle of production. If the industrial-ecosystem approach is to become widespread, changes in manufacturing must be matched by changes in consumers' demand patterns and in the treatment of materials once they have been purchased and used.

The behavior of consumers in the U.S. today constitutes an aberration in both time and space. Whereas a typical New Yorker, for example, discards nearly two kilograms of solid waste every day, a resident of Hamburg or Rome throws out only about half that—as New Yorkers did at the turn of the century. Moreover, U.S. consumer habits and waste-management practices form a complex pattern that hinders efforts to reduce waste generation and the growing pressure on municipal landfills. The vast bulk of consumer wastes consists of organic materials and plastics that could relatively easily be composted, recycled or burned to produce energy but instead are stored in landfills, for which land was readily available in the past and where costs were low.

Today, as landfills across the U.S. near capacity, many communities have initiated garbage-sorting programs to reduce the amount of unrecycled waste; more initiatives are likely to follow. Some other countries have already instituted fairly sophisticated collection and treatment practices that go well beyond standard sorting and recycling. Japan, Sweden and Switzerland, for example, have set up collection centers for batteries from portable radios and other consumer products. The batteries contain heavy metals that render composted wastes unsuitable for fertilizing crops; the metals also contaminate fly and bottom ash from incinerators, so that the ash must be disposed of as hazardous waste.

An effective infrastructure for collecting and segregating various consumer wastes can dramatically improve the efficiency of the industrial ecosystem. The American consumer may have to stop heedlessly generating huge volumes of unsorted wastes, but living standards in the U.S. as a whole will not be affected. Moreover, landfills for municipal wastes are running out of space as rapidly as are those for industrial waste; consumers will soon find themselves facing the same economic incentives for waste reduction that producers face today.

Creating a sustainable industrial ecosystem is highly desirable from an environmental perspective and in some cases is highly profitable as well. Nonetheless, there are a number of barriers to its successful implementation. Corporate and public attitudes must change to favor the ecosystem approach, and government regulations must become more flexible so as not to unduly hinder recycling and other strategies for waste minimization.

Federal hazardous-waste regulations are a case in point. They sometimes make waste minimization more difficult than waste disposal. Because of the strict requirements for handling and documenting the treatment of wastes classified as hazardous, many companies choose to buy their materials through conventional channels rather than involve themselves in the regulatory process. A few states do encourage innovative treatment of wastes: California, for example, publishes a biannual catalogue that attempts to match waste generators with waste buyers—manufacturers who need the materials they produce. About half a million tons of hazardous wastes that would otherwise have gone to landfills were recycled in 1987. A dozen other state, provincial and regional waste exchanges operate throughout the U.S. and Canada.

In addition to promoting innovative waste-minimization schemes, governments need to focus on the economic incentives for sustainable manufacturing. Increased landfill costs have forced companies to improve industrial processes and reduce unrecyclable waste, but many small emissions are still controlled by classic end-of-pipe regulations that specify how much of each pollutant may be discharged. Companies must meet regulatory requirements, but there are no direct advantages for manufacturers who capture and treat low-level effluents or who shift to production processes with more benign by-products.

Conventional economic methods take into account only the immediate effects of production decisions. If a manufacturer produces nonrecyclable containers, for example, taxpayers at large bear the increased landfill costs; if a power plant reduces emissions that cause acid rain, communities elsewhere are likely to reap the benefits. Returns to the manufacturer or utility are generally indirect.

Instead of absolute rules, economists have long advocated financial incentives to reduce pollution. These include investment or research credits, tax relief, or fees or taxes imposed on manufacturers according to the amount and nature of the hazardous materials they produce. Such measures can help pay for treatment or disposal; more important, they give companies an incentive to change their manufacturing processes so as to reduce hazardous-waste production. Fees and taxes for pollution make environmental costs internal, so that they can be taken into account when making production decisions [see "Toward a Sustainable World," by William D. Ruckelshaus, page 166].

Pollution fees have come under fire from environmentalists and industrialists as "licenses to pollute" and as "distortions of the market." Both criticisms are potentially valid. Companies can treat fees that are too low as a cost of doing business and pass them on to customers; fees that are too high may force companies to reduce emissions of specific pollutants without regard to other environmental effects or to financial burdens.

Suitably set charges or incentives, however, can be an effective means for manufacturers to incorporate societal costs of pollution and waste into their cost accounting systems. As in the case of rising landfill fees for hazardous wastes, cost feedback for other pollutants could make it more attractive to solve problems at the source rather than to destroy or dispose of effluents once they have been created. Such fees enable manufacturers to share in the overall economic savings accruing from reduced levels of hazardous materials. Providing economic incentives would harness manufacturers' strong competitive drive to reduce costs. Indeed, manufacturers who ignore this imperative perish from the marketplace, a situation that would not change if the societal costs of pollution were allocated to them.

Economic incentives alone are not enough to make the industrial-ecosystem approach commonplace. Traditional manufacturing processes are designed to maximize the immediate benefits to the manufacturer and the consumer of individual products in the economy rather than to the economy as a whole. A holistic approach will be required if the proper balance between narrowly defined economic benefits and environmental needs is to be achieved. (Broadly defined, of course, economic and environmental goals are the same: bad places to live do not make for good markets.)

The concepts of industrial ecology and system optimization must be taught more widely. Current engineering and technological education either omit these concepts entirely or teach them in such a limited way that they have little impact on the approaches taken to the environmental problems associated with manufacturing. Changing the content of technological education, however, will not be enough. The concepts of industrial ecology must be recognized and valued by public officials, industry leaders and the media. They must be instilled into the social ethos and adopted by government as well as industry.

Government regulation of emissions at the local, national and international level will continue to play a strong role in the transition from traditional methods of manufacturing to an industrial-ecosystem approach. The transition to an ecosystem approach would be accelerated by the early adoption of economic incentives as part of the regulatory system.

To make regulation as effective as possible, officials must base their policies on sound technology and make allowance for technological change. Rules must be cast so as to encourage (or at least not discourage) the development of alternative processes and innovative methods for dealing with industrial by-products. Regulators must take advantage of industry's technological know-how so as to avoid counterproductive control measures. Such a wise regulatory framework will be almost impossible to construct unless government, industry and environmental groups abandon their current adversarial relationships and work together to solve their shared problems.

Even with an industrial-ecosystem approach in place, decisions about how best to allocate resources will not always be easy. Petroleum, for example, is not just a source of energy but also a raw material essential for manufacturing chemicals, plastics and other materials. Some analysts have argued that it should be used only as a raw material and not for energy. A similar argument could be made for using coal as a feedstock instead of as a fuel. On the output side, plastics can be burned for energy, recycled into new products or even reduced to their chemical constituents; it is not clear which choice is unequivocally sounder. Careful analysis of the consequences by "industrial ecologists" will be required to answer such questions.

The ideal ecosystem, in which the use of energy and materials is optimized, wastes and pollution are minimized and there is an economically viable role for every product of a manufacturing process, will not be attained soon. Current technology is often inadequate to the task, and some of the knowledge needed to define the problems fully is lacking. The difficulties in implementing an industrial ecosystem are daunting, especially given the complexities involved in harmonizing the desires of global industrial development with the needs of environmental safety.

Nonetheless, we are optimistic. The incentive for industry is clear: companies will be able to minimize costs and stay competitive while adhering to a rational economic approach that accounts for global costs and benefits. Equally clear are the benefits to society at large: people will have a chance to raise their visible standards of living without incurring hidden environmental penalties that degrade the quality of life in the long run. Remembering that people and their technologies are a part of the natural world may make it possible to imitate the best workings of biological ecosystems and construct artificial ones that can be sustained over the long term.

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Strategies for Sustainable Economic Development

World economies are depleting stocks of ecological capital faster than the stocks can be replenished. Yet economic growth can be reconciled with the integrity of the environment

by Jim MacNeill

Since 1900, the number of people inhabiting the earth has multiplied more than three times. The world economy has expanded 20 times. The consumption of fossil fuels has grown by a factor of 30, and industrial production has increased by a factor of 50; four fifths of that increase has occurred since 1950. This scale of development has produced a world with new realities, realities that have not yet been reflected in human behavior, economics, politics or institutions of government.

The gains in human welfare made possible by this development have been breathtaking, and the potential for future gains is even more awesome. But many of the processes of development that produced these gains are degrading the planet's environment and depleting its basic ecological capital at an alarming rate, leaving increasing numbers of people poor and vulnerable. A decade after the landmark Stockholm Conference on the Human Environment, which was held in 1972, governments began to recognize that environmental destruction at a pace and scale never experienced before was undermining prospects for economic development and threatening the very survival of the earth's inhabitants.

Is there any way to meet the needs and aspirations of the five billion people now living on the earth without compromising the ability of tomorrow's eight to 10 billion to meet theirs? That, I believe, was the tacit question the United Nations General Assembly sought to answer when in 1983 it called for the establishment of a special, independent commission. The World Commission on Environment and Development, as it was later named, included 23 commissioners from 22 different countries, regionally balanced, including all the major power groups and with a strong majority from developing countries. Gro Harlem Brundtland, who was then Leader of the Opposition in Norway and is now the country's Prime Minister, chaired the commission; Mansour Khalid, a former foreign minister of the Sudan, was vice-chairman. I became secretary general and member (ex officio) and was responsible for directing and managing what became a global enquiry into the state of the world.

The commission went through a broad process of analysis, learning and debate. We contracted papers, established panels and invited world figures to meet with us. We also did something that no other international commission has attempted: we organized open public hearings in every region of the world, from Jakarta to Moscow, São Paulo to Oslo, Harare to Ottawa. We met and took evidence from nearly a thousand experts, political leaders and concerned citizens on five continents. In the process, we learned firsthand of the contradictions between the reality of environment and development—totally interlocked in the daily lives of people, communities and industries—and the artifical distinctions drawn between the two by academic, economic and political institutions.

In October, 1987, after three years of intensive work, the commission presented its report, "Our Common Future," to the General Assembly. Its answer to the Assembly's tacit question was a heavily conditioned "yes." The needs and aspirations of today could be reconciled with those of tomorrow, providing there are fundamental changes in the way nations manage the world's economy. While this article draws heavily on the commission's report, it reflects my own interpretation, as well as events since 1987 and information that has become available in the past two years.

During its three years of work, the commission returned constantly to what I call the "sustainability question": Can growth on the scale projected over the next one to five decades be managed on a basis that is sustainable, both economically and ecologically?

The answer is not evident, since the obstacles to sustainability are mainly social, institutional and political. Economic and ecological sustainabil-

PEDESTRIANS AND HIGHWAY in Ivory Coast epitomize the blend of old and new that is typical of developing countries. Not all the hallmarks of economic growth are as obvious; many of the changes that can bring about sustainable development must take place at the institutional level and should include new policies for regulation, subsidization and the division of responsibility.

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Growth, Distribution and Poverty

How quickly can a developing country expect to eliminate poverty? The answer will vary from country to country, but much can be learned from a typical case. Consider, for example, a nation in which half the population lives below the poverty line and in which the distribution of household income is as follows: the top one fifth of households have 50 percent of the nation's total income, the next fifth have 20 percent, the next fifth have 14 percent, another fifth have 9 percent and the bottom fifth have 7 percent. This is a fair representation of the situation in many low-income developing countries.

Now consider two scenarios for distributing increases in income: one in which 25 percent of the incremental income of the richest one fifth is redistributed equally to rest of the population and one in which there is no redistribution. For those two cases, the number of years required to bring poverty down from 50 to 10 percent will be between 18 and 24 years if per capita income grows at 3 percent a year, to between 51 and 70 years if it grows at only 1 percent a year.

Thus, if per capita income grows at 1 percent a year, the time required to eliminate absolute poverty will stretch well into the next century, with or without redistributions of income. To assure that the world is well on its way to sustainable development during the first part of the next century, a minimum of 3 percent annual per capital income growth will be necessary, as well as greater equity in income distribution within developing countries.

ity are still dealt with as two separate questions in all governments and international organizations, where they are the responsibility of separate agencies such as ministries of finance and departments of environment. But economic and ecological systems are in fact interlocked. Global warming is a form of feedback from the earth's ecological system to the world's economic system. So are the ozone hole, acid rain in Europe and eastern North America, soil degradation in the prairies, deforestation and species loss in the Amazon, and many other environmental phenomena.

A number of communities and regions have already crossed critical thresholds. In the case of the ozone shield and climatic change, the world as a whole may be on the verge of doing the same. Even so, the most urgent imperative of the next few decades is further rapid growth. A fivefold to tenfold increase in economic activity would be required over the next 50 years in order to meet the needs and aspirations of a burgeoning world population, as well as to begin to reduce mass poverty. If such poverty is not reduced significantly and soon, there really is no way to stop the accelerating decline in the planet's stocks of basic capital: its forests, soils, species, fisheries, waters and atmosphere.

A transition to sustainable development during the first part of the next century would require a minimum of 3 percent annual growth in per capita income in developing countries and vigorous policies to achieve greater equity within developing countries and between the industrialized world and developing countries [*see illustration at left*]. Although they have only one quarter of the world's population, industrialized countries consume about 80 percent of the world's goods. With three quarters of the world's population, developing countries command less than one quarter of the world's wealth. And the imbalance is growing steadily worse.

A fivefold to tenfold increase in economic activity translates into a colossal new burden on the ecosphere. Imagine what it means in terms of planetary investment in housing, transport, agriculture and industry. If current forms of development were employed, energy use alone would have to increase by a factor of five just to bring developing countries, with their present populations, up to the levels of consumption now prevailing in the industrialized world. Similar factors can be cited for food, water, shelter and the other essentials of life.

An increase in economic activity by a factor of from five to 10 sounds enormous, but because of the magic of compound interest, it represents annual growth rates of only between 3.2 and 4.7 percent. What government of any country, developed or developing, does not aspire at least to that? Indeed, such rates are hardly enough to keep up with projected population growth in developing countries.

Given population trends, per capita income growth of 3 percent a year would require overall national income growth of around 5 percent a year in the developing countries of Asia, 5.5 percent in Latin America and 6 percent in Africa and West Asia. During the 1960's and 1970's, many countries in these regions experienced growth of this magnitude.

Yet during the 1980's, growth in most developing countries came close to a halt. They faced debilitating domestic problems that were not just economic but also ecological and political. And, in many cases, there are clear connections among them. Population growth continued to outstrip economic growth in most developing countries, and two thirds of them suffered falls in per capita income, some as great as 25 percent. Deteriorating terms of trade, such as unstable commodity prices and growing protectionism in developed market economies, and stagnating flows of aid combined to force attention to short-term crises rather than long-term development.

The major problem, particularly in

LONG-TERM DEBT AND FINANCIAL FLOWS IN DEVELOPING COUNTRIES FROM 1983 TO 1988 (BILLIONS OF DOLLARS)

	1982	1983	1984	1985	1986	1987	1988
Debt Disbursed and Outstanding	562.5	644.9	686.7	793.7	893.8	996.3	1020
Debt Service	98.7	92.6	101.8	112.2	116.5	124.9	131
Principal Payments	49.7	45.4	48.6	56.4	61.5	70.9	72
Interest Payments	48.9	47.3	53.2	55.8	54.9	54	59
Net Flows	67.2	51.8	43	32.9	26.2	15.8	16
Net Transfers	**18.2**	**4.6**	**-10.2**	**-22.9**	**-28.7**	**-38.1**	**-43**

DEBT AND FINANCIAL FLOWS reflect the worsening financial situation of developing countries. The cumulative debt of developing countries is growing, having now reached more than $1 trillion, and beginning in 1984 the traditional net flow of capital reversed itself: today $43 billion a year is transferred from developing countries to developed ones. The figures in this table were supplied by the World Bank.

Africa and Latin America, was and still is the debt [*see bottom illustration on opposite page*]. The cumulative debt of developing countries has now reached roughly $1 trillion; the interest payments amount to $60 billion a year. The traditional net flow of capital from the industrialized to the developing countries was reversed in 1982: more than $43 billion annually is now transferred in the other direction. And that is only what the World Bank counts.

In addition, today's trading patterns effect a massive transfer of the environmental costs of global gross national product to the poorer, resource-based economies of the developing countries. A study conducted for the commission estimated these costs at about $14 billion a year—more than one third of the total amount of development assistance flowing annually in the other direction. And that $14 billion is a low estimate, because it only includes costs related to environmental pollution and not those related to resource depletion.

Most developing countries, and large parts of many industrialized countries, have resource-based economies [*see illustration on next page*]. Their economic capital consists mainly of their stocks of environmental resources: their soils, forests, fisheries, species, waters and parks. Their long-term economic development depends on maintaining, if not increasing, these stocks and on enhancing their ability to support agriculture, forestry, fishing, mining and tourism for local use and export.

During the past two decades, the poorer countries of the developing world have experienced a massive depletion of this capital. Just 40 years ago Ethiopia, for example, had a 30 percent forest cover; 12 years ago it was down to 4 percent, and today it may be 1 percent. Until this century, India's forests covered more than half of the country. Today they are down to 14 percent and are going fast. In the tropics, 10 trees are being cut for every one planted; in Africa, the ratio is 29 to one. Forest areas nearly equal to the size of the United Kingdom are disappearing every year. Brazil alone may be losing more than eight million hectares annually.

An area larger than the African continent and inhabited by more than one billion people is now at risk from desertification, and every year deserts grow by six million hectares. The WorldWatch Institute estimates yearly topsoil loss at 25 billion tons—roughly the amount that covers Australia's wheatlands. Water use has doubled at least twice in this century and could double again over the next two decades. Yet in 80 developing countries having 40 percent of the world's population, water is already a serious constraint on development.

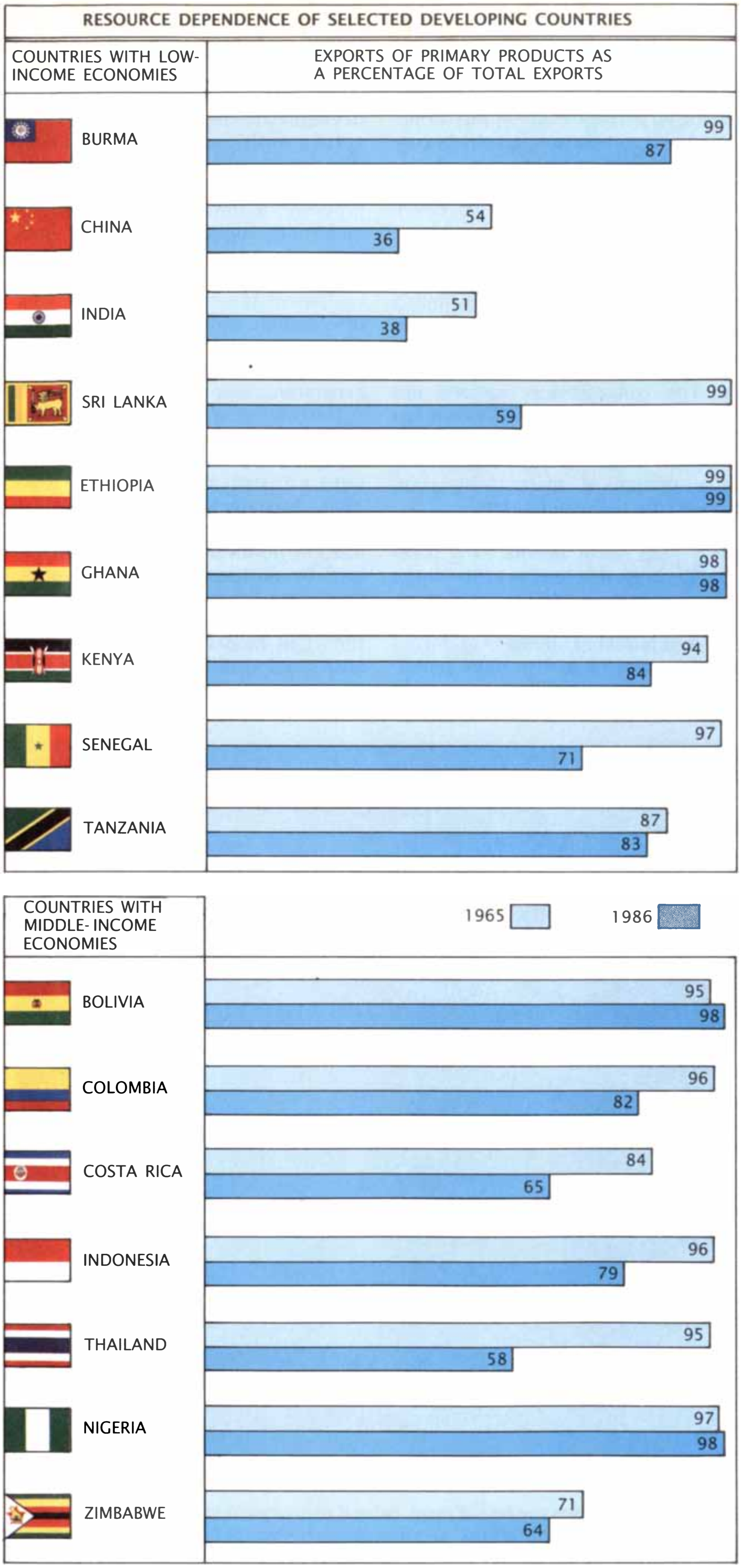
The basic economic capital of developing, and parts of some developed, countries—their environment and renewable resources—is being consumed faster than it can be restored or replaced. Some developing countries have depleted virtually all of their ecological capital and are on the brink of environmental bankruptcy. The consequences include not only increased hunger and death but also social instability and conflict, as resource depletion and degradation drives millions of environmental refugees across national borders.

With these factors as a backdrop, it is easy to envision the future as one of ever-increasing environmental degradation, poverty and hardship among ever-declining resources in an ever more polluted world. That could, of course, be the outcome of many current development policies and trends, but it is not inevitable.

The commission preferred instead to emphasize the possibility of a "new era of growth"—not the type of growth that dominates today but sustainable growth, growth based on forms and processes of development that do not undermine the integrity of the environment on which they depend. The commission defined sustainable development as consisting of new paths of economic and social progress that "meet the needs of the present without compromising the ability of future generations to meet their own needs."

The concept of sustainable development is not new. As William D. Ruckelshaus points out in his article, "Toward a Sustainable World" [*see page 166*], "sustainability is the original economy of the species." Modern civilization, however, has been characterized by unsustainable development, employing forms of decision making that systematically discount the future. Can modern economies be restructured against the criteria of sustainability? This is not an academic

GANGES RIVER suffers the fate of many natural resources: it has become polluted as a result of economic policies that sacrifice the environment for the sake of development. Prime Minister Rajiv Ghandi has launched a program to restore the Ganges.



question. It is probably a question of survival.

Such restructuring would require changes in societal values and goals, changes in incentives and changes in the dominant processes of decision making. A number of conditions will have to be met in order to make development sustainable. I have already mentioned a few: reviving growth, addressing equity and meeting essential needs and aspirations. Several others are equally important.

One is reducing rates of population growth. The issue is not simply one of numbers. A child born in a rich, industrialized country, where per capita consumption of energy and materials is high, places a much greater burden on the planet than a child born in a poor country. The industrialized world has found that development is the best means of population control. Accompanied by urbanization, rising income levels, improved education and the empowerment of women, development has even brought about negative rates of population growth in countries such as West Germany and Sweden.

Similar processes are at work in some developing countries. In addition, many developing countries are beginning to take strong direct measures to bolster social, cultural and economic motives for couples to have small families. Through family-planning programs, they are also providing to all those who want them the education, technological means and services required to control family size. These efforts require much greater research, financial and especially political support from industrialized countries than they have been getting.

Another essential condition for sustainable development is that a community's and a nation's basic stock of ecological capital should not decrease over time. A constant or increasing stock of natural capital is needed not only to meet the needs of present generations but also to ensure a minimum degree of fairness and equity for future generations.

RESOURCE DEPENDENCE of the economies of selected developing countries is apparent in the percentage of their total exports that are "primary products": fuels, minerals, metals and agricultural products. In many cases the percentage has fallen over the past two decades as resources have been depleted. The author took these figures from the World Bank 1988 World Development Report.

Can the world's expanding economies begin to live off the interest of the earth's stock of renewable resources, without encroaching on its capital? At the moment, world economies are moving backward at an accelerating pace, but the question remains open. If the annual draw on the earth's stock of renewable resources is to be brought within the capacity of natural systems to generate it, the industrialized world will need to increase by several orders of magnitude its support for strategies aimed at abating pollution, at protecting and preserving essential resource capital and at restoring and rehabilitating assets that have already been depleted or exhausted.

It is much more important, however, to reform the public policies that actively if unintentionally encourage deforestation, desertification, destruction of habitat and species, and decline of air and water quality. These policies and the often enormous budgets they command are much more powerful than any conceivable measures to protect environments or to restore and rehabilitate those already damaged. Unless and until such policies are reformed, nations will not be able to keep up, let alone catch up, with the increasing rates of depletion of their natural capital.

Take agriculture, for example. Agricultural subsidies provide one of the best examples of unwittingly destructive economic policies. Virtually the entire food cycle in North America, Western Europe and Japan attracts huge direct or indirect subsidies. These subsidies encourage farmers to occupy marginal lands and to clear forests and woodlands. They induce farmers to use excessive amounts of pesticides and fertilizers and to waste underground and surface waters in irrigation. Canadian farmers alone lose well over $1 billion a year from reduced production due to erosion stemming from practices underwritten by the Canadian taxpayer.

According to the Organization for Economic Cooperation and Development (OECD) and other sources, the farm-subsidy structure now costs Western governments in excess of $300 billion a year. What conservation programs can compete with that? These subsidies send farmers far more powerful signals than do the small grants usually provided for soil and water conservation.

The adverse effects of these subsidies extend beyond national borders. By generating vast surpluses at great economic and ecological cost, the subsidies create political pressures for still more subsidies: to increase exports, to donate food as nonemergency assistance to developing countries and to raise trade barriers against imported food products. All these measures hurt agricultural productivity.

During the next few decades, agricultural production must be shifted from developed to developing countries, where the growing demand is. Land and price reform is helping to encourage farming in some countries in Asia, Africa and Latin America, but those efforts could easily be undermined by the competitive dumping of Western surpluses. Governments of developing countries are seldom able to resist subsidized or nonemergency food aid. Apart from relieving an ever-present and pressing need, food shipments reduce the political pressures on governments to reform their own agricultural policies, many of which are equally perverse. It is their farmers who bear most of the brunt of the resulting inaction. Even the most efficient are unable to compete with surpluses dumped at subsidized prices.

These policies are not sustainable. Instead of providing nonemergency "aid" in the form of agricultural surpluses, developed countries should supply financial assistance in ways that encourage and support essential domestic reforms that in turn would increase production and reverse accelerating degradation of the resource base in developing countries. Agricultural and related trade policies in developed countries can also be redesigned and agricultural budgets, national and international, redeployed in ways that not only maintain farm income—which is vital for sustainable agriculture—but also encourage farmers to adopt practices that enhance, rather than deplete, the soil and water base. North American models for such policies go back to the 1930's, when the Soil Conservation Service in the U.S. and the Prairie Farm Rehabilitation Administration in Canada brought the Dust Bowl under control. The 1985 U.S. Food Security Act is a more recent example of the type of changes needed.

Government policies in developed and developing countries similarly abound in incentives to overcut the world's forests. The Brazilian taxpayer underwrites the destruction of the Amazon forests, just as the American taxpayer may be about to underwrite the clearing of the Tongass, the great rain forest of Alaska. Perverse incentives that encourage the overharvesting of temperate as well as tropical forests also mark world trade in forest products. If these policies and incentives remain in place, most of the world's remaining forests will probably be destroyed, with all that implies for food security, desertification, flooding and global warming.

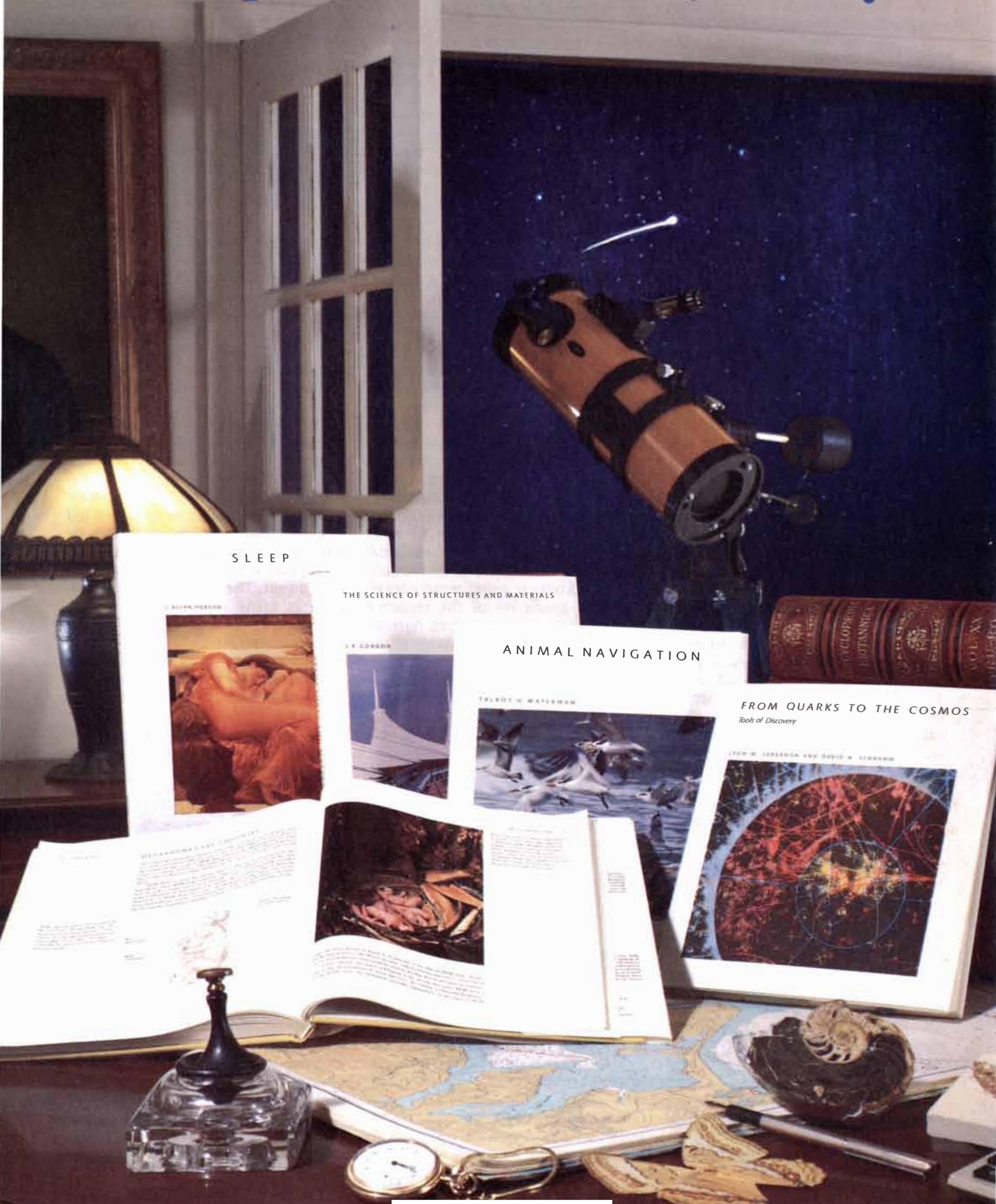
Yet another essential condition for sustainable development concerns the nature of production. If growth rates of up to 3 or 4 percent in the industrialized countries and up to 5 or 6 percent in developing countries are to be sustained, a significant and rapid reduction in the energy and raw-material content of every unit of production will be necessary.

During the past two decades, economic and technological changes have resulted in a leveling off of, or an absolute reduction in, the demand for energy and some basic materials per unit of product. The link between growth and its impact on the environment has also been severed. Nowhere has this been more marked than in energy. Following the first oil shock, between 1973 and 1983, the 24 OECD members, all industrialized nations, improved their energy productivity on average by 1.3 percent annually. Prior to the last oil shock, when prices fell sharply, some countries, including Japan and Sweden, had reached increases in productivity of more than 2 percent a year. The same trends are evident in many other areas, such as water, steel, aluminum, cement and certain chemicals.

The transition to recycled materials is an integral part of limiting the material content of growth, and this transition is already well under way in some countries. In the decade up to 1985, Austria, West Germany, Japan, Sweden and some other countries made significant gains in recycling aluminum, steel, paper and glass. The potential gains remain enormous, however, if only because most countries and industries have a long way to go just to catch up with the leaders. If Canada, for example, were to recycle its newspapers at the Japanese level, it could save 80 million trees a year—approximately 40,000 hectares of forest land.

When an industry reduces the energy and material content of its product, it saves on overall costs per unit of production and reduces environmental emissions and wastes as well. In fact, this is often a more effective way of reducing emissions than expensive "end of pipe" technologies that serve no other purpose. The environmental benefits of resource reduction and recycling extend back to the beginning

Begin a voyage of discovery that takes you from quarks to the cosmos, and beyond.



of the production cycle. They manifest themselves in decreased mining and mining wastes, decreased consumption and pollution of water, decreased air pollution, decreased deforestation and decreased erosion.

Increased energy productivity of from 1 to 2 percent a year could give a reprieve on global warming and bring about major reductions in acid rain. Nations could easily achieve such gains in energy productivity if they would pursue pricing and other policies to encourage efficiency with the same vigor they display in developing conventional sources of supply. And they could do it without sacrificing macroeconomic performance. In fact, the countries that have already made considerable progress in this direction are at the top of the international list of economic performers. Between 1973 and 1984, the energy and raw-material content of a unit of Japanese production dropped by 40 percent. Sweden, West Germany and some other countries did as well or better. Increasing the energy and resource efficiency of industrial plants or communities adds up to increasing the efficiency and competitiveness of the national economy.

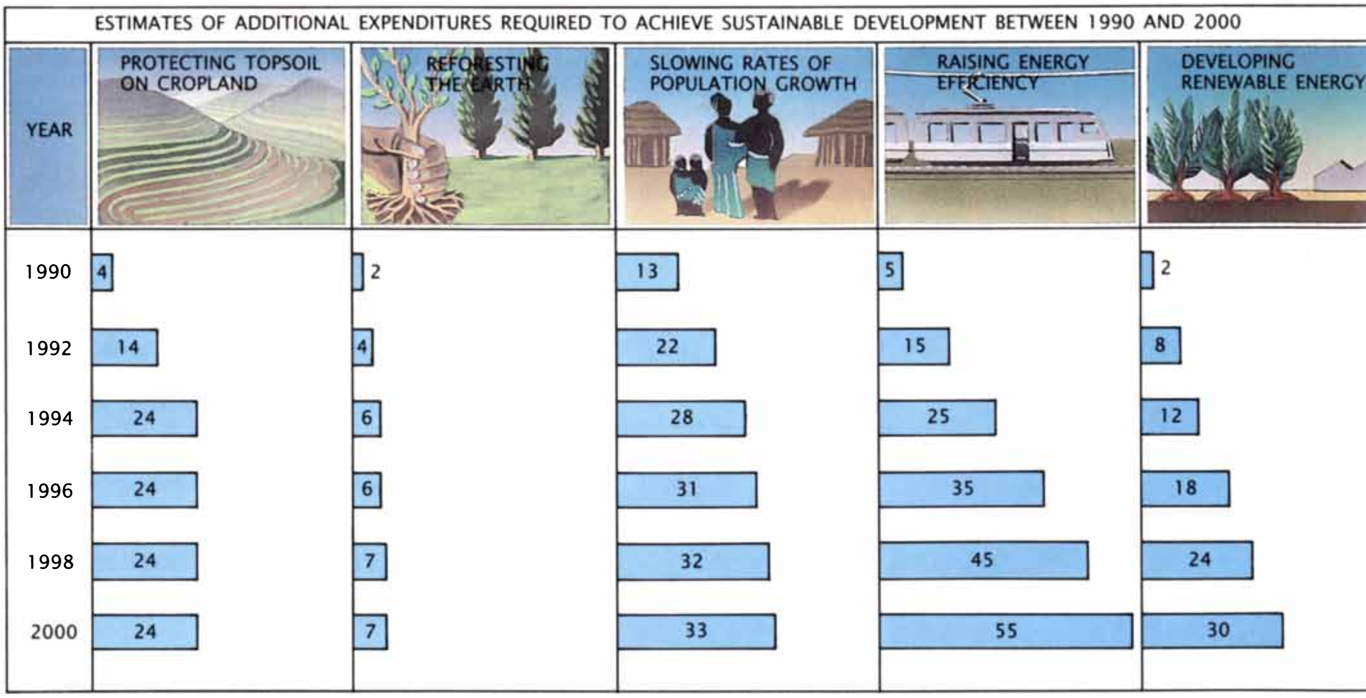
Developing countries too cannot ignore the implications of lagging behind in energy, resource and environmental productivity. There, as in industrialized countries, increased productivity is critical to sustaining growth, curbing pollution and maintaining competitiveness in the international marketplace. The developed market economies must continue to lead the way in energy and resource reduction and materials recycling, but developing countries must be quick to follow. Moreover, they must eschew older, more wasteful and inefficient technologies in favor of more advanced ones.

Some newly industrializing countries, such as Taiwan, South Korea and Brazil, are discovering this and are beginning to incorporate state-of-the-art technologies and processes in their industrial structures. Industrialized countries could deploy many policies, particularly policies of trade and aid, to actively promote the transfer to developing countries of advanced industrial processes and technologies that are more energy- and resource-efficient, less polluting and therefore more economically competitive.

Some of the changes required in governmental approaches to energy provide a flavor of those required more generally to reduce the resource and material content of growth. In order to make steady gains in energy efficiency, for example, governments will have to institute politically difficult changes in at least three areas. First, countries will have to consider "conservation pricing," that is, taxing energy during periods of low real prices to encourage increases in productivity. Second, stricter regulations should demand steady improvement in the efficiency of appliances and technologies, from electrical motors to air conditioners, and in building design, automobiles and transportation systems. Third, institutional innovation will be necessary to break utility-supply monopolies and to reorganize the energy sector so that energy services can be sold on a competitive, least-cost basis.

Demand reduction through energy efficiency would buy time to develop renewable energy sources, including substitutes for fuelwood in developing countries. Solar electricity, wind power, minihydroturbines, the recycling of waste biomass and the deployment of biomass digestors for making gas and liquid fuel are a few of the many renewable technologies that have enormous potential. Realizing that potential, however, will require a significant shift in research and development from conventional energy sources to new ones.

Once again, current subsidy structures often promote the opposite of what is needed for a sustainable energy future. They ignore the costs of depleting resources and of sullying air, land and water, they favor waste and inefficiency and they underwrite traditional sources of power—coal, oil



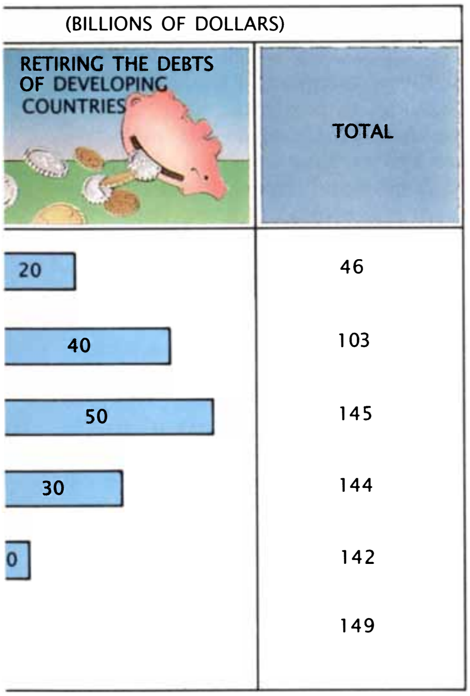
COST OF ACHIEVING SUSTAINABLE DEVELOPMENT in 10 years, estimated by the WorldWatch Institute, includes expenditures to reduce rates of population growth and to restore and maintain global resources. The figures should be weighed against

and nuclear—rather than renewables. In doing so, they impose enormous burdens on already tight budgets and on scarce reserves of foreign currency.

Governments should examine hidden and overt subsidies and reform those that penalize conservation and end-use efficiency. They should also excise policies that retard the development of new and renewable energy resources, particularly those that serve as substitutes for fuelwood. Given the proper incentives, industry itself could play a more effective role.

The most important condition for sustainable development is that environment and economics be merged in decision making. Our economic and ecological systems have become totally interlocked in the real world, but they remain almost totally divorced in our institutions.

During the 1960's and 1970's, governments in more than 100 countries, developed and developing alike, established special environmental-protection and resource-management agencies. But these agencies were hamstrung by limited mandates, limited budgets and little or no political clout. Meanwhile, governments failed to make their powerful central economic and sectoral agencies responsible for the environmental implications of their own policies and expenditures. The resulting balance of forces was grossly unequal. Environmental agencies had about as much chance as a small-town runner, with no training and no financial backing, trying to win a race against Carl Lewis. Despite good intentions, great effort and several leaps forward, they fell further and further behind.



the world's military expenditures, which alone total close to $1 trillion a year.

Environmental agencies must be given more capacity and more power to cope with the effects of unsustainable development policies. More important, governments must make their central economic, trade and sectoral agencies directly responsible and accountable for formulating policies and budgets to encourage development that is sustainable. Only then will the ecological dimensions of policy be considered at the same time as the economic, trade, energy, agricultural and other dimensions—on the same agendas and in the same national and international institutions.

One area in which the merging of environmental considerations with economic decision making could have an impact is market incentives. The market is the most powerful instrument available for driving development, and whether or not it encourages and supports sustainable or unsustainable forms of development is largely a function of policy.

As I have already mentioned, government intervention often distorts the market in ways that preordain unsustainable development. Tax and fiscal incentives, pricing and marketing policies and exchange-rate and trade-protection policies all influence the environment and the resource content of the growth that takes place. Yet the people responsible for setting these policies seldom consider their impact on the environment or on stocks of resource capital. When policymakers do take these things into account, they often assume implicitly that the resources are inexhaustible or that substitutes will be found before they become exhausted or that the environment "should" subsidize the market. The same is true of certain sectoral policies, such as the misguided food and energy subsidies that I have already cited.

It is surprising how few government and corporate leaders are aware of the ecologically and economically perverse nature of the incentive systems created by these policies and the often enormous budgets they command. Even the environmental movement is only dimly aware of it. Environmentalists have historically focused on the effects of economic development on health, property and ecosystems. Rarely have they addressed the policies behind such development.

A nation's annual budget establishes the framework of economic and fiscal incentives and disincentives within which corporate leaders, businessmen, farmers and consumers make decisions. It is perhaps the most important environmental policy statement that any government makes in any year, because in their aggregate these decisions serve to enhance or degrade the nation's environment and to increase or reduce its stocks of ecological capital.

A budget that levied taxes on energy, resources and pollution, matched by an equivalent reduction in labor, corporate and value-added taxes, could have a significant effect on consumption patterns and on the cost structure of industry without adding to the overall tax burden on industry and society. Reform of tax systems along such lines seems essential to encourage a transition to sustainable development.

With increased awareness, the politics of changing incentive systems should not be insurmountable. Some leaders of the most advanced industries have welcomed analyses linking economic incentives and environmental integrity. Provided their income is not jeopardized, farmers have everything to gain from incentive systems that encourage practices that maintain or enhance their soil, wood, water and other farm capital. For consumers, many such shifts in incentives would be neutral, and the impact on employment could even be positive.

Reforming tax and incentive systems, though crucial, will not be sufficient. The market is limited in several ways, the most important one being that it cannot take into account the external environmental costs associated with producing, consuming and disposing of goods and services. The market treats the resources of the atmosphere, the oceans and the other commons as free goods. It "externalizes," or transfers to the broader community, the costs of air, water, land and noise pollution and of resource depletion. The broader community shoulders the costs in the form of damages to health, property and ecosystems.

Internalizing these costs again requires government intervention. One attempt was the so-called Polluter Pays Principle (PPP), introduced by member countries of the OECD in 1972. The PPP requires that industries pay the full costs of protecting the environment from the pollution re-

CAMP OF DROUGHT REFUGEES in Upper Volta depicts the plight of millions of people driven from their homes by environmental crises. Such mass movements of populations can create international tension as refugees cross national borders.

sulting from their activities. It is important mainly because it has the potential to cause the environmental costs of development to be reflected in the prices that consumers pay for goods, thereby biasing consumer choice in favor of those goods whose production, use and disposal have the least impact on the environment. Unfortunately, governments have been notoriously slow to apply the principle, perhaps because it affects consumer prices. Another reason, no doubt, has been pressure from industry. Although as a rule industry is a strong advocate of the market, in this instance it has usually marshalled its forces against it.

Internalizing environmental costs in prices is one way of trying to represent the real costs of development in economic decision making. Integrating resource accounts in national economic accounting systems is another. At the moment, these systems are concerned mainly with the flow of economic activity. Changes in stocks of ecological capital are largely ignored. Integrating the two would enable governments to determine whether reported 3, 5 or 7 percent increases in the gross domestic product are real or whether they reflect instead corresponding or even greater declines in stocks of soils, forests, fisheries, waters, parks and historic places.

With this information, finance ministries and treasuries could get not only a more accurate picture of economic performance but also some idea of the way economic policies are affecting ecological systems. Basic work on resource accounting and on mixed-accounting frameworks has been done in France, Norway, Canada, the U.S. and some other countries. The OECD and a number of independent institutes are currently involved in advancing this work, and some institutes in developing countries have expressed a keen interest in it.

With the gradual integration of the environment in economic decision making, budgets for energy, agriculture and other sectors should begin to include funds to cover the environmental costs of their respective activities. Eventually, the burden of financing sustainable development should be assumed by such budgets. In the interim, sustainable development will demand large sources of new financing.

Developing countries, in particular, will need a significant increase in financial support. In 1988, the WorldWatch Institute attempted some rough estimates of the additional expenditures that would be required to meet certain targets it deemed essential for global sustainable development by the year 2000. The targets included slowing population growth, protecting topsoil on cropland, reforesting the earth, raising energy efficiency, developing renewable energy and retiring the debt of developing countries [*see illustration on preceding two pages*].

The institute estimated that those targets could be achieved with annual expenditures approaching $46 billion by 1990 and increasing to $145 billion in 1994 and $150 billion in 2000. A huge political effort would be necessary to raise expenditures to these orders of magnitude. The size of the effort can be judged, perhaps, by the amount of money governments have given to the United Nations Environment Program's Environment Fund since it was established at the 1972 Stockholm Conference: just $30 million a year and often less. At this year's meeting of the UNEP Governing Council, governments agreed only to consider increasing the fund to $100 million. They have a long way to go.

The debt remains the most urgent problem facing developing countries, particularly those in Africa and Latin America. It must be resolved before those countries can be expected to turn their attention to the pressing agenda of poverty and interlocked economic and ecological decline. At last year's meeting in Berlin of the World Bank and the International Monetary Fund (IMF), more countries than ever before seemed to be on the verge of recognizing that the debt situation is untenable. Although several plans for debt relief (most recently the U.S. Brady Plan) have been advanced, they all share two dubious characteristics: the types of measures normally attached as a condition for additional loans and the absence of any programs to sustain, let alone build up, the environmental resource capital of developing countries.

The strict conditionality imposed by the World Bank and the IMF has often appeared to take little account of the social and other consequences of the economic and fiscal measures required. In particular, structural-adjustment programs, as such measures are known, have taken no account of their potential impact on the environment and ecological resources of the country concerned. Measures to reduce budgetary deficits often have a disproportionate impact on such resources. With little else to fall back on, resource-based economies have to draw down their ecological capital even faster than they would otherwise in order to earn the foreign currency required for debt repayment. Programs to restore the productive capacity of depleted environments and to preserve habitats, gene pools and tourist areas from destruction are cut back or are simply not implemented. Policies requiring industry and local government to introduce pollution-control measures and programs aimed at providing clean water, sewerage and sanitary facilities are similarly dropped or not implemented.

A recent study by the World Bank confirms that structural-adjustment programs are not neutral in their implications for environmental resources. More significantly, the study argues that it is possible to design such programs so that they have positive, rather than negative, consequences for the nation's environment. Until that happens, the environmental consequences of structural adjustment will continue to be a matter of concern. A number of countries have instructed their representatives on the boards of the IMF and the World Bank to require that the environmental implications of their programs be integrated into background studies for all projects and also into the negotiations for program implementation.

Marshalling sufficient investment for sustainable development will require new initiatives. The World Resources Institute is currently conducting a study of the feasibility of a special international conservation banking program or facility linked to the World Bank. Such a facility could provide loans and facilitate joint financing arrangements for the protection and sustainable development of critical habitats and ecosystems, including those of international significance. There are also several possible international sources of revenue that could be tapped to finance action in support of sustainable development. For example, the use of the international commons or trade in certain commodities could be taxed. This may seem politically unrealistic at present, but global trends have been known to change political realities. In fact, something like that may already be happening.

In June, 1988, at the world conference on the atmosphere held in Toronto and hosted by the Canadian government, the conference participants called on governments to establish a World Atmosphere Fund that would be financed, in part, by a "climate protection" tax. Revenues would come from a levy on the fossil-fuel consumption of industrialized countries, and the proceeds would go to developing countries to help them to limit and adapt to the consequences of global warming and sea-level rise. Others have proposed that the tax should be related to the carbon content of fuels. Most recently, the Norwegian government proposed that, as a starting point, industrialized countries allocate .1 percent of their gross national product to such a fund. The recent Netherlands budget included provision for an annual contribution of 250 million guilders for a global-climate fund, and the government is currently assessing various options for financing and managing such a fund in preparation for an international conference in the Hague this fall.

Military expenditures also represent an enormous pool of capital, human skills and resources. Nations spend nearly $1 trillion a year on military security—more than $2.7 billion a day. Developing countries have increased their arms budgets fivefold in the past 20 years. Some are spending more on their military than they are on education, health, welfare and the environment combined.

A large proportion of these expenditures could well be shifted to more productive purposes. That would require a greater awareness of the growing scale of environmental threats to national and regional security, an awareness that some major political leaders are beginning to voice. It would also require a new and broader concept of security, a concept that encompasses environmental as well as economic and political security. With a broader approach, nations would begin to find many instances in which their security could be improved more effectively through expenditures to protect, preserve and restore basic environmental capital assets than through expenditures for arms.

The possibility of nuclear war undoubtedly represents the gravest potential danger to environmental resources, life-support systems and survival. Yet the geopolitical implications of interlocked economic-ecological change are enormous. In parts of the Middle East, Africa, Latin America and Asia, invading deserts, competition for water and the movements of ecological refugees are already significant sources of political unrest and international tension. These situations will only get worse. Climatic change alone will heighten tension as major shifts occur in the national boundaries defined by bodies of water, in centers of urban and agricultural production and in the numbers of ecological refugees.

Threats to the peace and security of nations and regions from environmental breakdown are potentially greater than any foreseeable military threat from conventional arms. If these threats stemmed from potential military action by unfriendly powers, any nation or group of nations would respond with a massive mobilization of diplomatic, military and other resources. Yet, faced with a security threat in the form of environmental destruction, nations and the world community seem to be incapable of mounting an effective response.

Countries must begin to treat the integrity of the environment and the sustainability of development as a foreign-policy issue of paramount importance. Measures to reduce debt and to increase the net flow of resources to developing countries should be backed up with coherent policies on aid, on agricultural and other forms of trade, and on the import or export of hazardous chemicals, wastes and technology. A "foreign policy for environment and development" could help to induce greater coherence in these areas. It could also serve to improve overall effectiveness, coordination and cooperation with regard to rapidly evolving developments concerning the management of the commons—the oceans, the atmosphere, Antarctica and outer space.

There is a rapidly growing potential for conflict over global warming and sea-level rise, the spread of deserts, the allocation of shared water and other resources and other "environmental" issues. Yet, properly approached within the context of promoting sustainable economic development, these issues could force a new spirit of international cooperation as well as fresh thinking about multilateral approaches to other global issues.

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Toward a Sustainable World

What policies can lead to the changes in behavior—of individuals, industries and governments—that will allow development and growth to take place within the limits set by ecological imperatives?

by William D. Ruckelshaus

The difficulty of converting scientific findings into political action is a function of the uncertainty of the science and the pain generated by the action. Given the current uncertainties surrounding just one aspect of the global environmental crisis—the predicted rise in greenhouse gases—and the enormous technological and social effort that will be required to control that rise, it is fair to say that responding successfully to the multifaceted crisis will be a difficult political enterprise. It means trying to get a substantial proportion of the world's people to change their behavior in order to (possibly) avert threats that will otherwise (probably) affect a world most of them will not be alive to see.

The models that predict climatic change, for example, are subject to varying interpretations as to the timing, distribution and severity of the changes in store. Also, whereas models may convince scientists, who understand their assumptions and limitations, as a rule projections make poor politics. It is hard for people—hard even for the groups of people who constitute governments—to change in response to dangers that may not arise for a long time or that just might not happen at all.

How, then, can we make change happen? The previous articles in this single-topic issue have documented the reality of the global ecological crisis and have pointed to some specific ameliorative measures. This article is about how to shape the policies, launch the programs and harness the resources that will lead to the adoption of such measures—and that will actually convince ordinary people throughout the world to start doing things differently.

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Insurance is the way people ordinarily deal with potentially serious contingencies, and it is appropriate here as well. People consider it prudent to pay insurance premiums so that if catastrophe strikes, they or their survivors will be better off than if there had been no insurance. The analogy is clear. Current resources foregone or spent to prevent the buildup of greenhouse gases are a kind of premium. Moreover, as long as we are going to pay premiums, we might as well pay them in ways that will yield dividends in the form of greater efficiency, improved human health or more widely distributed prosperity. If we turn out to be wrong on greenhouse warming or ozone depletion, we still retain the dividend benefits. In any case, no one complains to the insurance company when disaster does not strike.

That is the argument for some immediate, modest actions. We can hope that if shortages or problems arise, there will turn out to be a technological fix or set of fixes, or that technology and the normal workings of the market will combine to solve the problem by product substitution. Already, for example, new refrigerants that do not have the atmospheric effects of the chlorofluorocarbons are being introduced; perhaps a cheap and nonpolluting source of energy will be discovered.

It is comforting to imagine that we might arrive at a more secure tomorrow with little strain, to suppose with Dickens's Mr. Micawber that something will turn up. Imagining is harmless, but counting on such a rescue is not. We need to face up to the fact that something enormous may be happening to our world. Our species may be pushing up against some immovable

COEXISTENCE of nature and human activity is celebrated in *Progress*, painted by Asher B. Durand in 1853. It is an im-

limits on the combustion of fossil fuels and damage to ecosystems. We must at least consider the possibility that, besides those modest adjustments for the sake of prudence, we may have to prepare for far more dramatic changes, changes that will begin to shape a sustainable world economy and society.

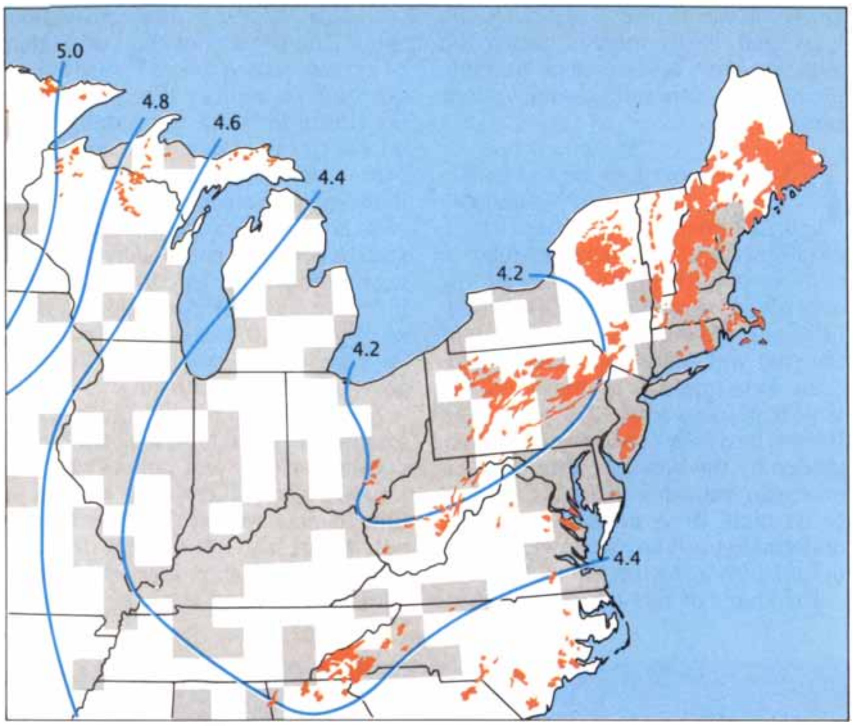
Sustainability is the nascent doctrine that economic growth and development must take place, and be maintained over time, within the limits set by ecology in the broadest sense—by the interrelations of human beings and their works, the biosphere and the physical and chemical laws that govern it. The doctrine of sustainability holds too that the spread of a reasonable level of prosperity and security to the less developed nations is essential to protecting ecological balance and hence essential to the continued prosperity of the wealthy nations. It follows that environmental protection and economic development are complementary rather than antagonistic processes.

Can we move nations and people in the direction of sustainability? Such a move would be a modification of society comparable in scale to only two other changes: the agricultural revolution of the late Neolithic and the Industrial Revolution of the past two centuries. Those revolutions were gradual, spontaneous and largely unconscious. This one will have to be a fully conscious operation, guided by the best foresight that science can provide—foresight pushed to its limit. If we actually do it, the undertaking will be absolutely unique in humanity's stay on the earth.

The shape of this undertaking cannot be clearly seen from where we now stand. The conventional image is that of a crossroads: a forced choice of one direction or another that determines the future for some appreciable period. But this does not at all capture the complexity of the current situation. A more appropriate image would be that of a canoeist shooting the rapids: survival depends on continually responding to information by correct steering. In this case the information is supplied by science and economic events; the steering is the work of policy, both governmental and private.

Taking control of the future therefore means tightening the connection between science and policy. We need to understand where the rocks are in time to steer around them. Yet we will not devote the appropriate level of resources to science or accept the policies mandated by science unless we

age in which a "balanced reconciliation of nature and culture seems to have been achieved," according to the art historian Barbara Novak. Durand's 19th-century view of industrialization might well serve as a metaphor for today's vision of sustainable development. The painting is in the Warner Collection of the Gulf States Paper Corporation, in Tuscaloosa, Ala.



ACID RAIN is a political problem because industrial emissions responsible for acidic precipitation cross political borders. Regions where the density of sulfur dioxide emissions was more than 1.5 tons per square kilometer in 1980 are shown in gray; states with the largest emissions are in the Midwest and along the Ohio River. The contours show the *p*H of precipitation; low *p*H means high acidity. Within the low-*p*H regions, lakes and streams are at highest risk of acidification where the water's alkalinity is lowest (*orange*)—largely in the Adirondacks and New England. Sulfur dioxide data are from the National Acid Precipitation Assessment Program, alkalinity data from James M. Omernick of the Environmental Protection Agency and his colleagues.

do something else. We have to understand that we are all in the same canoe and that steering toward sustainability is necessary.

Sustainability was the original economy of our species. Preindustrial peoples lived sustainably because they had to; if they did not, if they expanded their populations beyond the available resource base, then sooner or later they starved or had to migrate. The sustainability of their way of life was maintained by a particular consciousness regarding nature: the people were spiritually connected to the animals and plants on which they subsisted; they were part of the landscape, or of nature, not set apart as masters.

The era of this "original sustainability" eventually came to an end. The development of cities and the maintenance of urban populations called for intensive agriculture yielding a surplus. As a population grows, it requires an expansion of production, either by conquest or colonization or improved technique. A different consciousness, also embodied in a structure of myth, sustains this mode of life. The earth and its creatures are considered the property of humankind, a gift from the supernatural. Man stands outside of nature, which is a passive playing field that he dominates, controls and manipulates. Eventually, with industrialization, even the past is colonized: the forests of the Carboniferous are mined to support ever-expanding populations. Advanced technology gives impetus to the basic assumption that there is essentially no limit to humanity's power over nature.

This consciousness, this condition of "transitional unsustainability," is dominant today. It has two forms. In the underdeveloped, industrializing world, it is represented by the drive to develop at any environmental cost. It includes the wholesale destruction of forests, the replacement of sustainable agriculture by cash crops, the attendant exploitation of vulnerable lands by people such cash cropping forces off good land and the creation of industrial centers that are also centers of environmental pollution.

In the industrialized world, unsustainable development has generated wealth and relative comfort for about one fifth of humankind, and among the populations of the industrialized nations the consciousness supporting the unsustainable economy is nearly universal. With a few important exceptions, the environmental-protection movement in those nations, despite its major achievements in passing legislation and mandating pollution-control measures, has not had a substantial effect on the lives of most people. Environmentalism has been ameliorative and corrective—not a restructuring force. It is encompassed within the consciousness of unsustainability.

Although we cannot return to the sustainable economy of our distant ancestors, in principle there is no reason why we cannot create a sustainability consciousness suitable to the modern era. Such a consciousness would include the following beliefs:

1. *The human species is part of nature. Its existence depends on its ability to draw sustenance from a finite natural world; its continuance depends on its ability to abstain from destroying the natural systems that regenerate this world.* This seems to be the major lesson of the current environmental situation as well as being a direct corollary of the second law of thermodynamics.

2. *Economic activity must account for the environmental costs of production.* Environmental regulation has made a start here, albeit a small one. The market has not even begun to be mobilized to preserve the environment; as a consequence an increasing amount of the "wealth" we create is in a sense stolen from our descendants.

3. *The maintenance of a livable global environment depends on the sustainable development of the entire human family.* If 80 percent of the members of our species are poor, we can not hope to live in a world at peace; if the poor nations attempt to improve their lot by the methods we rich have pioneered, the result will eventually be world ecological damage.

This consciousness will not be attained simply because the arguments for change are good or because the alternatives are unpleasant. Nor will exhortation suffice. The central lesson of realistic policy-making is that most individuals and organizations change when it is in their interest to change, either because they derive some benefit from changing or because they incur sanctions when they do not—and the shorter the time between change (or failure to change) and benefit (or sanction), the better. This is not mere cynicism. Although people will struggle and suffer for long periods to achieve a goal, it is not reasonable to expect people or organizations to work against their immediate interests for very long—particularly in a democratic system, where what they perceive to be their interests are so important in guiding the government.

To change interests, three things are required. First, a clear set of values consistent with the consciousness of sustainability must be articulated by leaders in both the public and the private sector. Next, motivations need to be established that will support the values. Finally, institutions must be developed that will effectively apply the motivations. The first is relatively easy, the second much harder and the third perhaps hardest of all.

Values similar to those I described above have indeed been articulated by political leaders throughout the world. In the past year the president and the secretary of state of the U.S., the leader of the Soviet Union, the prime minister of Great Britain and the presidents of France and Brazil have all made major environmental statements. In July the leaders of the Group of Seven major industrialized nations called for "the early adoption, worldwide, of policies based on sustainable development." Most industrialized nations have a structure of national environmental law that to at least some extent reflects such values, and there is even a small set of international conventions that begin to do the same thing.

Mere acceptance of a changed value structure, although it is a prerequisite, does not generate the required change in consciousness, nor does it change the environment. Although diplomats and lawyers may argue passionately over the form of words, talk is not action. In the U.S., which has a set of environmental statutes second to none in their stringency, and where for the past 15 years poll after poll has recorded the American people's desire for increased environmental protection, the majority of the population participates in the industrialized world's most wasteful and most polluting style of life. The values are there; the appropriate motivations and institutions are patently inadequate or nonexistent.

The difficulties of moving from stated values to actual motivations and institutions stem from basic characteristics of the major industrialized nations—the nations that must, because of their economic strength, preeminence as polluters and dominant share of the world's resources, take the lead in any changing of the present order. These nations are market-system democracies. The difficulties, ironically, are inherent in the free-market economic system on the one hand and in democracy on the other.

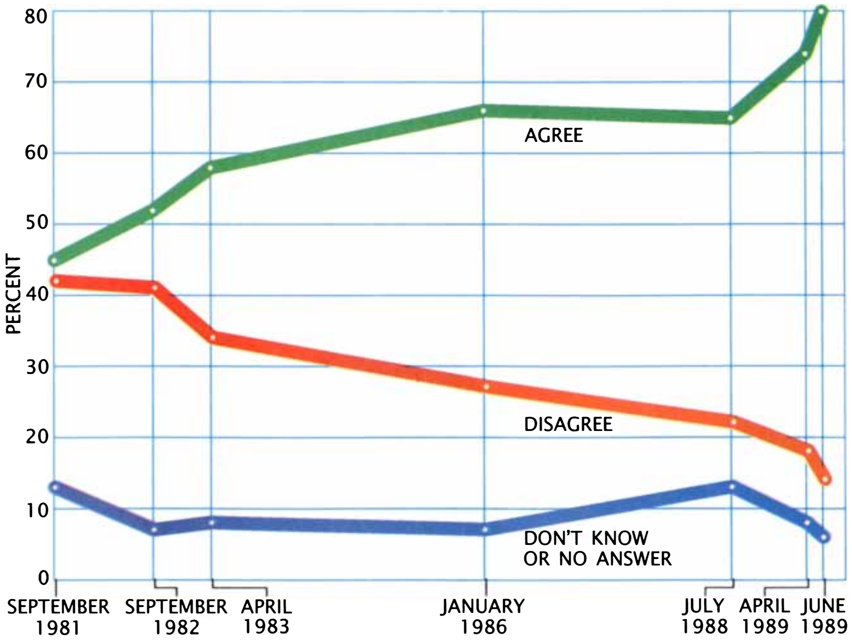
The economic problem is the familiar one of externalities: the environmental cost of producing a good or service is not accounted for in the price paid for it. As the economist Kenneth E. Boulding has put it: "All of nature's systems are closed loops, while economic activities are linear and assume inexhaustible resources and 'sinks' in which to throw away our refuse." In willful ignorance, and in violation of the core principle of capitalism, we often refuse to treat environmental resources as capital. We spend them as income and are as befuddled as any profligate heir when our checks start to bounce.

Such "commons" as the atmosphere, the seas, fisheries and goods in public ownership are particularly vulnerable to being overspent in this way, treated as either inexhaustible resources or bottomless sinks. The reason is that the incremental benefit to each user accrues exclusively to that user, and in the short term it is a gain. The environmental degradation is spread out among all users and is apparent only in the long term, when the resource shows signs of severe stress or collapse. Some years ago the biologist Garrett Hardin called this the tragedy of the commons.

The way to avoid the tragedy of the commons—to make people pay the full cost of a resource use—is to close the loops in economic systems. The general failure to do this in the industrialized world is related to the second problem, the problem of action in a democracy. Modifying the market to reflect environmental costs is necessarily a function of government. Those adversely affected by such modifications, although they may be a tiny minority of the population, often have disproportionate influence on public policy. In general, the much injured minority proves to be a more formidable lobbyist than the slightly benefited majority.

The Clean Air Act of 1970 in the U.S., arguably the most expensive and far-reaching environmental legislation in the world, is a case in point. Parts of the act were designed not so much to cleanse the air as to protect the jobs of coal miners in high-sulfur coal regions. Utilities and other high-volume consumers were not allowed to substitute low-sulfur coal to meet regulatory requirements but instead had to install scrubbing devices.

Although the act expired seven



ENVIRONMENTAL VALUES have drawn increasing support in the U.S. In *New York Times*/CBS News polls taken since 1981, respondents were asked to react to this statement: "Protecting the environment is so important that requirements and standards cannot be too high, and continuing environmental improvements must be made regardless of cost." The two latest polls were taken after the *Exxon Valdez* spill.

years ago, Congress found it extraordinarily difficult to develop a revision, largely because of another set of contrary interests involving acid rain. The generalized national interest in reducing the environmental damage attributable to this long-range pollution had to overcome the resistance of both high-sulfur-coal mining interests and the Midwestern utilities that would incur major expenses if they were forced to control sulfur emissions. The problem of conflicting interests is exacerbated by the distance between major sources of acid rain and the regions that suffer the most damage. It is accentuated when the pollution crosses state and national boundaries: elected representatives are less likely to countenance short-term adverse effects on their constituents when the immediate beneficiaries are nonconstituents.

The question, then, is whether the industrial democracies will be able to overcome political constraints on bending the market system toward long-term sustainability. History provides some cause for optimism: a number of contingencies have led nations to accept short-term burdens in order to meet a long-term goal.

War is the obvious example. Things considered politically or economically impossible can be accomplished in a remarkably short time, given the belief that national survival is at stake. World War II mobilized the U.S. population, changed work patterns, manipulated and controlled the price and supply of goods and reorganized the nation's industrial plant.

Another example is the Marshall Plan for reconstructing Europe after World War II. In 1947 the U.S. spent nearly 3 percent of its gross domestic product on this huge set of projects. Although the impetus for the plan came from fear that Soviet influence would expand into Western Europe, the plan did establish a precedent for massive investment in increasing the prosperity of foreign nations.

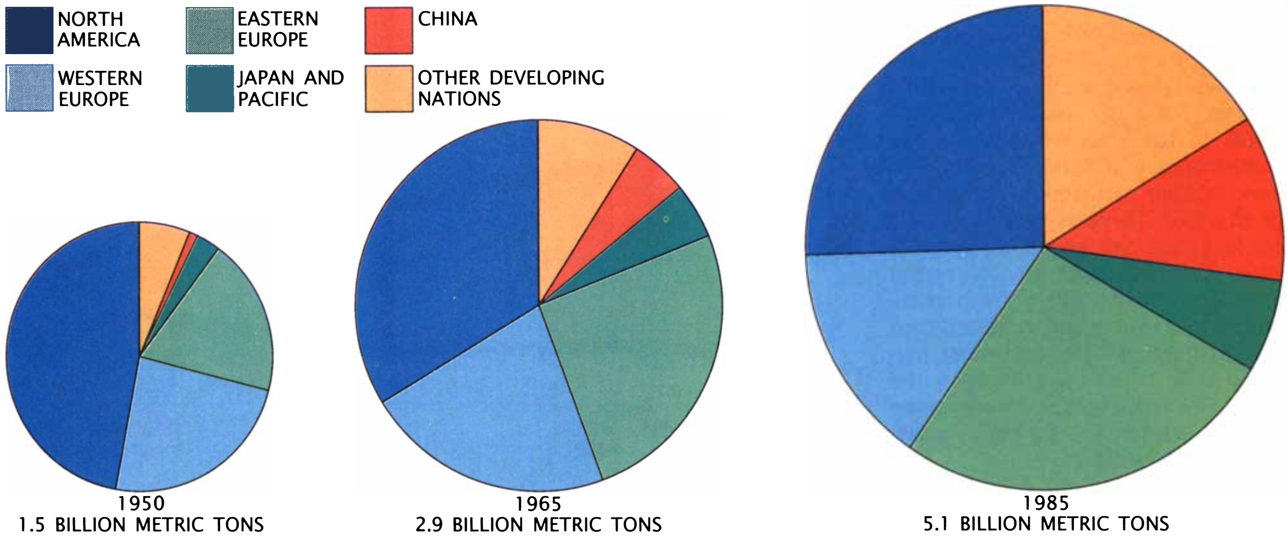
There are other examples. Feudalism was abandoned in Japan, as was slavery in the U.S., in the 19th century; this century has seen the retreat of imperialism and the creation of the European Economic Community. In each case important interests gave way to new national goals.

If it is possible to change, how do we begin to motivate change? Clearly, government policy must lead the way, since market prices of commodities typically do not reflect the environmental costs of extracting and replacing them, nor do the prices of energy from fossil fuels reflect the risks of climatic change. Pricing policy is the most direct means of ensuring that the full environmental cost of goods and services is accounted for. When government owns a resource, or supplies it directly, the price charged can be made to reflect the true cost of the product. The market will adjust to this as it does to true scarcity: by product substitution and conservation.

Environmental regulation should be refocused to mobilize rather than suppress the ingenuity and creativity of industry. For example, additional gains in pollution control should be sought not simply by increasing the stringency or technical specificity of command-and-control regulation but also by implementing incentive-based systems. Such systems magnify public-sector decisions by tens of thousands of individual and corporate decisions. To be sure, incentive systems are not a panacea. For some environmental problems, such as the use of unacceptably dangerous chemicals, definitive regulatory measures will always be required. Effective policies will include a mixture of incentive-based and regulatory approaches.

Yet market-based approaches will be a necessary part of any attempt to reduce the greenhouse effect. Here the most attractive options involve the encouragement of energy efficiency. Improving efficiency meets the double-benefit standard of insurance: it is good in itself, and it combats global warming by reducing carbon dioxide emissions. If the world were to improve energy efficiency by 2 percent a year, the global average temperature could be kept within one degree Celsius of present levels. Many industrialized nations have maintained a rate of improvement close to that over the past 15 years.

Promoting energy efficiency is also relatively painless. The U.S. reduced the energy intensity of its domestic product by 23 percent between 1973 and 1985 without much notice. Substantial improvement in efficiency is available even with existing technol-



DEVELOPED NATIONS are responsible for far more industrial emission of carbon dioxide, a major greenhouse gas, than are the developing nations. Total emissions have increased sharply since 1950. Data are from the World Resources Institute.

No More Wishful Thinking

For too long, wishful thinking has dominated energy policy. The wishful thinkers assume our nation will always have the electricity it needs "somehow." They tell us we don't need to build more power plants. They figure if we ever run short, we can simply use less.

They're dangerously wrong. Signs point to an energy crisis coming. First, electricity demand is growing faster than new supplies are being added because of our continued economic growth. In some parts of the country, electric reliability is already threatened.

Second, to meet increased energy demand, we're increasing our dependence on foreign oil and, in the process, gambling with our energy independence and our national security.

Third, there is a growing concern about "greenhouse" gases.

It's time to drop the wishful thinking and look at the facts.

GNP Growth Depends on Electricity

Since the 1973 oil embargo, the U.S. has made great strides in efficiency of energy use. But over this same period, demand for electricity has grown about 50 percent—roughly parallel with GNP growth. Clearly, electricity has fueled much of the growth in the U.S. economy. If our economy is to continue to grow, we must have additional, reliable, affordable supplies of electricity.

Yet, for many reasons—most of them beyond the electric industry's control—construction of new power plants is at a 15-year low. New generating capacity planned over the next 10 years will support growth in electric sales of only 1 percent per year. That is one-fourth the growth rate we've experienced over the last six years.

Using Oil for Electricity Presents Big Problems

Building new power plants is only part of the solution. We must also ask ourselves: what kind of power plants should be built?

Oil is one option (over 25 percent of U.S. electric capacity is fueled by oil and natural gas), but it's expensive and it presents other big problems, including environmental ones.

The U.S. is already dangerously dependent on foreign oil. Nearly half the oil we use is imported, causing one-third of our trade deficit. And it's getting worse.

Because electricity from oil-fired plants is costly, electric utilities try to reserve that capacity for times of very high demand. If we don't meet rising electric demand with domestic fuels—like nuclear energy and coal—utilities will be forced to use those oil-fired plants more of the time, worsening our foreign oil dependence and boosting our electricity costs.

Unfortunately, we're already moving in that direction. In 1988, the use of imported oil by utility companies increased 24 percent, and it's still growing. By the mid-1990s, utilities will be burning about 2 million barrels per day—almost all of it imported. Our nation is so dependent on foreign oil for other uses, such as transportation, we simply cannot afford to make the situation worse by using foreign oil to generate electricity.

Nuclear Energy—the Clean, Secure Solution

For generating electricity, nuclear energy has inherent advantages: It's a clean, secure, domestic source. And it helps preserve valuable natural resources for future generations.

Nuclear energy is our second largest source of electricity, after coal. Our nuclear plants have cut consumer electricity costs by over $50 billion since the 1973 oil embargo. The spent fuel from all our commercial nuclear plants has been managed scrupulously at carefully controlled sites. And our plants have operated safely.

We learned much from the Three Mile Island accident. The jolt it gave the industry's confidence led to substantial improvements in operation and design. The Nuclear Regulatory Commission and the Institute of Nuclear Power Operations report steady improvement in all areas of nuclear plant performance.

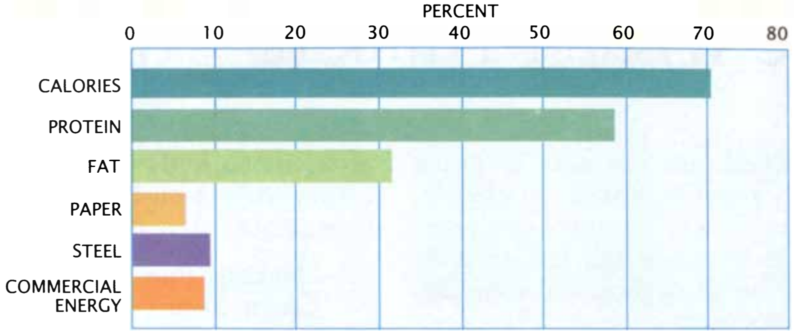
Finally, our nuclear plants have reduced oil imports, displacing nearly 4 billion barrels of oil and cutting our foreign oil payments by over $114 billion since 1973.

With such a record, there's no question that nuclear energy should play a larger role in supplying our future electricity needs. These are facts. Wishful thinking cannot deliver so well.

For more information on nuclear energy, write to the U.S. Council for Energy Awareness, 1776 I Street N.W., Suite 400, Washington, D.C. 20006-2495.

U.S. COUNCIL FOR ENERGY AWARENESS

Nuclear energy means more energy independence.



DEVELOPED NATIONS consume far more of the world's goods than do the developing nations—which have some 75 percent of the world's population. Per capita consumption in the developing nations is shown as a percent of that in the developed nations. Data are estimates by the World Commission on Environment and Development.

ogy. Something as simple as bringing all U.S. buildings up to the best world standards could save enormous amounts of energy. Right now more energy passes through the windows of buildings in the U.S. than flows through the Alaska pipeline.

Efficiency gains may nevertheless have to be promoted by special market incentives, because energy prices tend to lag behind increases in income. A "climate protection" tax of $1 per million Btu's on coal and 60 cents per million Btu's on oil is an example of such an incentive. It would raise gasoline prices by 11 cents a gallon and the cost of electricity an average of 10 percent, and it would yield $53 billion annually.

Direct regulation by the setting of standards is cumbersome, but it may be necessary when implicit market signals are not effective. Examples are the mileage standards set in the U.S. for automobiles and the efficiency standards for appliances that were adopted in 1986. The appliance standards will save $28 billion in energy costs by the year 2000 and keep 342 million tons of carbon out of the atmosphere.

Over the long term it is likely that some form of emissions-trading program will be necessary—and on a much larger scale than has been the case heretofore. (Indeed, the President's new Clean Air Act proposal includes a strengthened system of tradeable permits.) In such a program all major emitters of pollutants would be issued permits specifying an allowable emission level. Firms that decide to reduce emissions below the specified level—for example, by investing in efficiency—could sell their excess "pollution rights" to other firms. Those that find it prohibitively costly to retrofit old plants or build new ones could buy such rights or could close down their least efficient plants and sell the unneeded rights.

Another kind of emissions trading might reduce the impact of carbon dioxide emissions. Companies responsible for new greenhouse-gas emissions could be required to offset them by improving overall efficiency or closing down plants, or by planting or preserving forests that would help absorb the emissions. Once the system is established, progress toward further reduction of emissions would be achieved by progressively cranking down the total allowable levels of various pollutants, on both a national and a permit-by-permit basis.

The kinds of programs I have just described will need to be supported by research providing a scientific basis for new environmental-protection strategies. Research into safe, nonpolluting energy sources and more energy-efficient technologies would seem to be particularly good bets. An example: in the mid-1970's the U.S. Department of Energy developed a number of improved-efficiency technologies at a cost of $16 million; among them were a design for compact fluorescent lamps that could replace incandescent bulbs, and window coatings that save energy during both heating and cooling seasons. At current rates of implementation, the new technologies should generate $63 billion in energy savings by the year 2010.

The motivation of change toward sustainability will have to go far beyond the reduction of pollution and waste in the developed countries, and it cannot be left entirely to the environmental agencies in those countries. The agencies whose goals are economic development, exploitation of resources and international trade—and indeed foreign policy in general—must also adopt sustainable development as a central goal. This is a formidable challenge, for it touches the heart of numerous special interests. Considerable political skill will be required to achieve for environmental protection the policy preeminence that only economic issues and national security (in the military sense) have commanded.

But it is in relations with the devel-

ENVIRONMENTAL ISSUES look different to people and governments in the rich and in the poor nations. The cartoon was drawn by Scott Willis of the *San Jose Mercury News.*

Over 150 other airlines admire our maintenance so much, we work on their planes too.

How well an airline maintains its reputation depends largely on how well that airline maintains its planes. Which is why, after considering Lufthansa's record for on-time performance, so many other airlines have asked Lufthansa to help keep their planes in perfect working order.

After all, if so many other airlines ask for Lufthansa, shouldn't you?

People expect the world of us.

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Lufthansa is a participant in the mileage programs of United, Delta, USAir and Continental/Eastern. See your Travel Agent for details.

SUBSTITUTION is one route to the reduction of pollution. Substitution of methanol (already available at some gas stations in Los Angeles) for gasoline would cut down emissions of nitrogen oxides.

oping world that the industrialized nations will face their greatest challenges. Aid is both an answer and a perpetual problem. Total official development assistance from the developed to the developing world stands at around $35 billion a year. This is not much money. The annual foreign-aid expenditure of the U.S. alone would be $127 billion if it spent the same proportion of its gross national product on foreign aid as it did during the peak years of the Marshall Plan.

There is no point, of course, in even thinking about the adequacy of aid to the undeveloped nations until the debt issue is resolved. The World Bank has reported that in 1988 the 17 most indebted countries paid the industrialized nations and multilateral agencies $31.1 billion more than they received in aid. This obviously cannot go on. Debt-for-nature swapping has taken place between such major lenders as Citicorp and a number of countries in South America: the bank forgives loans in exchange for the placing of land in conservation areas or parks. This is admirable, but it will not in itself solve the problem. Basic international trading relations will have to be redesigned in order to eliminate, among other things, the ill effects on the undeveloped world of agricultural subsidies and tariff barriers in the industrialized world.

A prosperous rural society based on sustainable agriculture must be the prelude to future development in much of the developing world, and governments there will have to focus on what motivates people to live in an environmentally responsible manner. Farmers will not grow crops when governments subsidize urban populations by keeping prices to farmers low. People will not stop having too many children if the labor of children is the only economic asset they have. Farmers will not improve the land if they do not own it; it is clear that land-tenure reform will have to be instituted.

Negative sanctions against abusing the environment are also missing throughout much of the undeveloped world; to help remedy this situation, substantial amounts of foreign aid could be focused directly on improving the status of the environmental ministries in developing nations. These ministries are typically impoverished and ineffective, particularly in comparison with their countries' economic-development and military ministries. To cite one small example: the game wardens of Tanzania receive an annual salary equivalent to the price paid to poachers for two elephant tusks—one reason the nation has lost two thirds of its elephant population to the ivory trade in the past decade.

To articulate the values and devise the motivations favoring a sustainable world economy, existing institutions will need to change and new ones will have to be established. These will be difficult tasks, because institutions are powerful to the extent that they support powerful interests—which usually implies support of the status quo.

The important international institutions in today's world are those concerned with money, with trade and with national defense. Those who despair of environmental concerns ever reaching a comparable level of importance should remember that current institutions (for example, NATO, the World Bank, multinational corporations) have fairly short histories. They were formed out of pressing concerns about acquiring and expanding wealth and maintaining national sovereignty. If concern for the environment becomes comparably pressing, comparable institutions will be developed.

To further this goal, three things are wanted. The first is money. The annual budget of the United Nations Environment Program (UNEP) is $30 million, a derisory amount considering its responsibilities. If nations are serious about sustainability, they will provide this central environmental organization with serious money, preferably money derived from an independent source in order to reduce its political vulnerability. A tax on certain uses of common world resources has been suggested as a means to this end.

The second thing wanted is information. We require strong international institutions to collect, analyze and report on environmental trends and risks. The Earthwatch program run by the UNEP is a beginning, but there is need for an authoritative source of scientific information and advice that is independent of national governments. There are many nongovernmental or quasi-governmental organizations capable of filling this role; they need to be pulled together into a cooperative network. We need a global institution capable of answering questions of global importance.

The third thing wanted is integration of effort. The world cannot afford a multiplication of conflicting efforts to solve common problems. On the aid front in particular, this can be tragically absurd: Africa alone is currently served by 82 international donors and more than 1,700 private organizations. In 1980, in the tiny African nation Burkina Faso (population about eight million) 340 independent aid projects were under way. We need to form and strengthen coordinating institutions that combine the separate strengths of nongovernmental organizations, international bodies and industrial groups and to focus their efforts on specific problems.

Finally, in creating the consciousness of advanced sustainability, we shall have to redefine our concepts of political and economic feasibility. These concepts are, after all, simply human constructs; they were different in the past, and they will surely change in the future. But the earth is real, and we are obliged by the fact of our utter dependence on it to listen more closely than we have to its messages.

FURTHER READING

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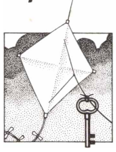
STATE OF THE WORLD 1989. Lester R. Brown et al. W. W. Norton & Company, February, 1989.

SMOKING GUN. A citizen of Nizhniy Tagil, an industrial center near Sverdlovsk in the U.S.S.R., stands on a soot-laden snowbank and contemplates the emission stacks of the local iron and steel mill. In the spring of 1988 a particularly dense smog prompted public demonstrations that led to the closing down of one of the mill's two coke ovens. Smoking chimneys, icons of economic activity, are also symbolic of the impact exerted by the works of human beings on the global ecosystem.

THE AMATEUR SCIENTIST

A drop of water becomes a gateway into the world of catastrophe optics



by Jearl Walker

Those of us who wear eyeglasses are sometimes annoyed when a raindrop lands on a lens and distorts the view. The troublesome drop actually offers a glimpse into a partially concealed world where light creates complex structures rivaling a pinnacled cathedral. If at night you look at a distant bright lamp through the drop, portions of these structures spring into view. (If you do not wear glasses, let a windowpane substitute for the lens, bringing your eye close to the drop.)

The perplexing patterns consist of bright lines along which the drop focuses the light your eye intercepts. Such a focused display is said to be a caustic—a term derived from the fact that a lens can focus sunlight to burn a hole in a surface. In recent years the patterns have been analyzed by means of what is called catastrophe theory, and so they are now referred to as examples of catastrophe optics.

The bright lines are often outwardly concave and converge to form cusps [*see bottom illustration on opposite page*]. Sometimes the region within a pattern is partly filled with a series of dimmer interference lines that mimic the orientation and curvature of the brighter ones; somewhere a small bright image of the lamp itself is seen.

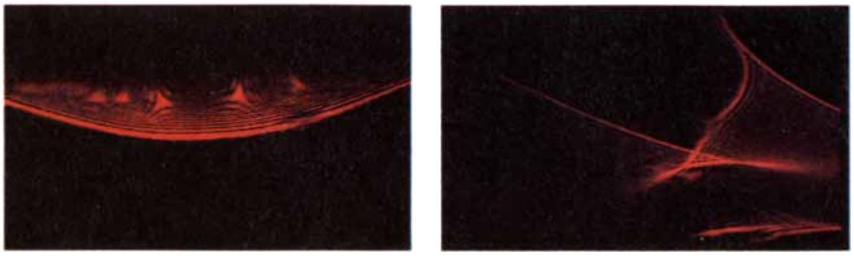
When a heavy drop hangs pendulously from the glass, the top of the pattern is outwardly convex and there are few cusps, if any, in the vicinity. Just within the border lie tiny, bright "stars." Their visibility is reduced by interference lines, but you can make them dance if you can gently wiggle the glass. If you can rotate the glass around your line of sight, follow one of the cusps. As it approaches the top of the pattern, it shrinks and then enters the interior of the pattern to become a star.

The variety of the patterns may seem endless, but close scrutiny reveals that they are composed of a handful of basic designs, members of the set of "elementary catastrophes." Study of the patterns also demonstrates something more powerful: the catastrophes seen through a drop are actually sections taken through three-dimensional structures, which in turn are sections taken through mathematical structures of higher dimensionality. Sorting out their linkage has been the work of several researchers, notably M. V. Berry and J. F. Nye of the University of Bristol. Here I explore their results and include others from James A. Lock, my colleague at Cleveland State University, and his student James H. Andrews. I shall also describe a simple experiment that produced the most stunning optical displays I have ever seen.

Before I deal with drops on a vertical surface, I should first examine one sitting on a horizontal surface (in the case of which the bright lines are always outwardly concave). Picture a drop on a horizontal microscope slide that is illuminated from below by vertical light rays. Whenever a light ray passes through a tilted surface, it is refracted: its direction of travel is altered. In this case the rays first encounter a tilted surface when they reach the top surface of the drop. To follow the refraction, consider a vertical section of the drop [*see top left illustration on page 178*]. Everywhere in the section the surface of the drop is outwardly convex. Pick a point somewhere along the curve, add a tangent to the surface there, and then construct a "normal"—a line perpendicular to the tangent. If the normal leans away from the vertical toward the left, a ray passing through the point is refracted toward the right. If you pick another point with a normal that tilts more to the left, the ray passing through the new point is deflected more to the right.

You can see the results of the refraction with a laser. Arrange for a microscope slide to span the gap between two boxes of equal height. Place a drop on the slide and position a mirror below it to reflect the laser beam up through the drop. To reveal the refracted light, hold a white card horizontally somewhere above the drop. If the base of the drop is perfectly circular, the rays all go through a "central axis" running vertically through the center of the drop; on the card you are likely to see only a bright point where some of the rays happen to focus. If the slide is soiled or has tiny scratches, minute irregularities break the circular base of the drop—a dust mote might pull out a "finger" of water or indent a "cove" along the perimeter. Either irregularity imposes ridges and gullies along the side of the drop that alter the refraction of light. If there are only one or two irregularities, though, the surface of the drop in any vertical section remains convex even at a ridge or gully, and the light still yields little of interest on the card.

The story picks up when at least three irregularities are present. Their pull distorts the curvature of the water surface in a new way. In a vertical section the surface is no longer entirely outwardly convex but instead has a section that is concave. The point at which the convex and concave curvatures meet is called a point of inflection. The inflections are not isolated but are arranged along a line running around the drop near the base.



***Catastrophes photographed in laser light: stars* (left) *and a swallowtail* (right)**

An evolution of catastrophe patterns

When rays pass through the region near an inflection, they are bunched by refraction and focus along a slanted path extending above the drop. If a card intercepts some of the focused light, the bunching at each inflection point gives rise to a bright spot on the card, and the succession of spots forms a bright line that is called a fold—the simplest of the elementary catastrophes. Because the refracted rays are slanted through the central axis, the fold appears on the opposite side of the central axis from the part of the line of inflections that generates it, that is, the pattern is inverted with respect to the drop.

The distance, horizontally, between a segment of the fold and the axis depends on the tilt of the normals in the part of the inflection line that produces the segment. If the normals are barely tilted, so are the rays, and the fold segment is near the axis. When the normals are tilted somewhat more, the fold segment is more distant. The shape of the fold, then, depends on how the tilt of the normals varies along the inflection line encircling the drop.

An overhead view of a drop (with its irregularities greatly exaggerated and with the inflection line indicated) is shown at the left in the middle illustration on the next page. As the inflection line passes through *a* and approaches the cove from the left, surface tension forces it to climb up the drop to avoid passing through a short gully at the back of the cove. Along the way the normals in the inflection line become more tilted. The resulting fold is labeled *A* in the drawing at the right in the illustration, which shows what you would see if you looked down through a translucent card held over the drop. Another segment of the inflection line passes through *c* and approaches the cove from the right. It too climbs up the drop, producing the fold labeled *C*. The two inflection lines meet at *b*, and their folds converge at a cusp (*B*)—another elementary catastrophe.

A finger irregularity has similar effects, because there is a gully on each side of it where the base perimeter becomes concave as it begins to curve outward. A finger may create two cusps that overlap or, if it is wide, two distinguishable cusps.

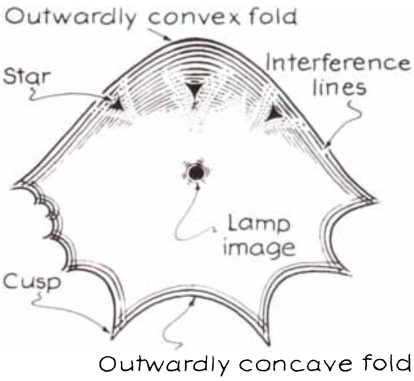
Folds and cusps are actually sections of three-dimensional catastrophes. Two such structures are the "swallowtail" (part of it resembles the tail of a swallow) and the "elliptic umbilic," which are illustrated at the bottom of the next page. Each is shown in perspective with its long axis extending away from you, but when the illustration applies to a waterdrop on a horizontal surface, the long axis is vertical. A horizontal card held over the drop takes a cross-sectional slice through the structure, a slice perpendicular to the long axis. What you see on the card is the part of the structure that is intercepted by the card.

Picture what happens as you mentally take a series of such slices through the swallowtail, starting at the right side of the illustration and moving toward the left. The first cuts yield an outwardly convex fold that gives no hint of the swallowtail's presence, but eventually the distinctive tail pattern begins to appear and then to grow. The point at which the pattern is about to emerge is said to be the "singularity" of the swallowtail. The mental exercise of shifting a slice along the length of a catastrophe's structure, beginning at its singularity, to disclose the presence of the structure is called "unfolding the catastrophe." Can you actually see an unfolded swallowtail on a card when the drop lies on a horizontal surface? The chances are slim: a small tail pattern is lost in the maze of interference lines, and the curvatures of the water surface are usually too mild to yield any larger tail pattern.

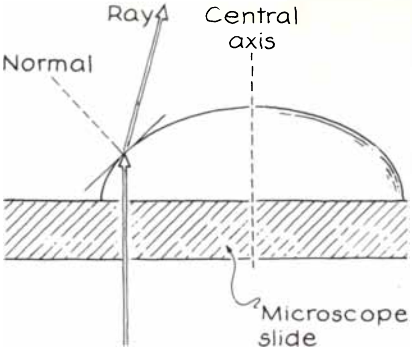
Now try the same mental unfolding with the elliptic umbilic. Here the singularity is a point, and the unfolded pattern is a triangular arrangement of three cusps and three outwardly concave folds. The unfolded pattern would reveal the catastrophe's presence, but again the irregularities usually fail to generate anything large enough to see. (An unfolded swallowtail or elliptic umbilic may seem elusive, but keep them in mind for what is coming up.)

The third and last of the three-dimensional catastrophes is the hyperbolic umbilic, which is also shown at the bottom of the next page. Its singularity consists of two straight folds that meet at a 60-degree corner. As you unfold the catastrophe from the singularity, the pattern splits into two parts. One is an outwardly convex fold. Inside it is a cusp where two short, outwardly concave folds meet. Either the singularity or the unfolded pattern would signal the catastrophe's presence. You cannot see either of them from a drop on a horizontal surface, however—not because they are too small but because a horizontal drop never has the right shape for creating them.

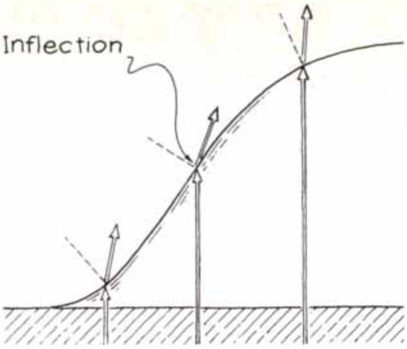
I now turn to a drop clinging to a vertical glass surface, but first I must explain a point of possible confusion. In the previous examples I argued that the pattern is inverted with respect to the drop. When you look at a distant lamp through a drop just in front of your eye, you do not see an inversion. For example, the bottom of the pattern comes from the bottom of the drop. The lack of inversion is an illusion. The pattern produced on the retina is actually inverted, as it is on a card, but



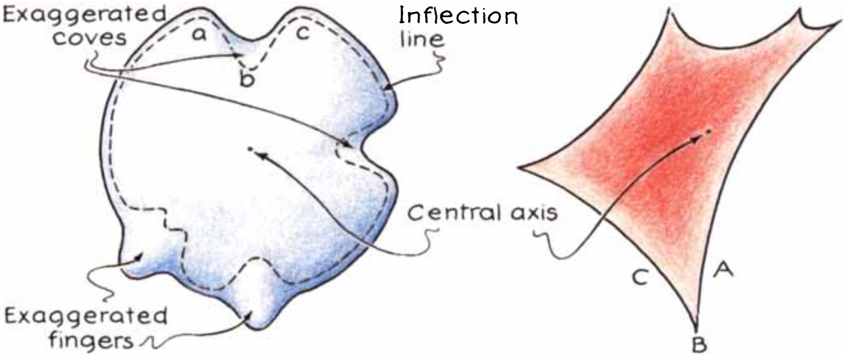
The pattern from a pendulous drop



Refraction by a waterdrop



Refraction near an inflection



***Overhead view of a drop* (left) *and its pattern* (right)**

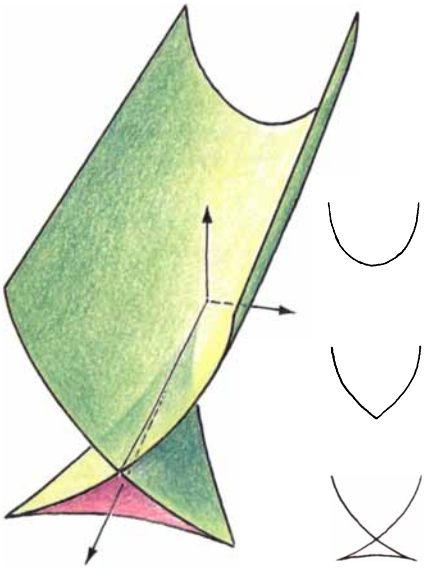
the brain introduces a second inversion so that the world, including the drop and its pattern, appears right-side up.

When the drop is on a vertical surface, the three-dimensional catastrophes unfold perceptibly because of the slump of the drop and the resulting sharper curvatures on the water surface brought about by surface tension. Recall what is seen through a drop on a spectacle lens. When the drop is small, cusps and outwardly concave folds appear. If the drop is distorted appreciably, they may overlap to yield an unfolded swallowtail. When the drop is pendulous, the cusps and outwardly concave folds are restricted to the bottom of the pattern. They result from irregularities along the lower part of the drop's base. The top of the pattern, coming from the top of the drop, is an outwardly convex fold with internal stars.

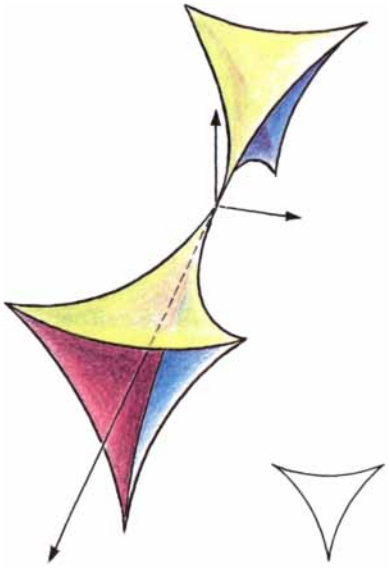
The fold is a tease, because it is the outside part of an unfolded hyperbolic umbilic. Each star comes from a slightly unfolded elliptic umbilic but only in a masked way. The catastrophe's triangular structure is present (with one cusp pointing down), but its folds produce interference lines that run perpendicularly through the folds. What you perceive is an inverted triangular arrangement of the interference lines, with one cusp pointing up.

Nye was able to unfold the hyperbolic umbilic (including the internal part) and the elliptic umbilic. He did it by attaching several layers of opaque tape to a microscope slide, cutting a hole in the tape, filling the hole with a waterdrop and then mounting the slide vertically or at a slant in a microscope. The hole provided a perch for the drop. When the hole was circular, it also ensured that the base of the drop remained circular in spite of the slide's tilt. Irregularities in the cut of the tape provided the catastrophes. By adjusting the focus of the microscope, he could control just where it effectively took a slice through the light, just in front of the drop. Such a close view is said to be in the "near field." The views in my examples are taken with a card or an eye in the "far field."

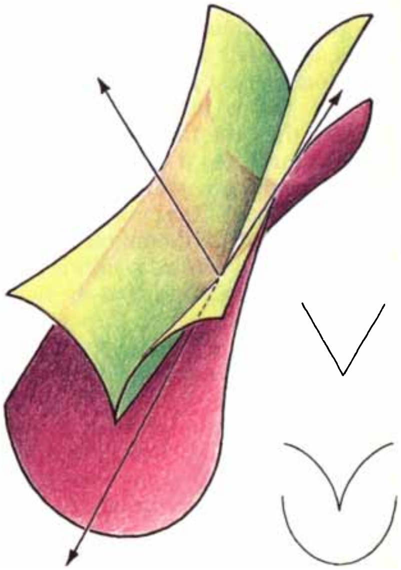
I wondered if the idea of a perch



A swallowtail catastrophe



An elliptic umbilic catastrophe



A hyperbolic umbilic catastrophe

might allow me to see unfolded catastrophes in the far field. Instead of using tape, I cut a circle 2.8 millimeters in diameter off of a plastic mechanical-drawing template of circles. I applied glue to one side of my one-circle template, laid that side on a sheet of paper to eliminate excess glue and then pressed the template onto a microscope slide, taking care not to smear glue over the circular aperture.

When the glue had cured, I cleaned the back of the slide and blew compressed air from a can into the aperture to clean it. Next I mounted the slide vertically in a laser beam by sticking one end into a mound of modeling clay. The beam was expanded by a lens so that it illuminated slightly more than the aperture, and then it continued on several meters to a white wall. I filled the aperture with tap water by simply touching it with a drop of water from the end of a syringe (an eyedropper would serve as well) and soaked up stray water around the aperture with tissue paper. The entire preparation took only 15 minutes, but when I switched off the room lights, I was prepared for a long search for unfolded catastrophes.

Instead something astonishing appeared on the first try. The top of the meter-wide display on the wall (which came from the bottom of the drop, which is to say from the bottom of the circle) consisted of the routine cusps and outwardly concave folds. Surprisingly, the bottom of the display was similar to the top, unlike what I expected from my experience with a drop on a spectacle lens.

Entranced, I watched as the drop began to evaporate and its curvature changed. All the cusps along the bottom of the display shrank, "pierced" the fold and were transformed into unfolded elliptic umbilics that were masked as stars [*see illustration on this page*]. The lowest cusp and its associated star led the way. The abandoned fold at the bottom straightened, and both it and the stars shifted upward. I felt I was watching things that were alive.

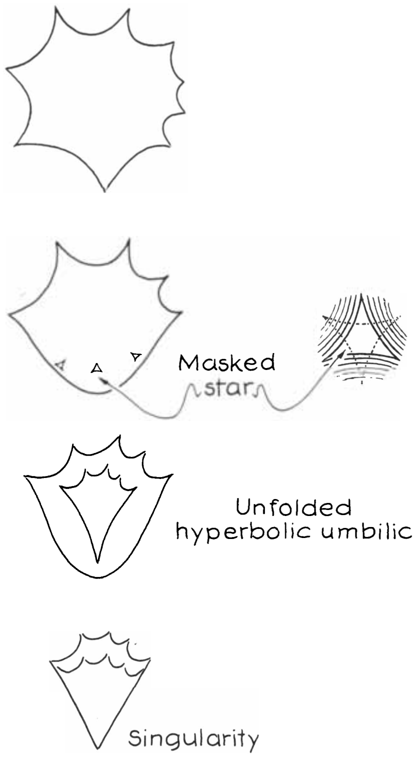
Soon the cusps of the hidden elliptic umbilic of the lead star began to appear. Two of them curved upward like the horns of a bull; the lowest one grew downward. By then the fold had became outwardly convex. Within minutes the emerging elliptic umbilic reorganized to become the internal structure of an unfolded hyperbolic umbilic—it consisted of a downward-pointing corner formed by two straightening folds. The structure marched downward while the fold at the bottom of the pattern advanced upward. When they met, they coincided neatly to form a single corner with straight sides at roughly 60 degrees: the singularity of a hyperbolic umbilic. Then the pattern split, one part becoming an outwardly convex fold and the other becoming an interior corner with curved sides. I had seen the complete unfolding of the hyperbolic umbilic from end to end and also its transformation from an unfolded elliptic umbilic!

I moved the slide and its mount to a window, refilled the aperture and then sighted through the drop at a distant streetlamp in the otherwise dark outdoors. This time the performance was tiny, inverted from what had been on the wall and in white light instead of the laser's red light, but it was no less intriguing. Other small circles cut from the original template worked just as well.

When Lock and I watched a similar performance later, we found I had seen only the first act of the play. The theatrical transformations of the act were dominated by inflection lines at the top of the drop. (When a card in the laser beam shadowed the top of the drop, the bottom of the wall display vanished.) The second act was a reversal of the first act, and its theatrics were dominated by inflection lines at the bottom of the drop. In the first act the wall pattern had been inverted from the drop, but in the second act evaporation had allowed the water surface to sink into the aperture, and the new curvature righted the pattern.

Here is a run-through of the entire play. The action starts when the bottom cusps retreat through the bottom fold and become stars. Recall that a star masks a triangular arrangement of folds and cusps, with one cusp pointing downward. When the first star begins to transform into a corner, the folds on the left and right sides of the triangle emerge from hiding and begin to straighten to form the corner.

Meanwhile, the top fold of the triangle moves upward on the wall, comes out of hiding and sprouts an upward cusp. The cusp is a clone of the one that created the star but is inverted in orientation. For example, if the original downward cusp was on the left side of the wall pattern, its upward clone is on the right side. As another star undergoes the transformation, its corner aligns with the first corner and another cloned cusp sprouts. As more stars are transformed, the corner pattern on the wall brightens and the region of sprouted cusps becomes crowded. The internal structure of the wall pattern comes to resemble an ice-cream cone with spikes sticking out of the top.



The metamorphosis of the wall pattern

In the meantime, the external structure of the pattern on the wall shrinks and takes on the same cone shape. The singularity of the hyperbolic umbilic is reached when the bottom parts of the cones are completely straight and overlapping. The roles of the two structures are then reversed: what had been the external structure continues to shrink while what had been the internal structure continues to expand. The new internal structure begins to release a flock of new stars, each of which migrates downward on the wall, passes through the bottom fold of the new external structure and becomes a cusp. The final pattern on the wall is largely an inversion of the initial one.

FURTHER READING

OPTICAL CAUSTICS IN THE NEAR FIELD FROM LIQUID DROPS. J. F. Nye in *Proceedings of the Royal Society of London*, Series A: *Mathematical and Physical Sciences*, Vol. 361, No. 1704, pages 21-41; May 3, 1978.

CATASTROPHE OPTICS: MORPHOLOGIES OF CAUSTICS AND THEIR DIFFRACTION PATTERNS. M. V. Berry and C. Upstill in *Progress in Optics*, Vol. 18. Edited by Emil Wolf. Elsevier North-Holland, 1980.

COMPUTER RECREATIONS

Two-dimensional Turing machines and tur-mites make tracks on a plane

by A. K. Dewdney

"[Termites] ... forge the complexion of a landscape like no other organism except man."

—WALTER LINSENMAIER,
Insects of the World

Anyone who has ever seen a termite mound must have been impressed by the complex patterns of tunnels built by the industrious but mindless insects. Paradoxically, artificial forms of life that make termites look like geniuses can produce equally astounding creations. Take tur-mites, for example. They are squarish, cybernetic creatures that have the most rudimentary of brains. And yet as they move about on the infinite plane on which they live, they trace out strange patterns that appear to reflect an underlying intelligent design.

The tur-mites were inspired in part by Greg Turk, a graduate student at the University of North Carolina at Chapel Hill. For some time Turk has been experimenting with a special type of Turing machine, a construct that has long served as a basic model of computation. A Turing machine is usually assumed to operate on an infinite linear tape that is divided into cells. Turk, however, has studied Turing machines that operate on a kind of two-dimensional tape—essentially the same plane on which the tur-mites roam. Converting a two-dimensional Turing machine into a tur-mite is simple and painless: abstract rules are replaced straightforwardly by a neural network. Such a conversion highlights an important theme in the theory of computation: one computational scheme often turns out to be equivalent to another, seemingly unrelated, one.

Turing machines are named after the British mathematician Alan M. Turing, who first proposed them as a way to define computation. In effect, a Turing machine is the ultimate digital computing machine. It can compute anything that a modern computer can—as long as it is given enough time.

One can visualize a Turing machine as it is shown in the illustration on the opposite page: a black box equipped with a device that reads a symbol in a single cell of an infinitely long tape, writes a new symbol in the cell and moves the tape either forward or backward in order to examine the symbol in an adjacent cell. What is inside the black box? It does not really matter, as long as the box adheres strictly to a given table that lists what the Turing machine must do for every symbol read and for every one of the machine's possible "states." These may change with each cycle of operation. A cycle consists of the following three steps:

1. Read the symbol currently under the read/write device.
2. Look up the table entry given by the machine's current state and the symbol just read.
3. Write the symbol given by the table entry, move the tape in the direction indicated and enter the state shown.

Each table entry therefore has three parts: a symbol to be written on the current cell, a direction in which to move the tape and a state to enter.

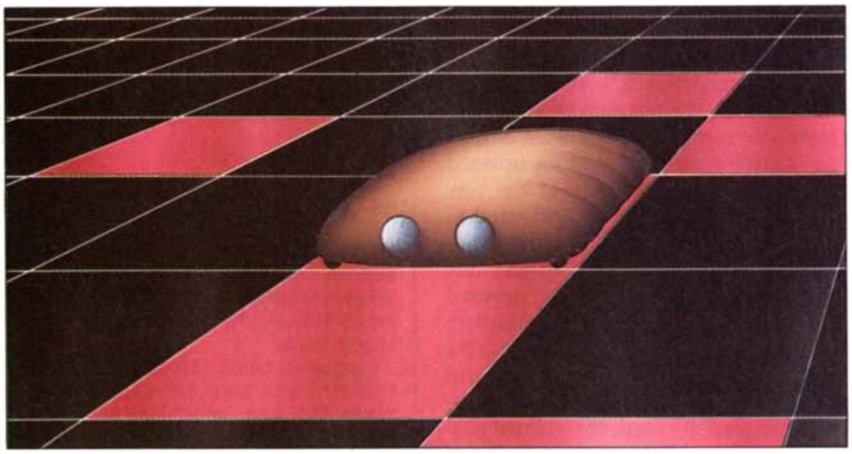
To a Turing machine the tape's motion is relative. One could just as easily arrange for the tape to remain fixed and the machine to move itself from cell to cell. In fact, once one contemplates the idea of moving the Turing machine and not its tape, it does not take much imagination to envision a two-dimensional "tape" on which the machine may move about freely.

Regardless of whether it has a one- or two-dimensional tape, a Turing machine's table is what ultimately determines its behavior. It is closely analogous to the program that controls a modern digital computer. In terms of computational capability, two-dimensional Turing machines are not more powerful than one-dimensional ones. They just have more interesting patterns of movement over the cells. The pattern shown in the illustration at the top of page 182, for example, was made by a single-state two-dimensional Turing machine. Its internal table is:

	BLACK	RED
A	(RED, LEFT, *A*)	(BLACK, RIGHT, *A*)

The machine's single state has been labeled *A*.

A slightly more complicated two-dimensional Turing machine that was discovered by Turk has two states,



A tur-mite occupies one square at a time designated *A* and *B*, and it follows this internal table:

	BLACK	GREEN
A	(GREEN, LEFT, *A*)	(BLACK, FORWARD, *B*)
	(GREEN, RIGHT, *A*)	(GREEN, RIGHT, *A*)

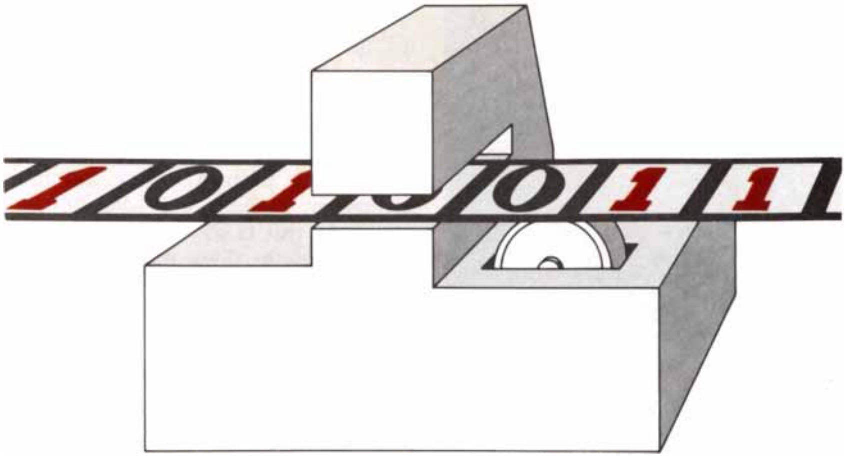
According to Turk, a two-dimensional Turing machine programmed with this table produces a marvelous spiral pattern. The machine creates "larger and larger patterned regions that are placed in orderly fashion around the starting point."

Any pattern generated by a two-dimensional Turing machine can be reproduced exactly by a tur-mite. A tur-mite's behavior, however, is not controlled by a mysterious black box. It is controlled by what can be loosely described as a brain. The fact that one can dissect and examine a tur-mite brain is what makes the creature so fascinating.

Judged only by its appearance and ethology, a tur-mite certainly is not fascinating. Its body is roughly square, so that it fits snugly into the squares that divide the infinite plane on which it lives. It has a flat bottom equipped with some form of locomotory apparatus. (I do not know what makes a tur-mite go, since I have never turned one over.) The apparatus enables the creature to rotate and to move exactly one square in the direction in which it happens to be facing. Actually, a tur-mite's face has no purpose except to let us know which way is forward; its "eyes" do not function. When a tur-mite changes direction, it merely swivels 90 degrees on its current square before moving to a new one.

Initially all the squares on the plane, including the one the tur-mite occupies, are black. Before it moves, however, a tur-mite may change the color of the square it currently occupies. (The tur-mite's color-changing organ is as mysterious as its locomotory apparatus.) A tur-mite that duplicates the pattern shown at the top of the next page, for example, must be capable of painting the square one of two colors (in this case, red or black). To produce the pattern shown at the bottom of the page, however, a tur-mite has to have more colors at its disposal.

How does a tur-mite know when to move or when to change the color of its square? Those actions are controlled by its brain, which consists of a collection of "neurodes," simplified versions of the neurons in our own brain. A neurode receives signals along fibers that originate at sensors (which are found on a tur-mite's underside) or at other neurodes and sends signals along fibers to effectors (such as the tur-mite's locomotory apparatus or its color-changing organ) or to other neurodes.



The standard visualization of a Turing machine

A neurode fires (sends a signal along its output fiber) if the number of incoming signals equals or exceeds the neurode's threshold, which is given by the number written on the neurode. Otherwise, it does not fire. Because time in the tur-mite's world proceeds in discrete steps, all excitatory and inhibitory signals are sent or received in discrete steps as well.

To illustrate how a tur-mite actually makes a decision, I shall dissect the brain of two specimens [*see left and middle drawings on page 183*], both of which produce exactly the same pattern as that generated by the single-state two-dimensional Turing machine described above. The brain on the left contains two neurodes that are not connected to each other. Each neurode has just one input fiber and one output fiber. When the tur-mite's color sensor detects red, it sends a single signal to the left neurode, causing the neurode to fire. The neurode's output fiber splits into two parts, one going to the color effector (which then colors the entire square) and the other going to the locomotory apparatus (which then swivels the creature 90 degrees to the right and advances it one square in the new direction). On the other hand, when the tur-mite's color sensor detects black, it sends a signal to the right neurode, causing it to fire. The neurode's output, in turn, causes the tur-mite to paint the square red before turning and heading to the square on its left.

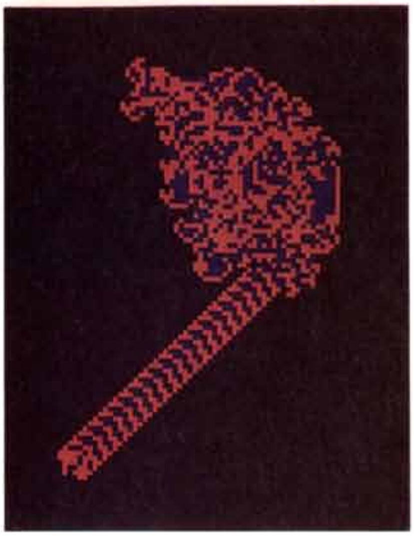
In short, when the tur-mite finds itself on a red square, it colors the square black and then moves one square to the right. And when the tur-mite occupies a black square, it changes the color of the square to red, then turns left and advances one square in its new direction.

The second tur-mite brain is more complicated, but it does exactly the same job as the first. It was derived by a method I shall presently describe. The two neurodes both have threshold 2; neither will fire unless it receives two input signals during the same time increment. Once the brain is set in motion, one neurode will always fire at each step in time.

The simple behavior embodied in the two neurode circuits just described results in the complicated image at the top of the next page: a red cloud of tiny squares from which an intricate structure extends straight to infinity. What causes that sudden sense of purpose in the tur-mite after what seems a great deal of pointless meandering? The answer has to do with the pattern of colored squares in the cloud. At a certain point, part of that pattern, in combination with the tur-mite's neurode-based rules, locks the creature into a repetitive sequence of moves that weaves the structure. (I wonder if any readers can discover the triggering pattern.)

Life is like that for tur-mites. Sometimes a seemingly random meandering turns into an almost deadly determinism. Of course, the appearance of randomness is purely illusory. All tur-mites are decidedly deterministic at all times.

Nonetheless, there are mysteries to be found in the tur-mite's world. Consider, for example, the pattern shown in the bottom illustration on the next page. The tur-mite that made that pattern is outfitted with four effectors that change the color of a square to



One of Turk's patterns

black, red, yellow or green. It abides by the following rules:

Square Color	Action
black	paint red, turn right
red	paint yellow, turn right
yellow	paint green, turn left
green	paint black, turn left

This tur-mite also has a very simple brain. It consists of four neurodes that are not interconnected. Each neurode executes one of the four behavioral rules in the manner of the first tur-mite's simplest brain. Turk is puzzled by the fact that this particular tur-mite produces a pattern having bilateral symmetry. Perhaps a reader can explain why this is so.

How exactly does one get a tur-mite from a particular two-dimensional Turing machine? The technique is actually quite simple. One merely replaces each entry of the machine's internal table with a threshold-2 neurode that receives input signals from a sensor for the color corresponding to the entry's column and perhaps from other neurodes as well. Each neurode's output fibers go to the effectors necessary to execute the moves and color changes listed in the table entry.

For example, suppose that a certain neurode corresponds to a table entry in a column labeled "red" and a row labeled "*B*." According to the conversion scheme, the neurode would have an input fiber from the sensor that detects red. If the table entry happened to be (black, left, *B*), then the neurode would send an output fiber to the effector that colors the occupied square black and to the effector that enables the tur-mite to execute left turns.

The various states of a particular Turing machine are realized by the connections between neurodes in a tur-mite brain. Because the table entry in the example requires the tur-mite to adopt state *B*, the neurode representing that entry would extend output fibers to each of the neurodes making up row *B* of the table.

In this context, such a neural network is nothing more (and nothing less) than a form of hardware embodying a behavioral table. Sample conversions are displayed schematically in the drawings in the middle and at the right on the opposite page. The one on the right shows how one would go about constructing the brain of the tur-mite that mimics the behavior of Turk's spiraling two-dimensional Turing machine.

It is fun to watch a tur-mite (or a two-dimensional Turing machine) wander about on a cellular plane. To follow the action, however, the reader must write a program that simulates the tur-mite's movements. How does one go from a table to a program?

Luckily, the process is nearly as simple as designing a tur-mite's brain. A program that I call TURMITE consults a Turing-machine table in the form of three separate arrays: *color, motion* and *state*. Each array is indexed by two variables, *c* and *s*. The variable *c* indexes the color of the present square, and the variable *s* indexes the Turing machine's (or the equivalent tur-mite's) current state. Because the indexes have to be assigned integer values, the colors and states used in the simulation must be numbered.

For example, the colors black and green can be assigned to the variable *c* by the numbers 1 and 2, respectively. Similarly, the states *A* and *B* can be designated respectively by the values 1 and 2 of the variable *s*. In this case, a simulation of a spiraling tur-mite would require the following arrays:

s \ c	1	2
1	2	1
2	2	2

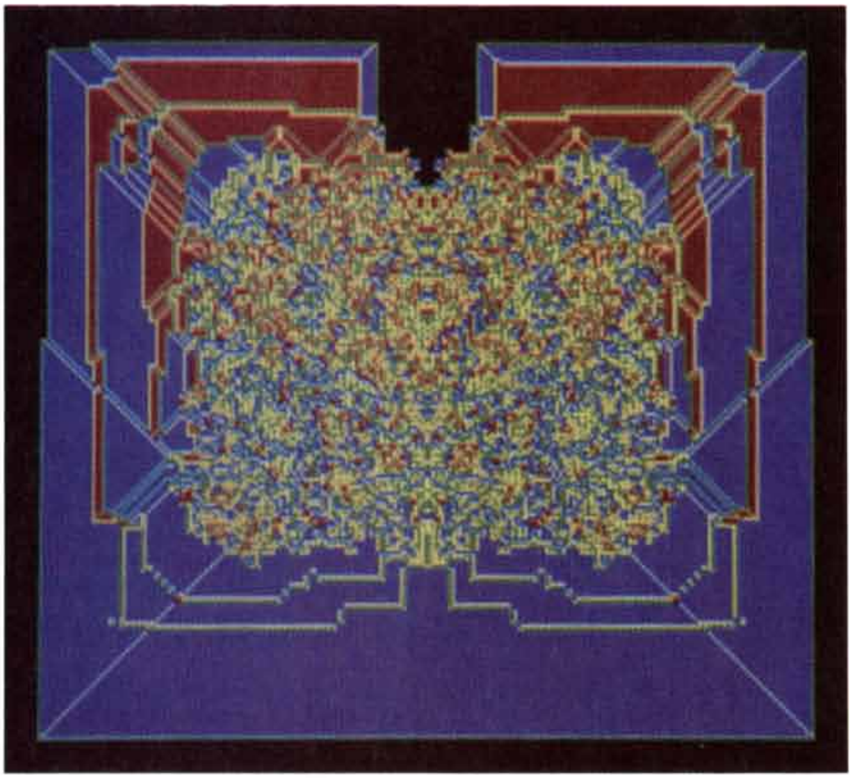
COLOR

s \ c	1	2
1	1	2
2	1	1

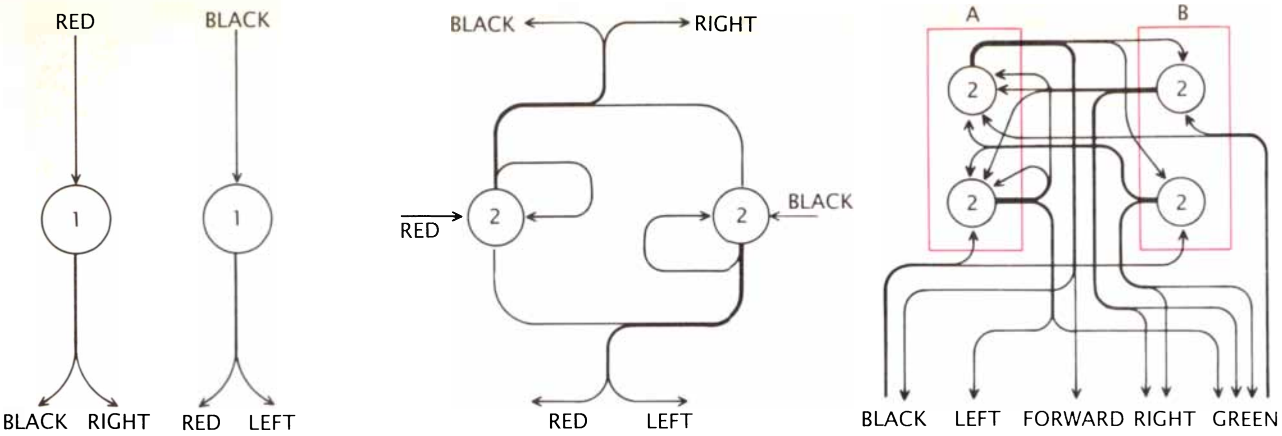
STATE

Directions of motion must also be coded in terms of numbers. Hence, forward, backward, left and right could be indicated respectively by the numbers 1, 2, 3 and 4, which are contained in the array *motion*.

The main purpose of TURMITE is to color small squares (perhaps individual pixels) on the computer's display screen that highlight a tur-mite's peripatetics. The program keeps track of



A multicolored tur-mite pattern



Three tur-mite brains, two of which* (left and middle) *do the same job

the displayed squares' colors in a two-dimensional array called *pattern*. Initially only one square is lit—the one lying at the center of the screen.

The value of *c* at any given time is provided by the entry in the array *pattern* corresponding to the turmite's current coordinates on the screen, say *i* and *j*. With *c* and *s* in hand, the program simply looks up the array entries *color*(*c*,*s*), *motion*(*c*,*s*) and *state*(*c*,*s*).

The program changes the color encoded in the entry in *pattern*(*i*,*j*) and then alters either *i* or *j*, depending on the value of *motion*(*c*,*s*). Here the program must translate the relative movement encoded in *motion* into an absolute movement by consulting another variable, *dir*, which contains the last direction moved: up, down, left or right. The final step in TURMITE's operating cycle consists merely of changing *s* to the number given by *state*(*c*,*s*). The rest can be left to the imagination and inventive skill of those readers who like to write their own programs.

While one is constructing a tur-mite's brain or simulating its behavior on a computer, it is interesting to reflect on the fact that, since tur-mites can carry out any computation a Turing machine is capable of executing, tur-mites can be just as powerful as some computers. If, as some claim, the human brain amounts to nothing more than a kind of digital computer, then some tur-mites could be just as smart as we are—if not smarter!

Simulated Evolution, the subject of the May column, drew an unusually heavy mail response. Several hundred readers requested copies of a detailed algorithm on which they could base their own version of the program. After all, it is not often that one has a chance to see pretend protozoa evolve into bacteria banqueters in an hour or less.

Michael Palmiter, the California high school teacher who developed the program, deserves the palm leaf for his creation. It was evidently an idea whose time had come. Swept into the simulated-evolution zeitgeist were a few readers who had independently developed programs that were remarkably similar to Palmiter's Simulated Evolution.

High school freshman Máté Sztipánovíts of Nashville, Tenn., won accolades at science fairs with a program that simulated oval bugs roaming on a two-dimensional space, looking for randomly distributed food. In Sztipánovíts's program, the medium surrounding the creatures exerts a drag that can be minimized through the evolution of streamlined shapes.

Christopher O'Haver of College Park, Md., also submitted a simulated-evolution program as a science-fair project. Unlike Palmiter's bugs, the organisms in O'Haver's program are stationary (more like algae than protozoa), absorb food continuously, grow and suffer predation.

Paul H. Deal of Moriarty, N.M., has developed a rather sophisticated evolution program that he has been distributing to educators. The genome of his creatures includes 13 genes that govern such characteristics as a creature's ability to feed on organic substrates, to absorb energy and to move (albeit somewhat feebly). Readers wanting to experiment with Deal's program may obtain it as shareware by writing Deal at P.O. Box 1398, Moriarty, N.M. 87035.

Among the readers who were able to set BUGS, my simplified version of Palmiter's program, in motion with only the spare description given in the column were Lewis V. Glavina of Burnaby, British Columbia, Ken Sheller of Bellevue, Neb., Jim Henry of De Kalb, Ill., and Albert H. Behnke of Boston, Va. Glavina, bothered by the amount of energy that bugs sometimes waste at the screen's boundary, gave his protozoa the power to bounce off the screen's sides. Sheller explicitly rewarded the gene that made the greatest contribution to food-gathering behavior. Finding it difficult to distinguish advanced bugs from their less evolved cohorts, Henry colored a bug according to its tendency to stay in the same place. Behnke endowed his bugs with a similar feature, causing a bug to change color as it changes directions.

Finally, a postscript on the April-fool anagram tangram gold scam. In the April column I quoted extensively from my correspondence with a shadowy character by the name of Arlo Lipof. Lipof maintained that he had driven down the price of gold by applying the Banach-Tarski theorem to make gold out of nothing. Recently I received an angry letter from the so-called International Gold Council in New York City in which I am held accountable for the "turmoil" and the "collapse of civilization" that might now result from the divulgence of Lipof's secret.

"For years the I.G.C. has made the Banach-Tarski paradox inaccessible to the general public.... We have always known that the apocalyptic reality of making more gold from less gold would have dire consequences for the international balance of world monetary systems."

FURTHER READING

MATHEMATICAL GAMES. Martin Gardner in *Scientific American*, Vol. 216, No. 3, pages 124–129; March, 1967.
MATHEMATICAL GAMES. Martin Gardner in *Scientific American*, Vol. 229, No. 5, pages 116–123; November, 1973.

BOOKS

Greenhouse mediarology, a well-taped worm, parts per billion, traces of the past

by Philip Morrison

GLOBAL WARMING: ARE WE ENTERING THE GREENHOUSE CENTURY?, by Stephen H. Schneider. Sierra Club Books, distributed by Random House, 1989 ($18.95).

In 1971 a packed house of geoscientists in a Washington meeting heard out one distinguished speaker's early views of the human impact on climate. A young postdoctoral fellow went up after the talk to describe to the authority some calculations of his own. "He asked me a question that was to change my life: Would I be willing to attend a three-week meeting ... in Stockholm ... that would help define the field?" That talented postdoc was Stephen H. Schneider, and he was just the man to help write the report of that meeting.

At the National Center for Atmospheric Research he has continued to think and calculate, as well as to communicate fairly and cogently in public what he finds. (This issue of *Scientific American* offers in evidence one of Schneider's clear, up-to-date summaries.) In his latest brief book he aims in particular at the policy issue—the weighing of prudent action in the face of uncertainty—in an account packed with anecdotes of debate around the clock and around the world, colloquies in hearing rooms and studios among politicians and journalists, skeptics, opportunists, even provocateurs. Here he minimizes detailed scientific presentation the better to center on the most visible issues, although still in the "context of scientific knowledge and ... policy values."

As far as he can make out, we are entering on the greenhouse century. Our models are patently imperfect (the most clarifying of the author's offerings are his accounts of just where models might fall into error), but everything we know and have tested against the past, or against other planets, suggests warming to come. The absorption of infrared radiation, by carbon dioxide and a few other gases added to the air by human activities, will act to warm the surface of the earth, other things being equal—not by much but enough to trigger a variety of mischief.

It could well be that our view is wrong: some underestimated or unknown feedback system might well reduce change or even prevent it. But it could equally be that the greenhouse will become warmer than we expect because some unknown feedback goes against us. Uncertain risk remains risk still.

Have we already felt the hot breath of the beast? Hardly; it is not clear that the hot U.S. summers signal a global warming. They fit imperfectly, and other transient causes seem at hand. Yet the chances may already have been skewed toward heat. The main signal is expected to appear within a couple of decades, out of the band of natural noise in which it is now masked. A clear signal will validate, as its absence will disprove, our estimates of global climatic sensitivity. The assembly of humanity has a question before it: is it wise simply to wait?

What can happen? The best grasp here comes from the Netherlands, where they have claimed so many broad fields from the salt sea within the past three centuries. Yet in 1988 their planners foresaw the future loss of considerable agricultural land, even within their rings of dikes; the 21st century would see Holland flooded anew, deliberately covered by recreational lakes! Schneider was amazed at this optimism; had they forgotten or suppressed the danger of a world ocean rising as warmed seawaters expand and glaciers melt?

The Dutch watermasters had forgotten nothing. For a typical dike, they allow "storm surge ... 5 meters above mean sea level; wave run-up, 9.9 meters; ... gust bumps 0.35 meters; dike settlement, 0.25 meters; and finally ... 0.25 to 0.5 meters sea-level rise for the next hundred years." They will sacrifice some good arable land—not because the sea will top their amply high dikes but because they intend deliberately to flood some of their land with fresh Rhine water, to prevent the slow contamination of groundwater by the infiltering sea.

The rise of sea level is the most probable and the most globally uniform consequence of any warming, and perhaps the most ominous. Most other effects—on freshwater storage and control, on forests and crops, on human health—seem mixed, if sometimes tragic. The Netherlands is well armed along its narrow frontier with its old enemy, the North Sea. But what about the wider and ill-defended frontiers of the Java Sea, the Gulf of Thailand, the Bay of Bengal or even the uncrowded wetlands of wealthy Australia and the U.S.? "We simply cannot allow uncertainty ... to prevent strategic planning" to help people control, slow down or move out of the way of increased sea flooding on the other side of A.D. 2000.

In Chapter 7 the author identifies a whole new body of knowledge essential for any public policy that touches science. He calls this contemporary discipline "mediarology." Like meteorology itself, the newer study is largely a matter of time scale. A half hour of exciting confrontation, even when it is forced and premature, is considered better TV or headline material than a protracted, step-by-step effort to set honest limits to doubt. But it is a poorer basis for public judgment. He documents his views with plenty of snippets from talk shows and TV specials, good examples and bad ones of how the public can learn even on the fly. In spite of all its defects, mediarology has brought the greenhouse effect to public attention worldwide. Now "a law of the [common] atmosphere" can arise, but only if and as the prosperous nations (those great fuel burners, now just a bit apprehensive) include among their urgent interests an apt investment in gentler ocean waves and more luxuriant forests a few decades ahead. Without a course change, the author fears, only inexpensive if valuable research can be done before the atmosphere itself has carried out its own definitive experiments.

The economists who look at costs and competitors are realists, not to say cynics; they gloomily anticipate that we will all have to adapt on our own, that we will not join to seek some control. There is one bright ray of hope: the powers have long overinvested in a curiously risky form of insurance, one taken out against wide warfare but ending in dangerous and costly arsenals. Wise action would cash in much of that half-trillion-dollar annual premium and from its proceeds begin to safeguard rich lands and poor lands alike, all who share the one big mobile pool of air.

THE NEMATODE *CAENORHABDITIS ELEGANS*, edited by William B. Wood and the Community of *C. elegans* Researchers. Cold Spring Harbor Laboratory, 1988 ($94).

Here is a singular monograph, an authentic modern Book of the Worm. This worm is no myth or monster but a slender thread: an animal about a millimeter long full-grown, a free-living species of soil nematode, found worldwide, that subsists as a filter feeder, mainly on bacteria. The high antiquity of the inconspicuous yet ubiquitous and abundant phylum of nematodes is undisputed, their body plan having been laid down in the Precambrian. This particular species is easy to grow in large numbers on agar plates coated with thriving lawns of human colon bacilli and in liquid cultures too. It matures as a hermaphrodite, producing both eggs and sperm, able to self-fertilize about three days after hatching. The mature young worm lays about 300 eggs during the next four days, then lives on to grow larger for two weeks more, without any additional cell divisions.

The beauty part is that the animal is transparent at all stages, and it browses contentedly on a little moist agar pad under the dissecting microscope. The result is that every cell division during development has been observed (by means of modern optical interference-contrast techniques and of video imaging), through all four stages of molting between egg and adult. The nematode can safely be anesthetized to keep it still for drawings or for microsurgery. At choice any single cell can be ablated by one well-controlled pulse from a dye laser. Development has been fully recorded within the egg as well, cell by cell from the first cleavage to hatching. The cellular ultrafine texture has been studied under the electron microscope, on many a serial microsection from nose to tail spike, enough to map out the entire cell architecture.

C. elegans follows an unfamiliar but well-understood reproductive pattern. The rare males that occur spontaneously in the population are able to fertilize the normal hermaphroditic forms, so that crosses are possible. Genes have been mapped on the six visible nuclear chromosomes, mostly by crossing recessive lethal mutations to see whether they lie on distinct genes. Drug-resistant mutants and those that lose mobility are known as well. Molecular DNA analysis has progressed quite far, although not yet to complete sequencing, base pair by base pair. The repetitive, garbled segments of DNA that space out the genes spelling meaningful recipes for proteins are common here, as in other animals and in plants. One copy of this entire genome is about 80 million base pairs long, half the size of the *Drosophila* genome, about 1 percent of the long human message.

Right now the Book of the Worm presents a descriptive paradigm that is unique in biology. Appendix 1 dares even to offer a complete parts list for this living creature: a dozen pages of coded components, cell by cell from founder cell to cells of the hermaphrodite vulva. Every cell of its body has been counted and mapped in space and time, from origin to death or to final division. Key cells of the germ line, both the embryonic founder cells and others present at hatching, have been followed too along their own distinct but indeterminate lineages.

Counting cells is best done by counting the easily recognized nuclei, even though the map is not exactly one to one: a few larger cells have become multinucleate by cell fusion, and a few cells are added by late division. In the adult animal there are just 959 somatic nuclei (plus those of the germ cells). Another 131 have died along the way (for example, in embryogenesis one cell serves to make the tail spike and then dies). The nervous system has more cells than any other, 302 neurons plus 56 of the neural support cells that tend and maintain the wiring. Fewer cells constitute the main wall layer of the body, fewer still the lengthwise muscles (no muscles engirdle the body tube), and so on for the gonadal structures, the alimentary and excretory systems and others.

The outermost layer that seals in the body fluid is a thin protein coat, secreted anew after each molting by busy cell layers just beneath it. The creature as a whole is an elastic cylinder that holds a pool of pressurized fluid, within which oxygen and nutrients diffuse without cellular aid. There are no blood cells, no immune cells, no circulating cells at all. A few special glandlike cells make some particles—not cells—that enter the fluid pool; the same glands even accumulate injected dyestuff, and yet the worm survives their ablation.

It is striking to scan the many pages of coupled diagrams that form a complete wiring schematic for the neural network. Every neuron is listed (100 or more different variants can be counted), and all their connections are indicated and classified, the result of long study under the electron microscope. Laser ablation of neurons has shown just which of the cells are required for forward and which for backward movement.

The worm has a modest repertoire of behaviors: it can recognize chemical compounds, even some pheromones of its own; it can migrate to familiar temperatures and eventually acclimates to a new temperature; it prudently avoids bumps on the nose, showing a more complex response to any touch by a fine hair on one of six sensitive surface cells. Functional analysis of this circuitry lags behind the geometric untangling of the wiring; surely simulations are on the way. Purposeful, routine male mating behavior is more complicated still; indeed, the uncommon male has about 10 percent more parts than the usual hermaphrodites, mostly neurons.

A family tree is drawn up for every cell in the embryo, division by division: its entire lineage from first cleavage to hatching, with maps of final nuclear positions. Genetic maps are here too, including a list of the mapped genes (now about a tenth of the estimated total of 5,000 or 6,000 genes), and other genetic data too.

This volume summarizes the outcome of some 25 years of enthusiastic collective effort initiated by Sydney Brenner at the MRC Laboratory of Molecular Biology in Cambridge in 1963. He put forward then the task of complete cell-by-cell description of the little multicellular nematode as a foundation for the understanding of animal development. "To start with," he wrote, "we propose to identify every cell in the worm and trace lineages." That first high task is now brilliantly complete, the work of those biologists who answered his call, of their students and now of their students' students, to be found in more than 60 laboratories around the world. The list of references includes about a thousand books and papers.

It is by no means clear that the secrets of animal development will in fact flow from the work on this single form, even if a fully interactive dynamics and the apropos software do some day come to complement these hardware specifications. Past choices of organisms for study have certainly been of major importance—consider the fruit fly, the white mouse, the grapefruit mold, the phages—but all the same, nature is not methodologically tidy. The tides of progress can rise in less elegant channels; major clues might come from elsewhere, to be fitted only later into some future user's manual of the worm.

The general reader should seek out this book, not only for its effective and explicit demonstration of so much of contemporary biology but even more for its high and audacious singleness of purpose. Old Aristotle put it well: from all the facts that science patiently assembles into an understandable whole, he said, "there arises in time a certain grandeur."

THE ART OF MEASUREMENT: METROLOGY IN FUNDAMENTAL AND APPLIED PHYSICS, edited by Bernhard Kramer. VCH Publishers, 1988 ($66).

The Physikalisch-Technische Reichsanstalt of Berlin (called the Bundesanstalt since its postwar translation due west to Braunschweig) was founded in 1887. From the start it was one of the major national laboratories responsible for precision standards. Its centenary can hardly be celebrated in this symposium without some look back at the glorious role that the PTR physicists Willy Wien, Otto Lummer, Ernst Pringsheim and Heinrich Rubens played in the great leap forward from classical to quantum physics.

It was almost soley their compellingly precise experiments that established the energy spectrum of blackbody radiation, for which Max Planck first derived the right form at the very end of 1900. He had to introduce his new constant, the quantum of action. The old curves are reproduced here, credible smooth peaks (apart from a few real dips due to molecular absorption in the air path). One 1901 result, measured with thermal detectors deep in the infrared at a wavelength beyond 20 microns, shows a tight fit to Planck's law but marked discrepancies with the two competing theories of the day. The quantum was here to stay.

The title of the book suggests an introductory account, but apart from the fine initial historical chapter the volume is meant for rather adept artists. Three topics are treated, each in several very knowing essays, nonmathematical but by no means elementary. First is a set of reviews of some current fundamental physics, including the use of lasers for testing a variety of deep issues: no other instrument "has proven similarly useful for basic physics." Next is an exposition of a few up-to-date experiments of precision, seen here not merely as "nervously delicate" measurements turned into ends in themselves but as part of the essential work of physics. Third come a fresh pair of papers. One reviews the varied applications in medicine of lasers at several distinct levels of peak power. The other tells of the clinical detection and mapping (with superconducting quantum interference devices) of the weak magnetic fields surrounding very small currents that flow in the brain and heart.

Here a few of these novelties must suffice. Plainly the precision metrologist seeks to be free of the complications of our imperfect artifacts: the distorting creep within the most stable metal rods, the frictional losses of vibrating quartz crystals, the corrosion and dustiness of the best weights. On to nature's perfect modules! The trend is decades old; we all know that a beam of cesium atoms—rather than crystal or the spinning earth—now defines time and frequency.

Holding a single atom (or a small cloud of them) tightly in place for a considerable period of radiative probing is the new path open to strictly modular definitions of key physical quantities. Ion traps—electrodes with artfully maneuvered electric and magnetic fields—have long served to store ions in the vacuum. The key new step is the clever use of laser light to remove random motion from such trapped particles, by inducing each moving atom to give some thermal energy to the copious photons in a well-tuned beam; it is much better than depending merely on cold walls to reduce random thermal motion. The trapped ion, once it is cool enough, sees mainly the fields of the trap slowly drifting by.

Any isolated ion of course dwells in its own inertial frame, innocent of any contact with the earth, aside from the weak field of gravity. One particular transition of a beryllium ion is known to respond only to a rotating component of the applied radio-frequency field. The direction of that electromagnetic field is fixed in the lab, of course, but it rotates nonetheless as trap, laboratory bench and supporting floor turn around with the earth once every sidereal day. The requirement for detecting that very slow field rotation is an accuracy of about a part in 10^{14}, and it is on the verge of realization. Surely such mastery will one day make a time and frequency standard of unmatched precision; it is no dream to foresee an isolated atom that controls a clock good to a part in 10^{18}.

A second modularity also tempts

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the standard-givers. The mass unit is currently kept as a fist-size chunk of metal, neither reproducible nor unchanging; the relative atomic masses that have long been so well measured through particle beams in electromagnetic fields cannot to this day be compared with precision to any visible and weighable masses. A small gap remains open in our basic physics.

A report by an American guest, the physicist responsible for this work at the National Bureau of Standards, reviews the changing state of affairs. Between 1970 and 1980 a joint effort was made by the NBS and the Physikalisch-Technische Bundesanstalt to relate X-ray wavelengths to optical ones with modern precision. The concept was to use the purest, most perfect crystal of silicon as the physical structure of a monolithic interferometer. The X-ray wavelengths match that atomic lattice pretty well; those interference patterns are not hard to measure. A common baseline defined on the same piece of silicon would then be measured also, but in terms of optical wavelengths; the calibrated atomic lattice spacing would be known to many decimals in terms of some sharp, laser-generated optical wavelength. From its optically measured dimensions you could then compute the number of atoms in one simple block of silicon; weighing that block would define the kilogram anew in atomic terms.

By the early 1980's it became plain that the National Bureau of Standards results and those of the PTB—the only measurements—disagreed in the parts-per-million range, four times their estimates of combined error. It was the NBS that had less control over its systematic errors, and so its experiment was redesigned. By 1986 it became clear that a subtle geometric tilt had entered during the scanning of a hundred fringes under laser feedback control in visible light while the crystal was advanced through a million atomic spacings checked by X ray.

The new design has improved matters, and yet the last word has still to be pronounced, a cautionary example of what high precision demands. "I expect," the physicist says (of the atomic repeat distance of the ultrapure sample of silicon now at hand), "that the 'final' result will lie near 0.19201554(2) nanometer." That gap in physics will soon be closed.

DINOSAUR TRACKS AND TRACES, edited by David D. Gillette and Martin G. Lockley. Cambridge University Press, 1989 ($54.50). **THE LOST WORLD & THE POISON BELT: PROFESSOR CHALLENGER ADVENTURES BY SIR ARTHUR CONAN DOYLE.** Chronicle Books, 1989 (paperbound, $8.95).

It was Holmes himself who told us that "there is no branch of detective science so important and so much neglected as the art of tracing footsteps." This delightful volume, a fully technical symposium report of uncommon readability, takes to heart what Holmes implied. Some 70 students of dinosaur prints (and of their eggshells, nests and droppings) gathered in Albuquerque in the spring of 1986. Under one roof were the majority of the world's dinosaur-trace experts from all continents. The first modern volume ever published in the subdiscipline was assembled, all papers expertly and multiply reviewed and edited, with unusual devotion and success, into a handsome book. Even its taxonomic rigors need not put off a general reader. Some history, more interpretation, many regional and individual site reports, and new techniques for recording and comparison are addressed, with a useful introduction and summary.

The gaits of living animals are distinguished by the sequence and duration of the footfalls. Dinosaurs, whose timing cannot be observed, need special treatment. Three gaits—walk, trot and run—can be considered (not the eight or nine gaits described for mammals). Not even study of the skeleton can decide whether diagonally opposite limbs move as in a normal walk or whether two limbs on one side move in synchrony, in the gait called ambling. Most dinosaur trackways record ancient walking; rarely, what is found implies running.

A sandstone and claystone quarry in Queensland, Australia, offers 4,000 dinosaur footprints that are the setting for a brief drama. A dozen really big prints are there from one carnosaur, and very close to it are the tiptoe tracks of 160 or more little bipedal fellows: surely this was a stampede of small dinosaurs, slipping and scraping away from a fierce predator stalking their waterhole.

Were the carnivores fast runners? The fact is that predators today do not show much ability at sustained running (cheetahs, if as fast as claimed, are exceptional); it is the big quadruped herbivores that run best, and so it was among dinosaurs. Big crocodiles can charge for 100 feet or so, and powerful dinosaurs could do even more. They were not long-distance runners but agile, multiton springing, sprinting hunters.

There are curiosities in plenty. Many sites show dinosaur trampling that is dense enough to disturb the sedimentary layers themselves. There is a name for the process: dinoturbation. In Utah there are working coal mines whose ceilings bulge with casts that formed in dinosaur prints made across what was once the upper surface of a layer of swamp peat. The peat turned to coal; the hollow print filled with silt or sand that turned to stone, and eventually the thick seam of coal was entered and removed by the miners. The footprint casts are still there in the ceiling of the emptied mine gallery. They are hazards well known to the miners, for sometimes they fall; one big stony cast weighed 140 kilograms. It is usual to fasten them to the roof with long steel bolts. No other dinosaur activity is known so to endanger human beings across the 80 million years since the Cretaceous!

In 1909 Arthur Conan Doyle moved to a country house in Sussex, on the Weald. Soon he noticed big fossil tracks of dinosaurs in a quarry nearby. They were nothing rare, but they were wonders all the same; he persuaded an expert to come to examine them, and he made casts for himself. By 1912 he had written—on a bet that he could produce a fresh adventure—his inspired story of bullfroglike Professor Challenger, who led three other articulate Edwardian types to clamber up an isolated basalt plateau somewhere between the Amazon and the Orinoco. They found the place astonishingly populated by dinosaurs big and little, by ape-men and by cavemen, all forms that had come up at very different times (for Doyle knew his geology).

That huge three-toed print before their eyes was "the father of all birds" for sure, said one explorer. (The Reverend Edward Hitchcock of Amherst College had first come to that same wrong conclusion in the 1830's.) "I'll stake my good name as a shikari that the track is a fresh one." The Professor, though, understood at once: "—a dinosaur. Nothing else . . . " That experience on Maple White Land and in the Albert Hall, artful composite of romance and realism, has given important pleasure to many a reader, some of whom sought and found a way into paleontology. This new edition of *The Lost World* is bound to find an enthusiastic new audience of many ages. (The second tale in the book is a slighter one, an extended short story with a single implausible surprise, hardly worthy of the grandly irascible Professor Challenger.)

ESSAY

How to secure our common future

by Gro Harlem Brundtland

When the 20th century began, neither human beings nor human technology had the power to radically alter the global ecosystem. Today, as the century draws to a close, human beings in ever-increasing numbers have that power, and as a result of their activity on the planet, major unintended changes are taking place in the atmosphere, the biosphere and the hydrosphere. These changes outstrip our present ability to cope; the world's financial and political institutions are out of step with the workings of nature.

Poverty is a major cause and also a major effect of global environmental problems. It is futile to seek solutions to environmental disturbances without considering them from a broad perspective that encompasses the factors underlying world poverty and the inequalities within and among nations. For developing countries, poverty lies at the heart of all issues. The poor are forced to eat next year's seed corn, to cut scarce forests for fuelwood. Although such practices may be rational short-term tactics for survival, in the longer term they can only result in disaster.

Yet it is both futile and an insult to the poor to tell them that they must remain in poverty to "protect the environment." The World Commission on Environment and Development concluded in its 1987 report, "Our Common Future," that sustained economic growth, which is a precondition for the elimination of mass poverty, is possible only within a more equitable international economic regime. The commission called for a new era of economic growth—growth that enhances the resource base rather than degrades it. We know now that growth and development need not be environmentally degrading, that in fact growth can create the capital and the capacity necessary to solve environmental problems. And without growth, how can we provide for twice the present population some time in the next century, when we cannot provide for everybody today?

Those of us who live in the industrialized world have an obligation to ensure that international economic relations help rather than hinder the prospects for sustainable development. It is our duty, as well as in our own self-interest, to do so. Commodity prices must be adjusted to provide a fair international distribution of income. Official development-assistance programs and private loans to developing countries, as well as private investment, must be improved, both in quality and in quantity. Policies—both national and international—will have to be changed so that capital transfers are sensitive to environmental impacts and can contribute to long-term sustainability.

Energy is another area of vital importance. As nations continue to develop they will require more, not less, total energy; their industrialization and rapidly growing populations will depend on it. Yet global energy consumption, even at its present levels, has already created serious environmental woes. How can an increase in energy use be tolerated without further deterioration of the global ecosystem? The solution, we believe, is to place energy-efficiency policies at the cutting edge of national energy strategies, regardless of the relatively low price of such traditional fuels as coal and petroleum.

The commission found no absolute limits to growth. Limits are indeed imposed by the impact of present technologies and social organization on the biosphere, but we have the ingenuity to change. And change we must. The report of the commission offers governments and international institutions an agenda for change. After a period of standstill and even deterioration in global cooperation, the time has come for higher aspirations, for increased political will to address our common future.

The United Nations system with all of its specialized agencies has the capacity to reach our common goals. We call for a fundamental commitment by all governments and institutions to make sustainable development the guiding principle of the international community. To secure our common future, we need a new international vision based on cooperation and a new international ethic based on the realization that the issues with which we wrestle are globally interconnected. This is not only a moral ethic but also a practical one—the only way we can pursue our own self-interests on a small and closely knit planet.

Environment and development have come to the top of the international agenda. Policies to promote sustainable development must be devised by nations both in the Northern and in the Southern Hemisphere, and they must also take into account the imbalances in international economic relations that prevail today.

Our ambition should now be to make the 1990's a decade of rapid social, economic and environmental cooperation rather than confrontation. A global economic consensus for growth should be developed. To be consistent with sustainable development, such a consensus must observe ecological limitations. It should include sound economic policies within developing countries and be particularly sensitive to the poorer nations in Asia, Africa and Latin America.

It is time for a global economic summit. Would it not be timely to consider both our economic and environmental concerns at such a summit, given the critical linkage between the two? The large ecological issues—the greenhouse effect, the disappearing ozone layer and sustainable utilization of tropical forests—are tasks facing humankind as a whole. The World Commission on Environment and Development presented innovative ideas on how to mobilize additional financial resources. The time is now ripe to explore these problems both institutionally and financially.

Our generation is the first one to have seen planet earth from a distance. And from that perspective it is all too apparent that our species is dependent on a single tiny, fragile globe floating in space, a closed and vulnerable system.

The report of the commission offers a challenging agenda. We were asked to offer strategies for the future and to provide motivation for adopting new policies. In demonstrating the real threats to both our present and our future and showing that workable solutions are at hand, our report provides that motivation. We hope that it will ultimately achieve its purpose of generating the debate and discussion that are necessary to revitalize international cooperation.

GRO HARLEM BRUNDTLAND, who was chairman of the World Commission on Environment and Development, is the Prime Minister of Norway; she served as Norway's Minister of Environment from 1974 to 1979.

The Pressure Extrapolation

This report on research at General Motors first appeared in December, 1986.

The Pressure Extrapolation

Modern automotive catalytic converters contain rhodium which promotes chemical reactions to remove pollutants from a car's exhaust. Scientists at the General Motors Research Laboratories have recently made discoveries about one such chemical reaction, the reaction between nitric oxide and carbon monoxide, pointing the way toward new or improved catalysts.

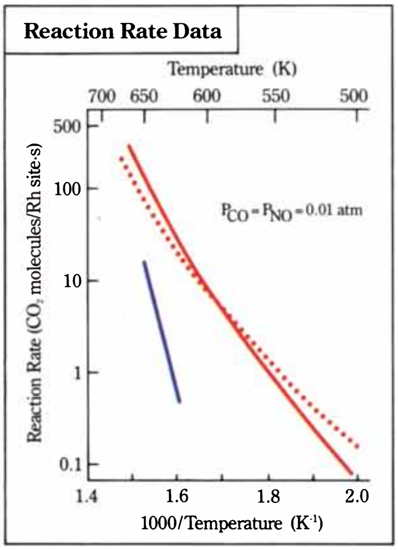


Figure 1: Rate comparisons for the NO-CO reaction. Measured data over single crystal Rh(111) (solid red line) and over supported Rh (blue line); model predictions (dotted red line).

Figure 2: Schematic representation of the elementary intermediate steps for the NO-CO reaction.

MOST FUNDAMENTAL catalytic studies using surface science techniques require an ultrahigh vacuum environment (10^{-13} atm). They are best suited for studying well characterized materials, such as metal single crystals. Catalytic reactions of practical interest, however, involve polycrystalline materials, in the form of small metal particles dispersed on supports. And they take place at atmospheric pressures rather than in an ultrahigh vacuum.

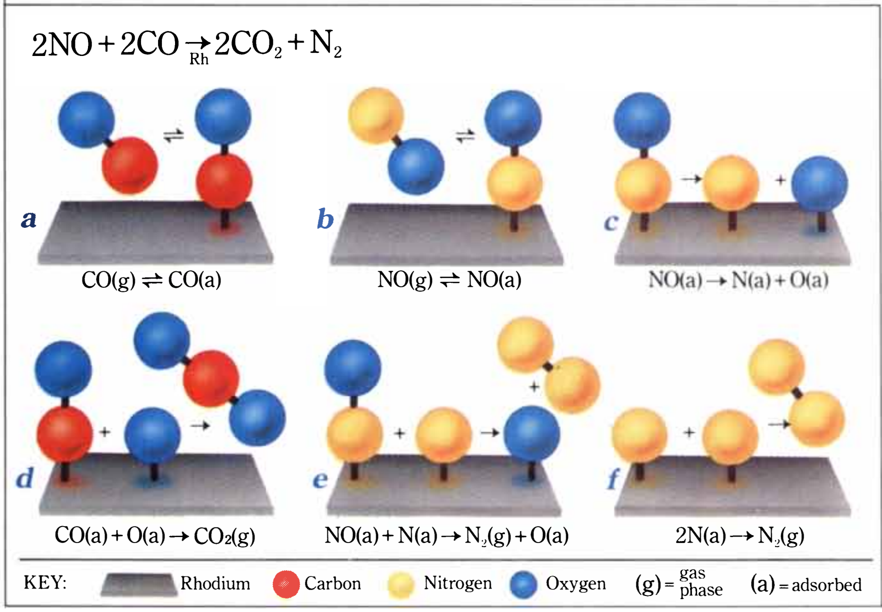
Now Dr. Galen B. Fisher and Dr. Se H. Oh have demonstrated how the wealth of chemical information obtained from ultrahigh vacuum (UHV) studies of ideal, single-crystal catalysts can be applied to the understanding of real-world systems that have different catalyst environments and that operate at much higher pressures.

These researchers concentrated their studies on the many chemical reactions that occur in modern automotive catalytic converters. One such reaction is the reduction of nitric oxide (NO) by carbon monoxide (CO) over a rhodium (Rh) catalyst to yield carbon dioxide (CO_2) and nitrogen (N_2) (Figure 2).

Dr. Fisher used various surface science spectroscopies in ultrahigh vacuum to study all of the elementary reactions over a rhodium single crystal [Rh(111)] that might be involved in this specific reaction. Over several years he measured the rates and determined the activation energies of each of these reactions. For most of these reactions, this was the first time these parameters had been measured. Based upon these results, Dr. Fisher hypothesized that the elementary reactions shown in Figure 2(a-f) were the significant steps involved in the NO-CO reaction and that nitrogen recombination and desorption (Figure 2f) was the rate-controlling step on Rh(111).

Dr. Fisher and Dr. Oh also initiated kinetic studies of this reaction at realistic reactant partial pressures and temperatures using two different catalysts—one was a rhodium single crystal [Rh(111)], and the other consisted of rhodium particles supported on alumina [Rh/Al_2O_3]. The rhodium concentrations on the support were similar to those used in an automotive catalytic converter. The studies with the single crystal at realistic, high pressures were done in collaboration with Dr. D. Wayne Goodman of Sandia National Laboratories.

At the same time, Dr. Oh devised a mathematical model for this reaction. The model consists



This research is an example of the depth of GM's understanding of the interaction between the automobile and the environment. Drs. Fisher and Oh have since studied the effects of rhodium particle size and support material on the CO + NO reaction. Their coupling of UHV and kinetic studies has also led to a fuller understanding of the CO + O_2 *reaction.*

of steady-state conservation equations for the surface species, based on the reaction mechanism and the rate expressions for the individual reaction steps determined in Dr. Fisher's UHV studies. Overall reaction rates could then be computed from the surface concentrations satisfying the conservation equations. The reaction rates predicted by this model, which depend only on reactant partial pressures, are shown in Figure 1 (dotted red line).

The kinetics of the NO-CO reaction measured over a rhodium single crystal using realistic reactant partial pressures are shown in Figure 1 (solid red line). The agreement with the model predictions indicates that Drs. Fisher and Oh had correctly identified all of the intermediate reaction steps and confirms that, in this case, nitrogen recombination and desorption (Figure 2f) is the rate-controlling step on Rh(111). The fact that the agreement is so good also indicates that the rates of the elementary reactions measured under UHV conditions are still valid at realistic reactant partial pressures—a pressure extrapolation of more than ten orders of magnitude.

THE KINETICS of the NO-CO reaction measured over the supported rhodium catalyst (Figure 1, blue line), however, were much slower than predicted by the model. In addition, infrared studies have shown that NO is the predominant surface species on the catalyst, suggesting that in this case NO dissociation (Figure 2c) is the rate-controlling step. In fact, if the rate constant for NO dissociation measured under UHV conditions and used in the model is reduced by a factor of 2000, the kinetics of the NO-CO reaction measured over the supported rhodium catalyst are correctly predicted.

The difference between the kinetics of the NO-CO reaction measured over a rhodium single crystal and the kinetics measured over supported rhodium shows that this reaction depends on the environment of the rhodium in the catalyst. The reaction model strongly suggests that the NO dissociation reaction is the reaction step most sensitive to the rhodium environment.

"While our reaction model cannot tell us why NO dissociation is slower on supported rhodium," observes Dr. Oh, "it can help identify the kinds of studies necessary to clarify the origins of such sensitivity." Comparative kinetic studies can also provide useful insights for developing improved NO reduction catalysts. "Our studies have already told us," adds Dr. Fisher, "that one possible path to improving automobile catalysts is to make modifications that increase the NO dissociation rate."

General Motors

MARK OF EXCELLENCE

THE MEN BEHIND THE WORK

Dr. Galen B. Fisher (left) and Dr. Se H. Oh are both Section Managers in the Physical Chemistry Department at the General Motors Research Laboratories.

Dr. Fisher is a Senior Staff Research Scientist, and heads the Surface Chemistry Section. He attended Pomona College as an undergraduate and received his graduate degrees in applied physics from Stanford University. Before coming to GM in 1978, he did postdoctoral studies at Brown University and worked at the National Bureau of Standards. Galen now lives in Birmingham, Michigan, with his wife and their two sons.

Dr. Oh is a Principal Research Engineer, heading the Heterogeneous Rate Processes Section. He received his undergraduate degree from Seoul National University and holds a doctorate in chemical engineering from the University of Illinois. Dr. Oh did postdoctoral work at the University of Toronto prior to joining GM in 1976. Se and his wife now live in Troy, Michigan, with their two sons.