SCIENTIFIC AMERICAN

THE BIOSPHERE

ONE DOLLAR

September 1970


SIEMENS
INTERNEINHEIT PROGRAMMSTEUERUNG 2
RÜCKSETZEN
BETR. KLAR
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INTERNEINHEIT PROGRAMMSTEUERUNG 2
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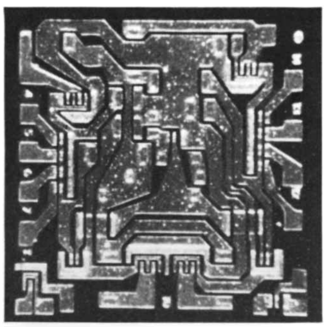
Siemens

A three billion dollar name in quality products. Our new data communications exchange moves information 1000 times faster. First big test, '72 Olympics.

Athletes at the next Olympic Games will undoubtedly be the fastest in history. And the demand for fast, accurate information concerning their record-setting events will be unprecedented.

To satisfy this demand, reports, stories, statistics, and predictions, as well as other kinds of messages and data, must be routed, processed and transmitted around the world.

A major part of this job will be done by a completely new kind of data exchange that Siemens is now installing in Munich. We call it an electronic data switching system. EDS for short.


Microcircuit design permits high-speed data transfer.

The new system is the only one of its kind now in operation offering the capacity to handle data traffic loads of this size. It handles data 1000 times faster than a conventional switching system.

The need for the EDS system is critical because the increase in data traffic even during the next few years will be staggering. For example, projections indicate 50,000 computers will be linked through public networks to 1,200,000 terminals by 1974.

Like a computer controlled automatic telephone exchange, the Siemens EDS system provides interconnections between various communications channels. But there are very significant differences.

High speed digital messages from data processing systems consist of combinations of short pulses. Since these signals are completely unlike the complex waveforms of voice transmissions, noise that is common in telephone connections can often result in disastrous errors when data is transmitted on voice channels. In addition, data signals must often be translated, stored, speeded up or slowed down to match equipment at the receiving end. And this is what the new system provides.

EDS contains a unique asynchronous time-division multiplex system making it code and speed transparent. This is particularly advantageous in transmitting binary signals and handling data switching functions.

Siemens has designed comprehensive software in order to safeguard the high availability of the system.

Siemens EDS systems are designed to meet exacting requirements of data communications networks like Telex, TWX, Hotline, and various inquiry systems as well as international carriers and independents.

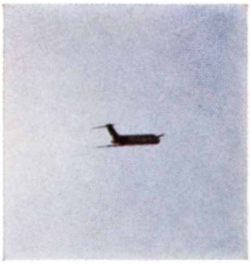
For more information, please contact Peter Stummvoll, Siemens Corporation, 186 Wood Avenue South, Iselin, N.J. 08830.

Siemens. A worldwide company in telecommunications, instrumentation, medical equipment, power engineering, electronic components and data systems.

Georgia, the unspoiled.

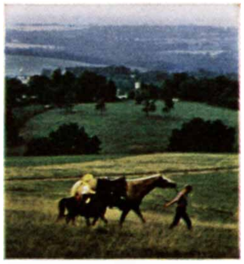
America, there's still a part of you left the way you were meant to be: Clean. Green. New. And full of promise.
This is Georgia, the unspoiled–with the right balance of industry and environment, and a proper respect for both.

Offering those who believe in–and practice–private free enterprise, a unique package of industrial advantages.
Advantages in land, sea, air, water, and quality of life.
From time to time, we'll be showing you what the advantages of Georgia, the unspoiled, could mean to you. Your family. Your company. And your company's profits.
In the meantime, the Fantus Company has put all the profit potential facts together for you. Just send us the coupon. And we'll send you the way things are in Georgia.



Air you can breathe.
Yet carries tons of cargo from the nation's third busiest airport.

Water you can drink.
Yet an abundant supply for industry.

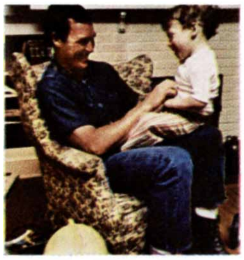


Land to raise children on.
Yet plenty of room for industry growth.

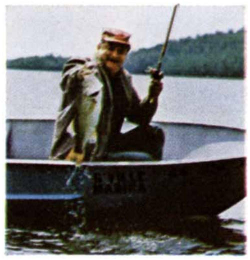
A sea fit to swim in.
Yet handles cargo through two deepwater ports.

Gleaming beaches and deepwater frontage plant sites.

A father and son sharing the joys of major league sports.



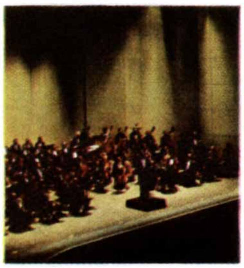
People. Trained for you free.
Prepared to work hard for an honest wage.



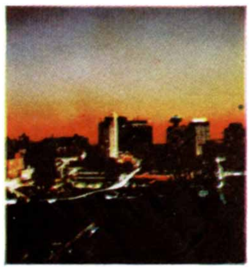
Fresh and salt water fishing.

A highway system serving the distribution center of the Southeast.

Exciting nightlife, unspoiled by garish neon signs.



A place where a great symphony plays.



And tall, unspoiled cities.

A computerized system to select industrial sites.

Georgia Department of Industry & Trade, Industry Division,
P.O. Box 38097, Dept. SC-1, Atlanta, Georgia 30334
Send free information on: ☐ **Fantus Cost Studies,**
☐ **other industrial data,** ☐ **travel attractions.**

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company ____________
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city ____________ state ____________ zip ______

The Fantus Company has prepared for Georgia, locational cost analyses for 31 SIC industries. They show in detail, the profit potential for a Georgia operation. And they're free.

Established 1845 **SCIENTIFIC AMERICAN** September 1970 Volume 223 Number 3

ARTICLES

DEPARTMENTS

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THE COVER

The picture on the cover symbolizes the theme of this issue of SCIENTIFIC AMERICAN: the biosphere, or the thin film of living matter at the surface of the earth that maintains itself by cycling many of the chemical elements (notably hydrogen, oxygen, carbon and nitrogen) and energy from the sun. The picture is a detail from "The Dream," painted by Henri Rousseau in 1910. The painting, a gift of Nelson A. Rockefeller to the Museum of Modern Art in New York, is reproduced in its entirety above. Both reproductions are presented with the generous permission of the Museum of Modern Art.

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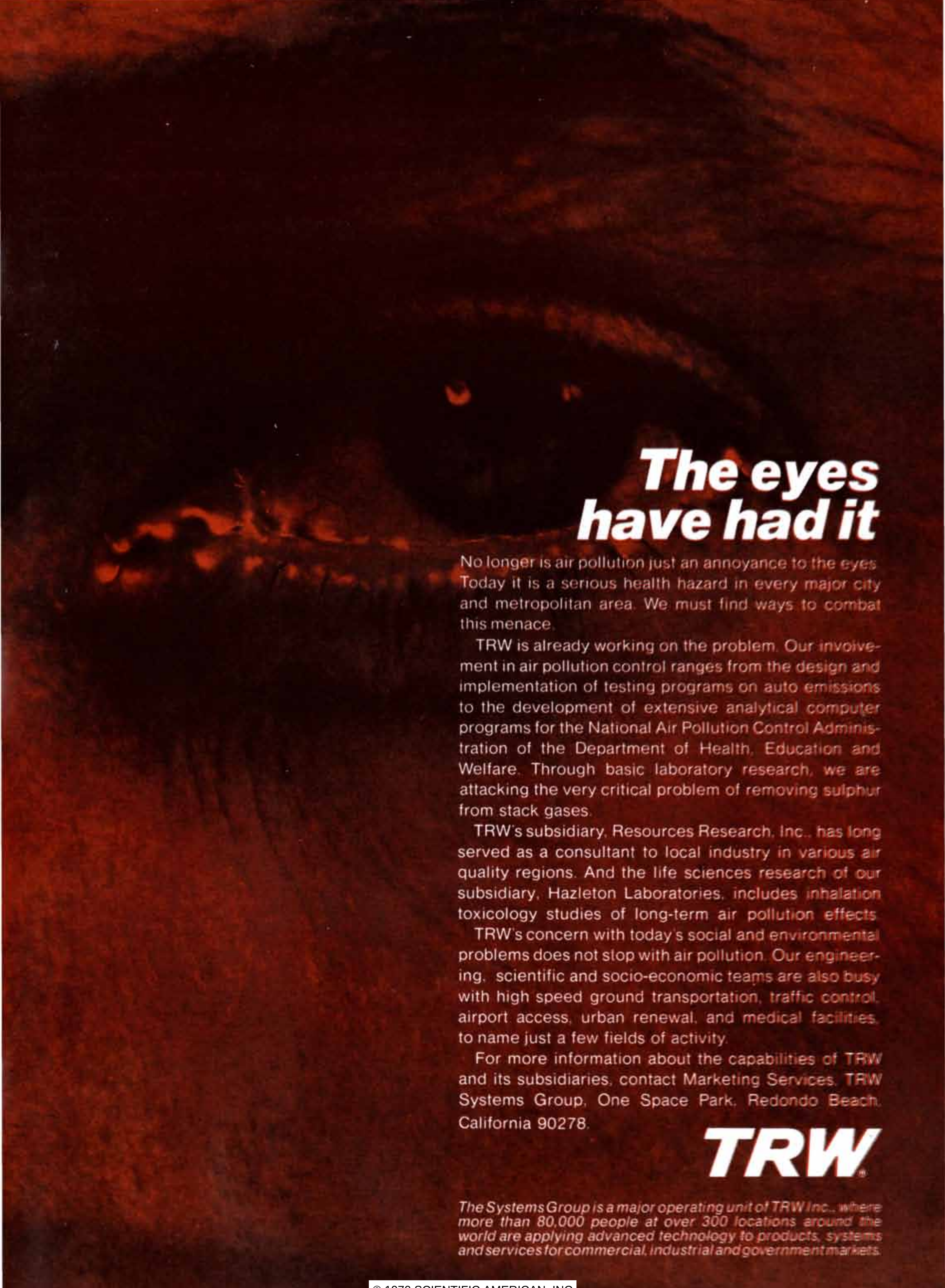
The eyes have had it
No longer is air pollution just an annoyance to the eyes. Today it is a serious health hazard in every major city and metropolitan area. We must find ways to combat this menace.
TRW is already working on the problem. Our involvement in air pollution control ranges from the design and implementation of testing programs on auto emissions to the development of extensive analytical computer programs for the National Air Pollution Control Administration of the Department of Health, Education and Welfare. Through basic laboratory research, we are attacking the very critical problem of removing sulphur from stack gases.
TRW's subsidiary, Resources Research, Inc., has long served as a consultant to local industry in various air quality regions. And the life sciences research of our subsidiary, Hazleton Laboratories, includes inhalation toxicology studies of long-term air pollution effects.
TRW's concern with today's social and environmental problems does not stop with air pollution. Our engineering, scientific and socio-economic teams are also busy with high speed ground transportation, traffic control, airport access, urban renewal, and medical facilities, to name just a few fields of activity.
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SCIENCE/SCOPE

NASA's Atmosphere Explorer satellite, proposed by Hughes following a study for Goddard Space Flight Center, will carry a propulsion system that will enable it to climb to an apogee of 2500 miles in its variable orbit. Every two hours it will dip back into the upper atmosphere for 10 to 20 minutes, swooping within 90 miles of earth.

The "yo-yo" satellite's scientific objectives will be to obtain data on the behavioral relationship of the upper and lower atmospheres, solar energy absorption, density of the atmosphere's charged-particle structure, and the diurnal bulge that appears to circle the earth as the sun heats the atmosphere.

The longer, sharper noses of modern missiles and high-speed aircraft make mechanically scanned antenna systems more and more difficult to use. The elongated radomes increase boresight errors; the space between nose tips and antennas cannot be used for other equipment. An approach to the problem is a conformal-array antenna system that Hughes is investigating in a research program for the U.S. Navy.

Because it has no moving parts, this electronically scanned system eliminates the conventional radome. Its radiating elements are set flush in the surface of the nose cone. Rapid-beam scanning over a wide field of view, including the direction of the missile's axis, is under investigation.

When NASA's Synchronous Meteorological Satellite is launched in 1972 it will carry an instrument that can map the clouds over North America by night as well as by day. Called VISSR (for Visible Infrared Spin-Scan Radiometer), it is being built by Santa Barbara Research Center, a Hughes subsidiary. Earlier spin-scan cameras by SBRC, which are now taking daily cloud pictures from Applications Technology Satellites I and III, are limited to the visible spectrum. VISSR will also operate at infrared wavelengths to take nighttime pictures of "excellent" definition.

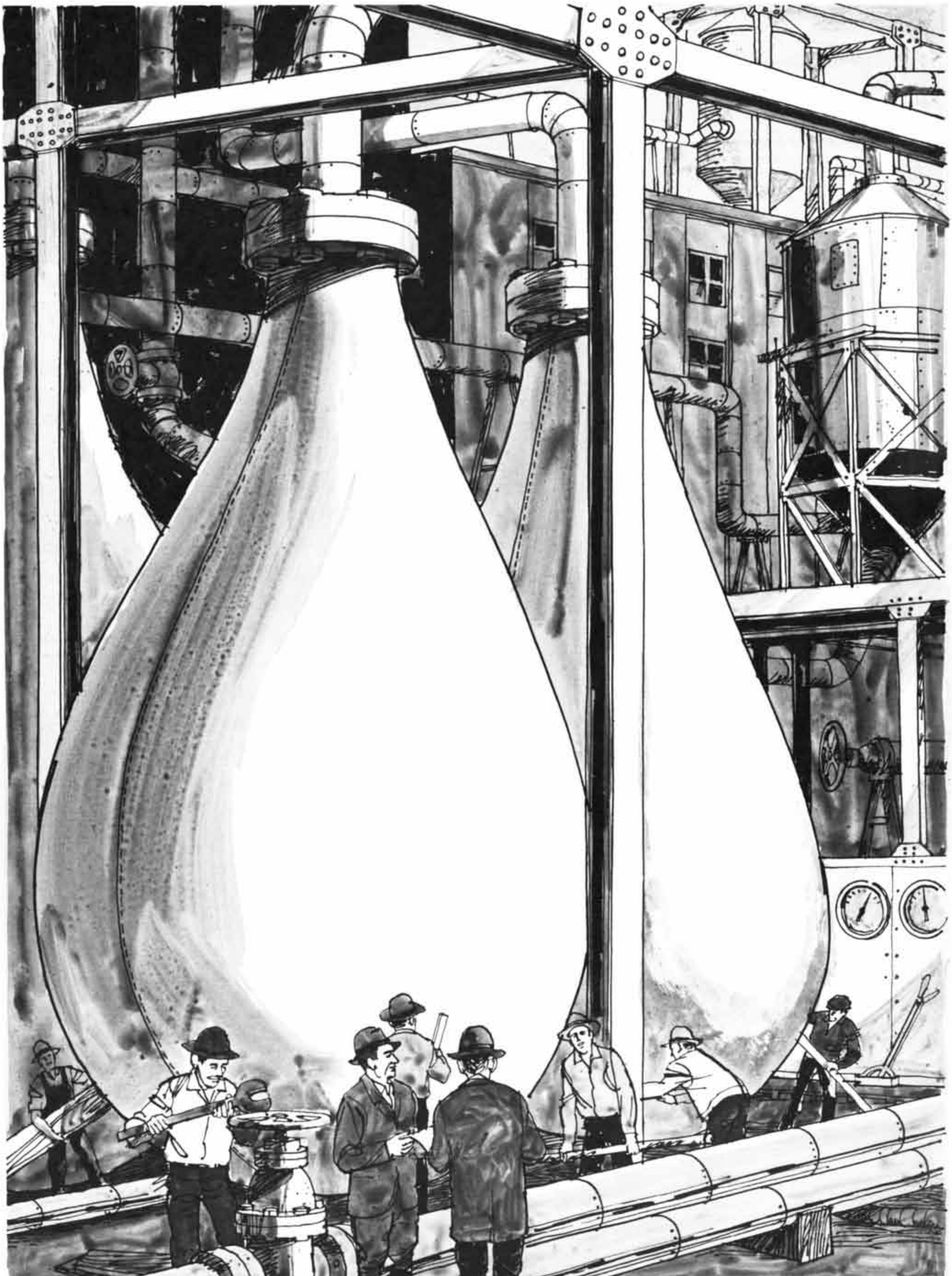
Additional radar receiver engineers will be hired by Hughes for work on the U.S. Air Force's AWACS (Airborne Warning and Control System) program. Requirements: BSEE, U.S. citizenship, at least three years experience in design of complex receivers and frequency synthesizers, including exciter circuits and MTI, pulse doppler, and ECCM techniques. Please write: Mr. R. S. Roth, Hughes Aircraft Company, P.O. Box 3310, Fullerton, California 92634. Hughes is an equal opportunity employer.

A new generation of display devices -- cockpit readouts, large screen projection, and even thin, flat TV screens -- may eventually result from Hughes' applied research in liquid crystals. Liquid crystal devices are simple, rugged, low in cost. They reflect light instead of emitting it, and thus require very little power (less than one milliwatt per square inch of display). Pictures can be viewed in bright sunlight without being washed out, or by ordinary instrument-panel lighting in the dark. Images can be short- or long-lived, can be stored temporarily or indefinitely, can be erased immediately and recalled later.

Creating a new world with electronics

HUGHES

HUGHES AIRCRAFT COMPANY



Environmental Innovation: 1952

It may look like a Rube Goldberg. But it was the beginning of the Vaporsphere and part of a $125 million environment improvement program that's keeping air and water cleaner around Weyerhaeuser mills.

The year was 1952. The contraption: the first steps taken to eliminate certain industrial air pollutants from kraft pulp mills.

Three 3,000-cu.-ft. World War II barrage balloons were used to hold a peak gas flow of hydrogen sulfide, methylmercaptans, methylsulfide, methyldisulfide, turpentine vapors and other volatile organics.

The gas was mixed with primary air in a furnace and burned. Gas ratios of 200 to 1 gave sufficient safety margins of combustibility.

The barrage balloons safely survived the surges of gas into them and then the slower release of gas from them.

This was the pilot plant. Eighteen years ago. At a time when a smoking smokestack meant economic prosperity, not a choking planet.

It was part of a concentrated pollution abatement program by Weyerhaeuser that has now grown to an annual investment of more than $15 million. And since World War II has totalled more than $125 million for improvement in environmental quality.

Out of the barrage balloon grew the Weyerhaeuser Vaporsphere — a real breakthrough in control of kraft pulp mill air pollutants.

The Vaporsphere design is a steel sphere with a semispherical plastic lined cloth diaphragm connected to the equator of the sphere.

The gas leaves the Vaporsphere and passes through a flow controller and flame arrester. Then it is mixed with the primary air of the lime kiln. The weight of the diaphragm and the slight suction of the primary air intake are adequate to move the gas from the Vaporsphere to the lime kiln. Ratio of air to gas is sufficiently high to dilute the gas well below the limits of inflammability.

The Weyerhaeuser Springfield, Oregon, mill was the first to be equipped with a Vaporsphere. Other Weyerhaeuser kraft pulp mills now have the equipment. And, as has been the practice in the pulp industry for years, the invention was made available to other pulp manufacturers.

The Vaporsphere and other Weyerhaeuser applications of technology like the black liquor oxidation process, chlorine gas scrubbers and a turpentine recovery system have reduced odorous gas emissions at some Weyerhaeuser mills 95%. Now Weyerhaeuser is at work with Nalco Chemical, Chicago, on a process of removing additional kraft mill odor producing compounds from the air.

Improvement in air quality is just one of the many concerns at Weyerhaeuser. Water quality is an equal concern. At the Plymouth, North Carolina, pulp mill, a new $2 million waste-water treatment system with 21 aerators occupying 500 acres is helping keep the Roanoke River clean.

For more than 40 years Weyerhaeuser has been committed to various forms of environmental research and implementation. Specifically: more than 1,100 of our employees devote a substantial amount of their time to environmental protection.

After all, we have 44,000 employees who would like to make this a decent place to live and breathe, too.

For free booklet: "Our Environment," write Director of Air and Water Resources, Box N-5S, Tacoma, Washington 98401.

Weyerhaeuser

LETTERS

Sirs:

Philip E. Converse and Howard Schuman ["'Silent Majorities' and the Vietnam War," SCIENTIFIC AMERICAN, June] note that a Gallup poll in March, 1968, showed that 40 percent of the population were in favor of stopping the bombing of North Vietnam and 51 percent were opposed. Shortly thereafter President Johnson announced his decision to stop the bombing and in April the same poll showed that 64 percent approved of this decision and 26 percent did not. In their article Drs. Converse and Schuman conclude "it is safe to assume that the shift of some 25 percent in one month was largely due to the President's speech."

In reality it is safe to assume only that the shift was due to the President's decision. Indeed, it indicates that a great portion of the American people tend to support any action of their leaders rather than formulate an opinion of their own.

Consider the Gallup poll in the summer of 1966, when 70 percent of the people approved of the current policy of bombing oil storage dumps in Haiphong and Hanoi, compared with the poll two months later that indicated 51 percent agreed with the proposition that the U.S. submit the Vietnam problem to the United Nations and agree to accept the decision, whatever it might be. Although these two polls appear odd in juxtaposition, they can also be explained by a willingness to allow someone else to make the decisions on Vietnam. Such an explanation also explains public support of President Nixon's November speech that indicated we were getting out of Vietnam, albeit slowly, and the similar support given the Cambodian operation, which many view as inconsistent with the President's expressed intentions in November.

The implication of this explanation is that there is indeed a "silent majority" supporting President Nixon's policies in Vietnam, a majority that will accept any decision the President makes that he indicates, in his judgment, will eventually bring this long war to a conclusion. The "silent majority" are therefore well named. The members of this group are silent because they have little opinion of their own, except dissatisfaction that we've been there so long. That they are a majority indicates America still has a long way to go before the goal of participatory democracy is reached. In failing to emphasize this the authors have missed the forest in their preoccupation with the trees.

ROBERT B. MARTIN, JR.

Law Offices of Keatinge
and Sterling
Los Angeles

Sirs:

The excellent article on "Conversion to the Metric System" [SCIENTIFIC AMERICAN, July] by Lord Ritchie-Calder covers well the technical side of the problem but neglects the human side. As various wags have pointed out, the changes in our language arising from going to the metric system will be substantial. One will soon have to say, "I wouldn't touch him with a three-meter pole"; "A miss is as good as 1.6 kilometers"; "I'll thrash you within 2.54 centimeters of your life"; "All wool and .9 meter wide," and perhaps even "Hectares and hectares, and they're mine, all mine."

Yea, verily. Changes are coming.

ALAN POPE

Director of Aerothermodynamics
Sandia Laboratories
Sandia Corporation
Albuquerque, N.M.

Sirs:

In his most interesting article "How Snakes Move" [SCIENTIFIC AMERICAN, June] Carl Gans says that a Russell's viper could not have killed the victim in A. Conan Doyle's "The Adventure of the Speckled Band" because a Russell's viper is incapable of climbing a rope. The only trouble with this charming anecdote is that the snake in "The Adventure of the Speckled Band" is not a Russell's viper but a swamp adder. If the swamp adder happens to be a constrictor, Holmes is still right.

SUSAN KUHLMAN

New York, N.Y.

Sirs:

Miss Kuhlman is, of course, entirely correct that Holmes referred to a "swamp adder," yet the description only

fits the snake known as Russell's viper and neither this nor any other poisonous snake of the region in question is a constrictor. Indeed, the late Laurence M. Klauber wrote an article ("The Truth about the Speckled Band") in *Journal of the Baker Street Irregulars* (Vol. 3, pages 149–157, 1948) in which he argued in the best tradition of literary scholarship that the speckled band was not a snake but actually a lizard, namely a hybrid between a snake and a Gila monster. This observation later led Charles M. Bogert (*Bulletin of the American Museum of Natural History*, Vol. 109, pages 206–209, 1956) to a tongue-in-cheek description of this mythical monster, which he named *Sampoderma allergorhaihorhai.* Unfortunately the years have not brought forth any specimen of such a fascinating creature. Hence my reference to a Russell's viper.

CARL GANS

Department of Biology
Faculty of Natural Sciences
and Mathematics
State University of New York
at Buffalo
Buffalo, N.Y.

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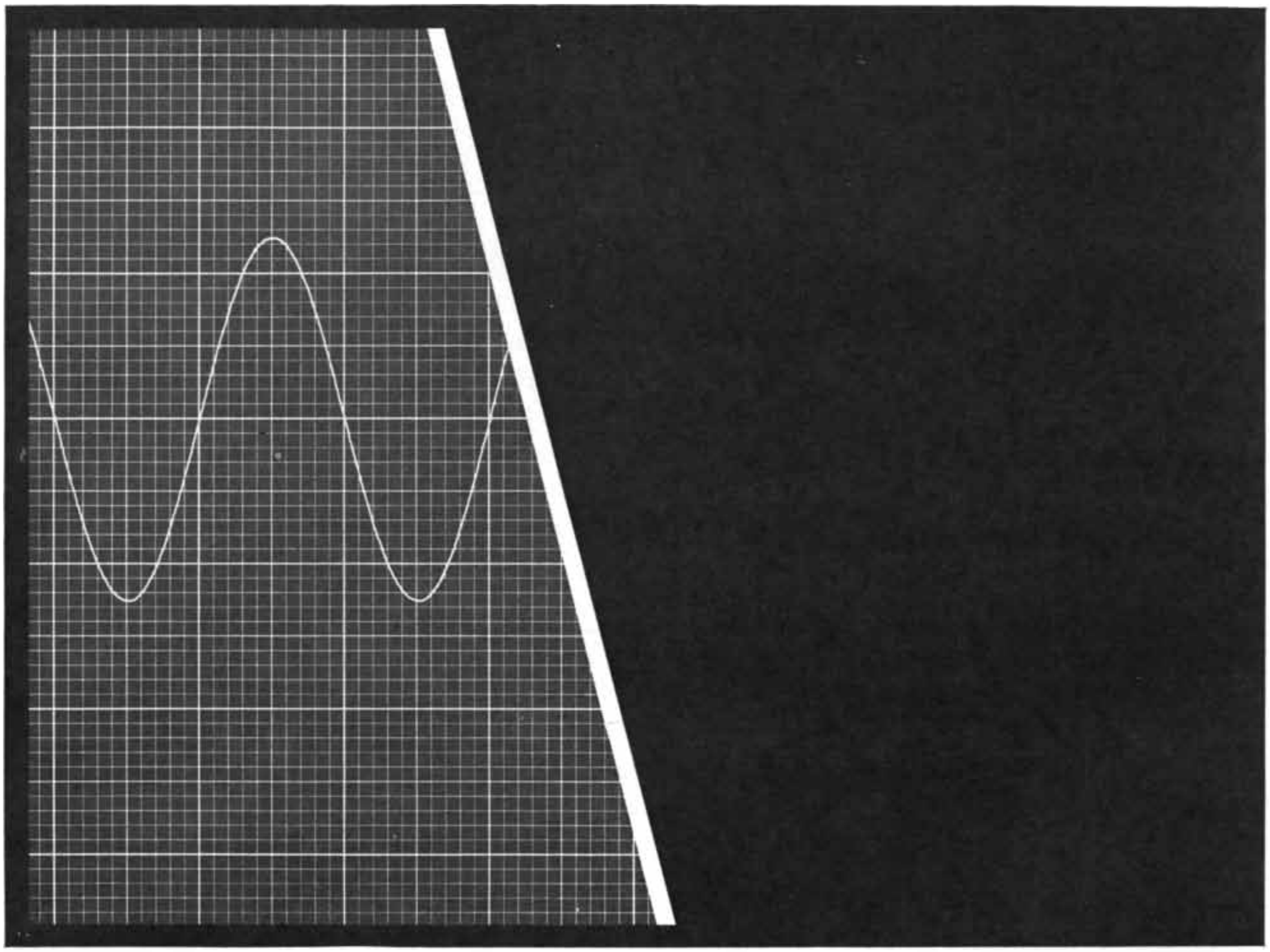
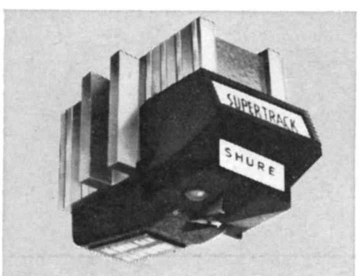
NAME

NEW ADDRESS

OLD ADDRESS

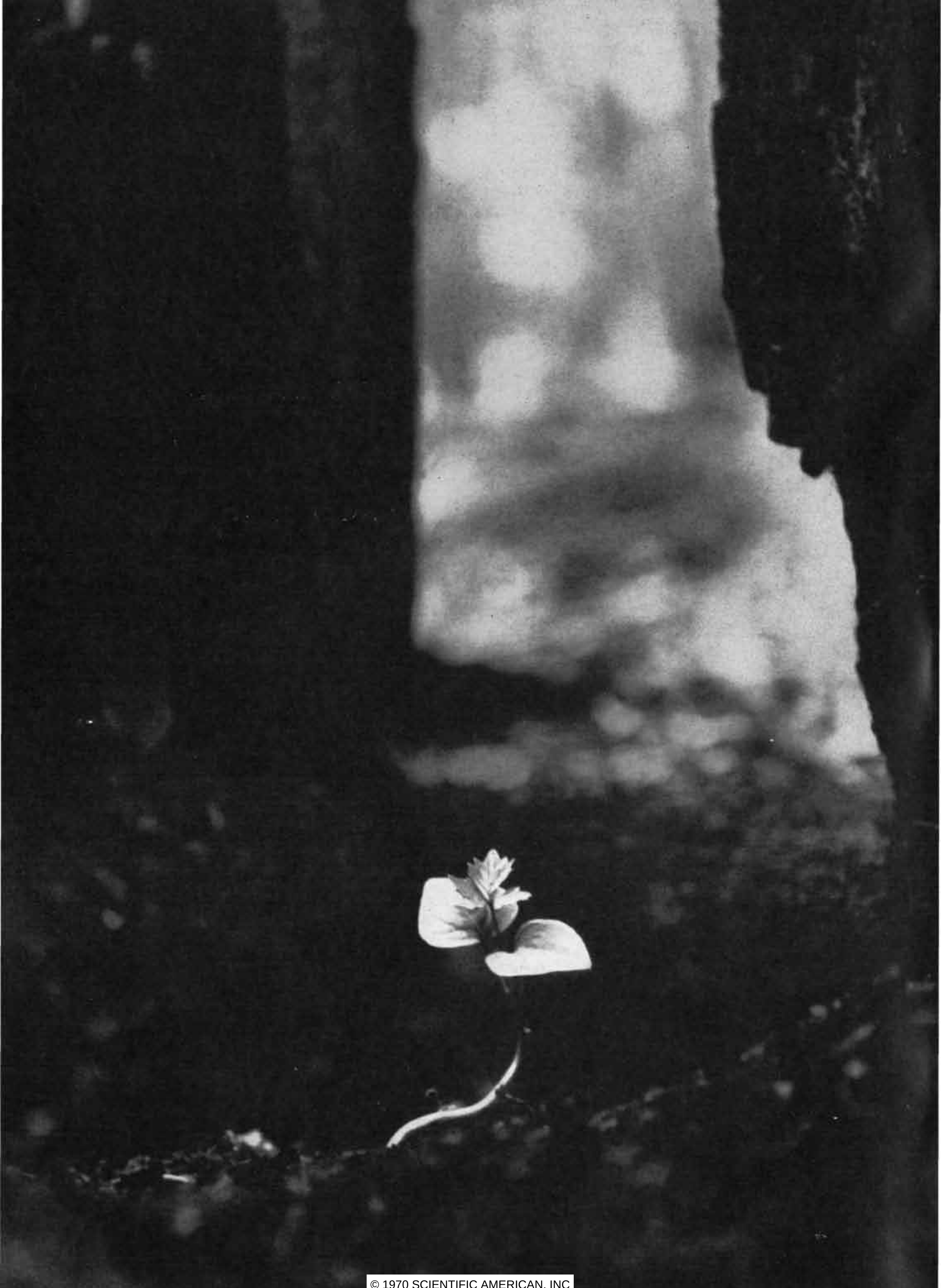


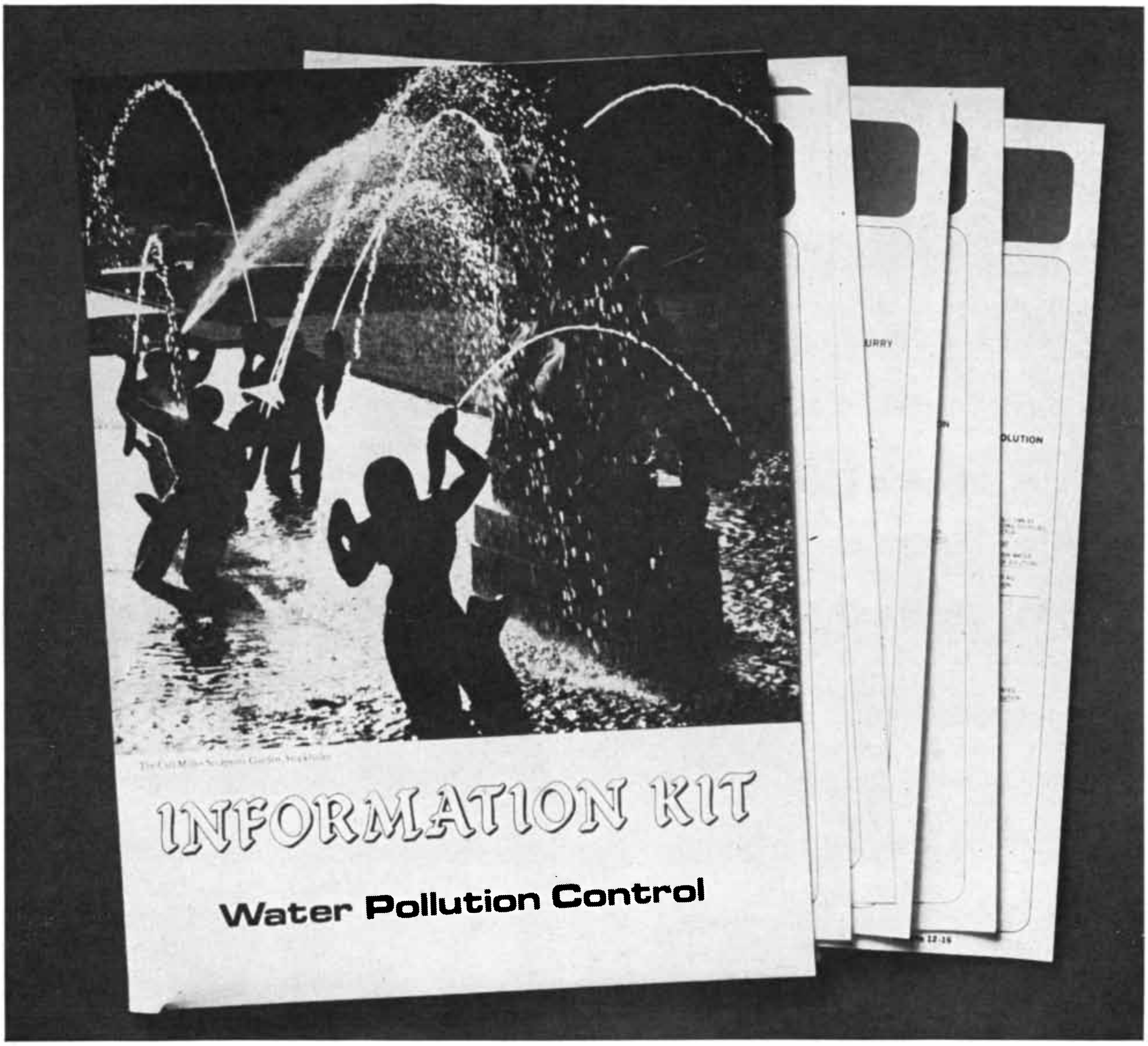
Finally! A visually perfect sine wave!



The sine wave above was generated by Shure's design computer—it looks like the sine wave that was generated by the *Shure V-15 Type II Improved* Super Track Cartridge in the Hirsch-Houck testing laboratories . . . "the first cartridge we have tested to have done so," according to their published report. This perfect sine wave was generated during the playing of the heavy bass bands on the Cook Series 60 test record at ¾ gram, and the 30 cm/sec 1,000 Hz band of the Fairchild 101 test record at 1 gram. They were impressed, and we were pleased. And we'll be pleased to send you the full Hirsch-Houck Report on the "trackability champion." Shure Brothers Inc., 222 Hartrey Ave., Evanston, Ill. 60204.

SHURE





How to invest the first 6¢ of your pollution control budget

Basic information on the engineering approach to pollution control problems, and the economic advantages of water reuse. The Calgon Pollution Control Kit offers practical advice on wastewater treatment and includes information on water quality monitoring devices that can improve results and help cut water treatment costs.

The contents of the kit reflect Calgon's forty years of water management experience, and contain such articles as "Water Management and Pollution Control," "Water: Its Economic Reuse Via the Closed Cycle," and "Three-Way Cooperation Develops Complete Waste Treatment System."

For your copy of "Water Pollution Control Information Kit," write W. H. Weitzel, Vice President, Calgon Corporation, Calgon Center, Pittsburgh, Pennsylvania 15230.

CALGON CORPORATION

SUBSIDIARY OF MERCK & CO., INC.

50 AND 100 YEARS AGO

SCIENTIFIC AMERICAN

SEPTEMBER, 1920: "One of the surprises of the year just past has been the rôle played by the Japanese in the American copper market. On every recession in values, buying by such interests has been an important factor, and comment as to the object behind it has been general. In other years Japan has exported about half of her own copper output. It is therefore surprising that she has made a complete reversal of policy. This may be partly explained by the statement that Japan's production of copper has decreased and her consumption increased. But there is something more than this. Japanese manufacturers and laborers have now learned how to produce in the mass, and the country has undoubtedly started on an era of great industrial expansion. Whether or not, as not a few think, this heavy buying of metals and other materials portends the existence of a Germany of the Far East, it is certain it means that Japan with her cheap labor and great imitative power will be, or already is, a most important factor in the world's international trade."

"The great international race for the Gordon Bennett Cup is to be staged in France on September 27th, and there is little doubt that the world at large will be astounded at the bursts of speed of many of the contending machines. In the coming contest no machine which cannot attain a speed well over 200 miles an hour need be entered. It would be ludicrous to enter such a 'slow' machine. Again, it seems that any machine with less than 250 horse-power has no place in the coming race; indeed, we shall no doubt witness machines with as high as 600-horse-power engines participating. It has been rumored that some of the European contestants may employ engines of 1,000 horse-power!"

"When Gaston Chevrolet climbed from his little green racing car after winning the 500-mile automobile race at Indianapolis recently, after having

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It's a pail that holds products like waxes, dry chemicals, detergents—without any chemical reaction. Or a practically indestructible open-top container for foods and food products that can be repeatedly steam sterilized, hot filled or frozen.

That's what the pail and container makers wanted . . . and in quantity. That's what their Marlex Sales Engineer helped them get.

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And that's why, if you have any reason to work with plastics, you have every reason to work with Phillips . . . inventors of the leading process for producing high density polyethylene. The only producers of genuine Marlex, the resin that's worth more.

Get help from the Marlex Marketing Team. Call:

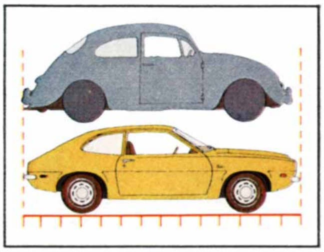
Robert F. Lynch, Fairfield, N. J. 201 227-6600. • *Gerald Tucker,* Southfield, Mich. 313 353-6666. • *Ralph Porter,* Villa Park, Ill. 312 834-6600. • *Harry House,* Memphis, Tenn. 901 682-8317. • *David Day,* Los Angeles, Calif. 213 685-6380.

PHILLIPS 66

At Phillips 66 it's performance that counts

Ford's new Pinto. The little carefree car.

Pinto is one little car that can free you from car cares, big and little. From cares about high price and big gas bills. From cares about maintenance and repairs, power and stability, roominess and quiet.



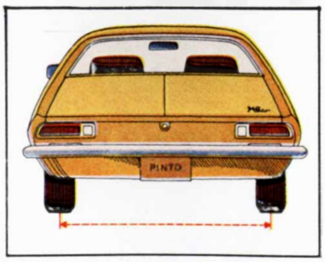
Sized like the little imports... on the outside. Pinto is only a little longer than a VW. But it

ighter. So it can slip into the same kind of little parking spaces.

But a big car where it counts . . . on the inside. Pinto has more knee and head room in back than some cars three feet longer. And more room overall than the leading import.

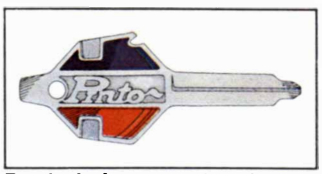
Quiet, smooth and 25 mpg. Pinto has a front-mounted, high-efficiency engine that's backed by 50 million owner-driven miles. It delivers 75 hp,

averages over 25 mpg in simulated city/suburban use.



Pinto takes a firm stand. Pinto has a wider stance than any economy import for better stability on turns and in high crosswinds. And for better road feel, Pinto has rack & pinion steering, like Porsche and Jaguar—something you won't find in any other American car.

Do it yourself and save. Pinto is designed so you can do most servicing yourself. The owner's manual shows you how. And the free Do-It-Yourself Key (below) helps you do everything from gauge the spark plug gap to adjust the headlight beam.



Don't do it yourself and save. When your Ford dealer handles Pinto's maintenance, you still save. For example, Pinto needs an oil change half as often as the leading import and a chassis lube one-s

No kidding. No changes. Pinto's style will last. And its heavy-duty ball joints, starter motor, and wheel bearings will do the same.

Priced like the little economy imports. Your Ford Dealer will show you Pinto's got a little care-free price that includes high-back buckets, 4-speed synchronized transmission, Uni-Lock harness, and more.

For information, see your Ford Dealer or write: Pinto Catalog, Box 1503, Dearborn, Michigan 48121.

Pinto

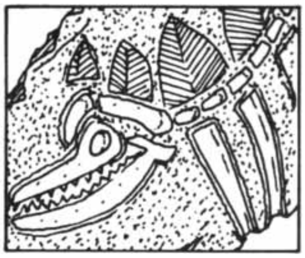
driven steadily for nearly six hours at the average speed of 88.16 miles per hour, his eyes appeared almost lifeless. His face was haggard and drawn. The muscles of his legs and forearms were cramped and knotted. His head drooped and his steps faltered. He looked like a man who had just taken a dose of poison. That is exactly what happened! 'The extreme exhaustion suffered by Chevrolet from the physical exertion and severe strain of driving 500 miles without a stop at the terrific speed he maintained,' declares Dr. Clyde Leeper of Akron, Ohio, 'caused certain chemical changes to create poisonous decomposition in the muscles of his body—in other words, the production and accumulation of waste substances such as carbon dioxide and lactic acid. In large quantities these are typical fatigue poisons. Chevrolet after the race had the "dead" eye which we found so often among wounded men overseas, among men who had endured long suffering from wounds and exhaustion and men who had become shell-shock victims.' "

SCIENTIFIC AMERICAN

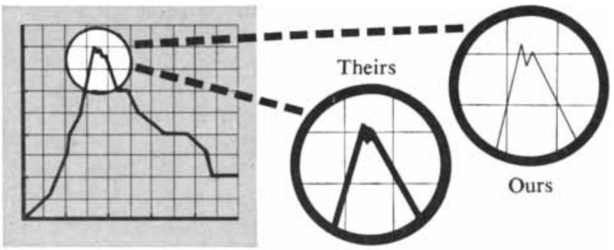
SEPTEMBER, 1870: "The war which for seven weeks has been waged between France and Prussia with such terrible destruction of life and property is virtually ended by one of the most brilliant and most successful campaigns, on the part of the Prussians, in modern history. The French, though fighting with indescribable bravery and desperation, have not succeeded in making the least headway against their stern antagonists, and have not won a single victory worthy of the name. Recent events, culminating in the surrender of MacMahon's army and the capture of Napoleon, practically terminate the contest. It is impossible that the French nation can much longer hold out against superior skill and numbers. The facts seem almost incredible. On the 15th of July the Emperor of France—supported by his government—declared war against Prussia. On the 2nd of August the first gun was fired by the French at Saarbrücken, thence followed in rapid succession the sanguinary battles of Wörth, Haguenau, Gravelotte, Beaumont and Sedan. On the 2nd of September the French armies had either surrendered or were closely besieged in their fortified places. The Emperor gave up his sword to his royal antagonist, King William, and became a prisoner. The Empire fell, a republic

It started as be serious.

Send for free color sample.



Stopping evolution can be hazardous to health.



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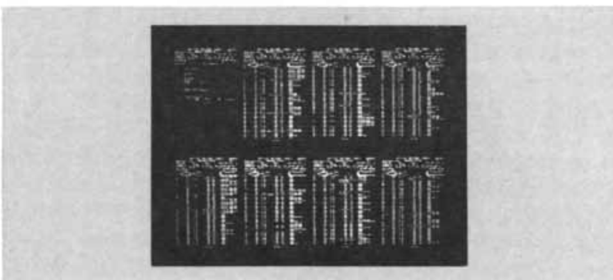

Eight pages at a crack.

PC-board drawings.

Eight exposure levels.

Recently, some of the guys were toying with the color option of our FR-80 (a high-speed digital computer integrated with the world's most precise electro-optical imaging that becomes a virtually universal, graphic COM recorder). To prove a point, they borrowed a tape from NASA. The tape contained digital information sent from the 1100-mile-high ATS-C three-color (red, blue, green), spin-scan multispectral scanner. What came out, after suitable massaging, was a 35-mm color slide of the earth. *This is the first time such a picture has been generated, on a production basis, with a single pass through a machine.* And from start to finish, humans did not need to be involved.

We think this says quite a bit, not only about Information International's scientists but also our FR-80. And if you'd like to see what the digitized, filtered earth looks like in living, giant-screen, microfilm color (with a cast of billions!), write us for a sample.

CYBER-ECO-LUTION? Well... we can't really steer the FR-80's applications into any ecological niche. Because you, and we, keep evolving new applications. For instance, from the NASA color re-creation — which, flatly, just wasn't in our original plans for the FR-80 — we're projecting other interesting earth-resources uses: crop-blight indications months before farmers are aware of them; ocean farming of fish; tree censuses; and possibly even subsurface geological surveys... each with photographic fidelity. All this, and much, much more, because the FR-80 has the highest resolution, flexibility, quality, and accuracy available.

All those applications are dependent first on resolution. Ours starts with a plotting raster of 16,384 data points. It's a resolution better than twice anyone else's — even those on the drawing boards.

In turn, it means no other COM recorder can do all of these tasks nor do them as well: reproduce complex curves and graphs (individual or multiple),

fun. It could

mathematical models viewed from a variety of angles, strip and bar charts, computer-generated flow charts. Or PC-board drawings, PERT charts, catalog listings, logic diagrams, schematics, animated drawings for engineering analysis.

Or are you more interested in business activities? Such as plotting all 3000-odd stocks on both the New York and American exchanges—and printing them six individual stocks to the page. How about one of NCR's customers? Using NCR's ultrafiche system, *the FR-80 reduced a 21,000-page catalog* (that needs revision and publishing monthly) *to six 4x6 pages, with a projected annual savings of 1.2 megabucks!*

In short, *the FR-80 does what previously couldn't be done*—and we haven't even scratched the surface yet—*while saving turnaround time, film, printed pages, money.*

(f)F, OR: THE FUNCTION OF FLEXIBILITY. Information International's FR-80 physically accepts, without adjustments, the print and plot tapes from any large computer. As for software, it has a large library that we're constantly adding to. Right now, the machine can print multiple pages per frame, output any number of columns or lines. *And you can select size, rotation, or accommodate various readers without reprograming or changeover costs.*

There are other advantages. Like an external monitor screen so you can check what you're filming (not standard on any other COM recorder). Or 128 different characters in 64 sizes, selected by console pushbutton. Or eight different exposure levels, eight different line widths, eight different plot rotations from 0° to 315°. The color option we mentioned: while you may not want to reproduce the earth, perhaps you'd like charts and graphs in color. Or, there's viewer adaptability: *The FR-80 adapts to any microfilm-viewer magnification without need for changes.*

PSST, BUDDY! WANNA BUY SOME CLEAN PICTURES? The FR-80 blows back to produce fuzz-free, sharp, clean lines of the highest quality, though admittedly that's a highly subjective characteristic. Our accuracy offers the highest repeatability with minimal geometric distortion.

FREE TRIAL OFFER. One of our big problems, frankly, is getting potential users to believe in the FR-80. Not that they doubt our claims—it's just that this system is so overwhelming, it often doesn't register when we talk about it. Of course, we invite you to write for additional information, but we also make this offer: come to Information International with your own tape, and play it on the FR-80... just for fun. *Then* we can talk delivery and the free training course. Seriously.

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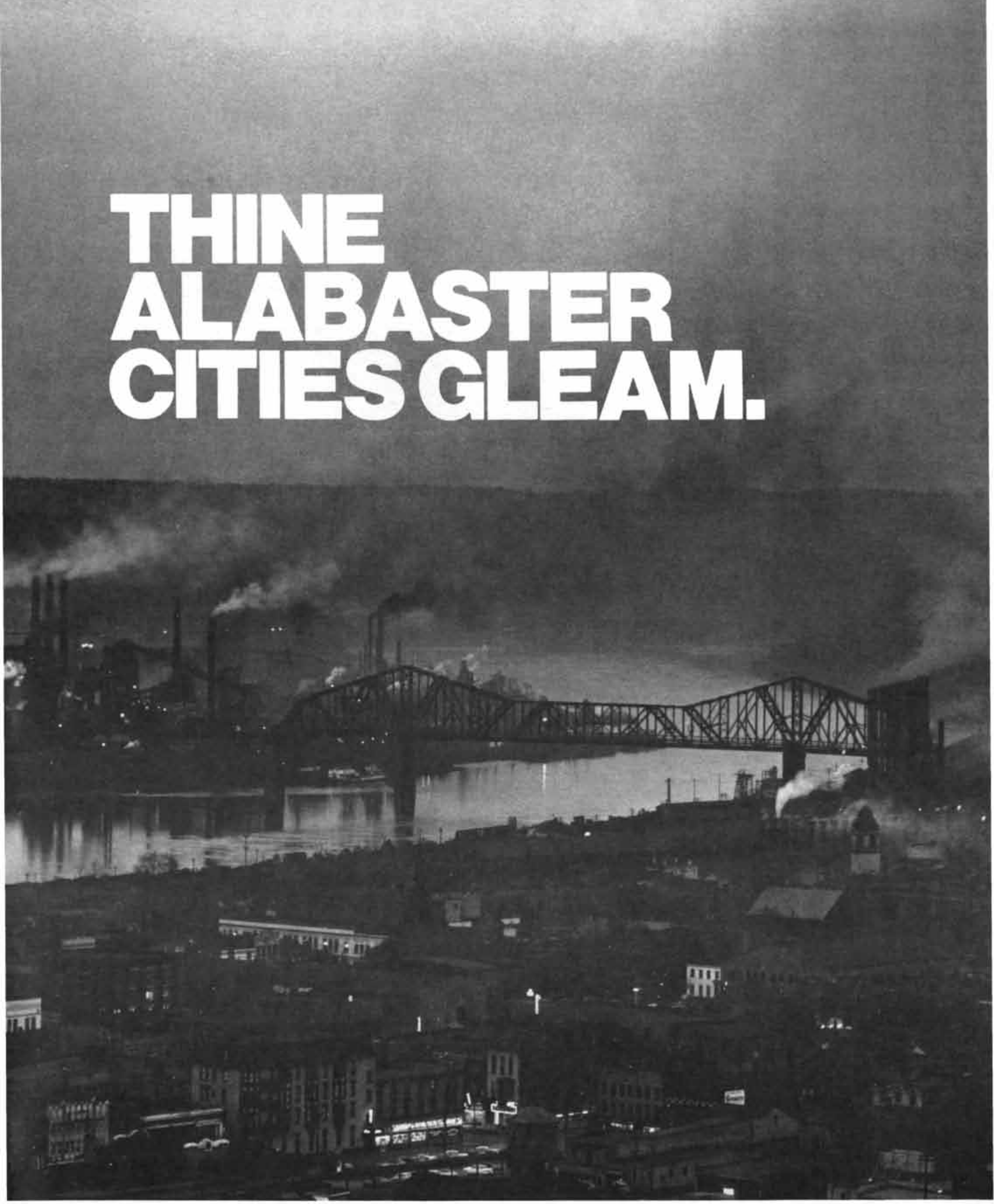
The hardware, the software, and the vision.

was speedily proclaimed, and France is humiliated in the eyes of all nations."

"William Thomson, the celebrated physicist, has lately been performing a very interesting calculation with a view to determining approximately the size of atoms, the calculation being based upon the phenomenon of capillary attraction (the work performed in overcoming the contractile force of soap bubbles), the kinetic theory of gases and the laws of optical dynamics. As a result of these calculations he concludes that the diameters of gaseous molecules, or atoms of elementary gases, are .0000000007942 of an inch. He says that if a drop of water should be magnified to the size of the earth, and each molecule magnified in the same proportion, the molecules would even then be smaller than cricket balls."

"The meeting of the American Association for the Advancement of Science commenced at Troy, N.Y., on the 17th of August and closed on the 24th. It was a gratifying success; the proceedings were harmonious, dignified and vigorous; many of the papers read were valuable. Of course there were clap-trap, private ax-grinding and speeches for Buncombe, yet probably no more than at former meetings. Because we respect the Association so highly we desire to see it improved if possible, and it is for the same reason we see its defects. In some respects it is better than it was before the war: it is more in earnest, and it has more members. In other respects the Association has sadly changed. There are lately more trashy papers. Perhaps it is impracticable to prevent such papers' being offered, but there surely must be some way of keeping them out of the printed transactions."

"The question of what women can do and what they cannot do well is one that has been much debated of late, and it is safe to say the facts and arguments laid before the public in the course of the discussion have done much to shake the belief, once so universal, that women are adapted to doing nothing well but the domestic duties of the household. There is a great variety of occupations which women have begun to claim as fields for individual effort from which no intelligent, refined man who views things as they really are would seek to exclude them. These occupations in no way injuriously affect the qualities admired by the other sex. They may and ought to be made as remunerative to women as to men now engaged in them."



Clouds of smog hover over our cities. Cities once crowned by canopies of stars. Grime on our windowsills and soot in our eyes no longer surprise us. And we bring tiny babies out of sterile hospitals into an atmosphere so polluted, plants choke on it in a matter of weeks.

America, the beautiful. Our America. The crisis isn't in our cities; the crisis is in our hearts. With a change of heart, we can change the picture. **AIA/American Institute of Architects**

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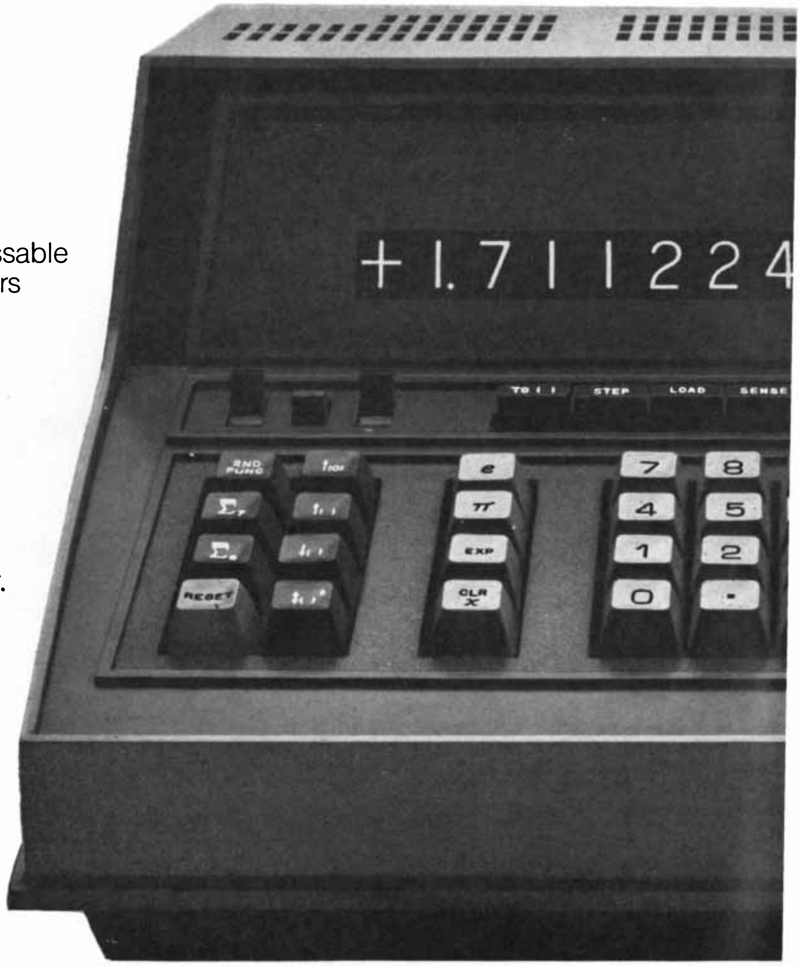

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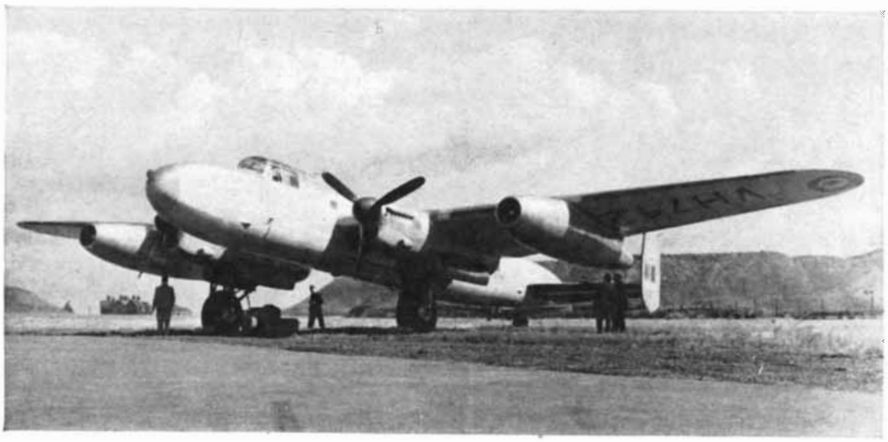
Rolls-Royce

▲ RB.211 flies for the first time
The RB.211, the advanced-technology fanjet that Rolls-Royce is producing for Lockheed's new L-1011 jetliner, flew for the first time on March 6th.

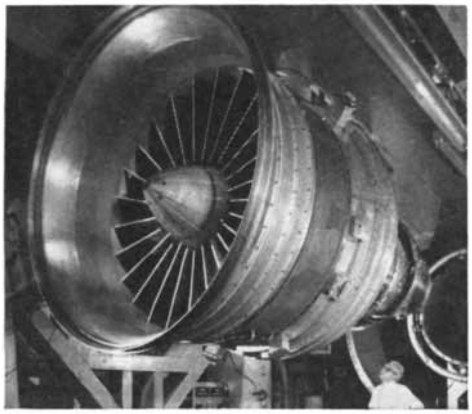
It was mounted on a VC-10 jetliner. Two of the VC-10's four Rolls-Royce Conway engines were replaced by a single RB.211. The test flight marks the beginning of a thousand hours of flying testbed operation. In its first flight the RB.211 flew at 15,000 feet at speeds up to 460 mph.

Flying testbeds give data available by no other means. They duplicate precisely the operating routines engines will face in service. Rolls-Royce is a firm believer in flying testbeds, having created in 1946 the first multi-engine nonmilitary jet aircraft as a flying testbed for the early Nene turbojet. For more on this early flying testbed, see the item below.



◀ World's first jet transport was a Rolls-Royce testbed. An Avro Lancaster bomber, converted to a 9-passenger airliner and dubbed "Lancastrian," became aviation's first jetliner when Rolls-Royce used it as a flying testbed. The objective was to find out if the Rolls-Royce Nene turbojet was smooth, robust and safe enough to make passenger jets possible. The testbed flew with two Nenes and two of its original Merlin piston engines. When the Merlins were throttled back the Nenes took over without fuss or vibration, and, as the cliché would have it, history was made.

unlimited.



◀ **RB.211: the quiet one**

The Federal Aviation Administration has just set up a new definition of how quiet jets should be. And Lockheed's new L-1011, with three Rolls-Royce RB.211 engines, falls well within the acceptable limits.

A just reward. Rolls-Royce has worked long and hard to civilize the jet engine. They gave their RB.211 three driveshafts where all other engines have only one or two. The extra shaft lets the pilot slow the fan on landing, to mute its whine. The RB.211 also has what engineers call a high bypass ratio. That means air leaves the engine at relatively low velocity, thus reducing the typical jet roar at takeoff.

Smoke is almost as great a nuisance. Rolls-Royce has made the RB.211 virtually smokeless. Instead of the usual eight or ten small combustion chambers, the RB.211 has one big one. This means fewer internal surfaces, and less inadvertent cooling of the exhaust. The hotter the engine gets, the more efficiently and cleanly it burns its fuel. An American jet fuel expert gave Rolls-Royce top marks in the anti-smoke league.

Fokker foils Murphy's Law ▶

Murphy's Law is simple and dire: if something *can* go wrong, eventually it will. Fokker kept it firmly in mind when they designed their new F-28 Fellowship, a 530-mph 65-passenger jetliner being sold in the U. S. by Fairchild-Hiller.

For instance, to make sure everything goes back together the right way after servicing, control rods have been made of different lengths, turnbuckles on parallel cables are staggered instead of adjacent, and electrical or mechanical connectors that have to be adjacent are mutually exclusive, so nothing can be plugged into the wrong socket.

Fellowship's engines are mounted high on the fuselage, so they don't inhale rubbish from the runway. They are self-starting, so they don't have to wait for help. And the entire electrical system has built-in facilities for testing itself at the touch of a few buttons before each flight.

Reasonably enough, the engines are Rolls-Royce Speys, the engine that powers more different airplanes than any other jet.

◀ **The propellers steer**

Great Britain's newest tug is the *Broodbank,* built expressly for the Port of London. Big, ugly and very efficient, the *Broodbank* is powered by twin Rolls-Royce diesels, mounted so low in the hull that they do yeoman duty as ballast. Four-foot-long belts connect the engines to a pair of special units that swivel the propellers left or right so they become, in effect, powered rudders. Thus, for all its 62-foot length and 31-foot beam, the *Broodbank* can turn in little more than its own length.

It's powerful, too: it will push a 1,000-ton barge at 8 knots. Pushing, incidentally, is often more efficient than towing, which is why so many tugboats don't tug.

Rolls-Royce Limited
Derby, England
Rolls-Royce Aero Engines, Inc.
551 Fifth Ave., New York, N.Y. 10017

THE AUTHORS

G. EVELYN HUTCHINSON ("The Biosphere") is Sterling Professor of Zoology at Yale University, where he has been a member of the faculty since 1928. Born in England, he was educated at the University of Cambridge and taught for two years at the University of the Witwatersrand in South Africa before going to Yale. His principal work has been in limnology, which he has pursued in many parts of the world, including Indian Tibet. In connection with this activity he has finished two volumes of a projected three-volume work titled *A Treatise on Limnology.* The range of Hutchinson's interests is suggested by the titles of other books he has written, including *The Ecological Theater and the Evolutionary Play, The Itinerant Ivory Tower* and *A Preliminary List of the Writings of Rebecca West.*

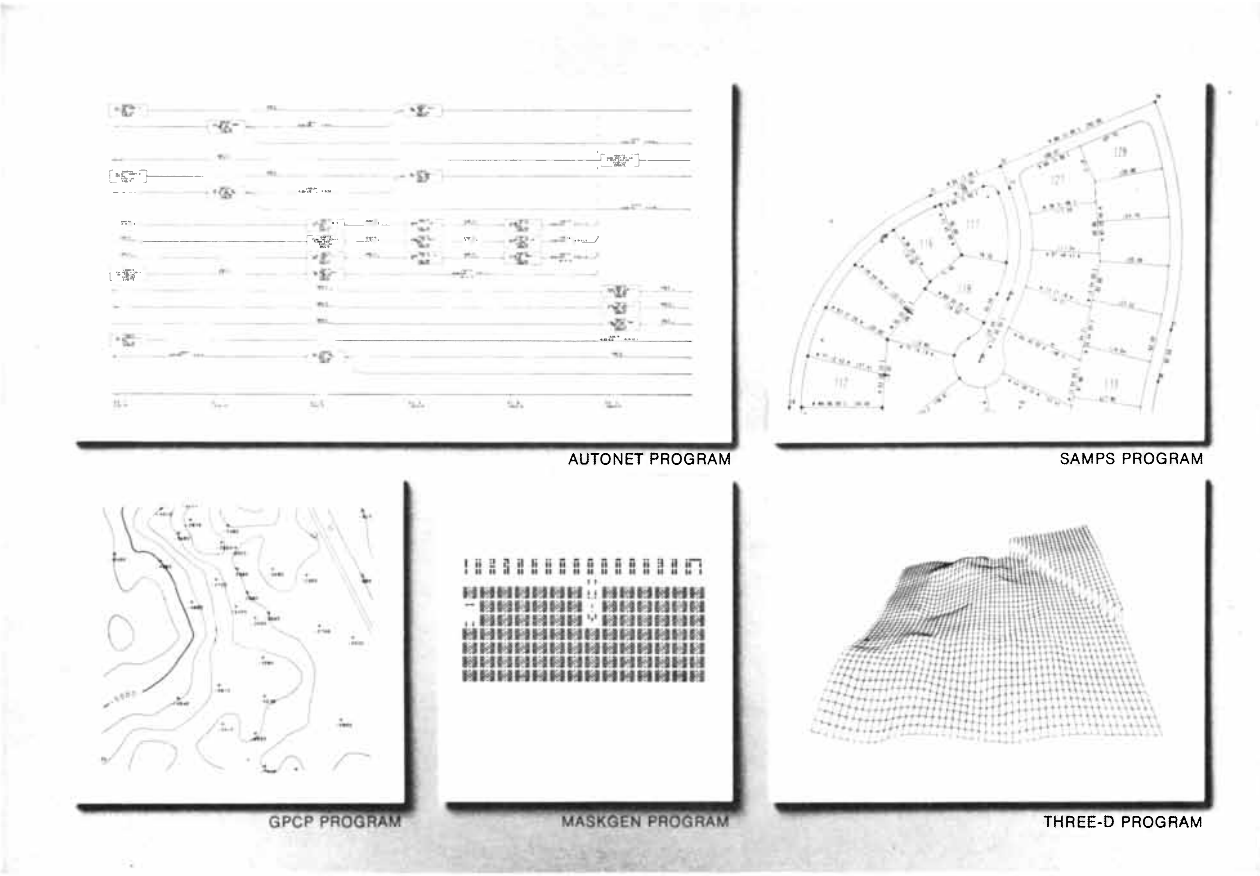
ABRAHAM H. OORT ("The Energy Cycle of the Earth") is research scientist with the Environmental Science Services Administration of the U.S. Department of Commerce, working at the agency's Geophysical Fluid Dynamics Laboratory in Princeton, N.J. Born in the Netherlands, he did his undergraduate work at the University of Leiden. For two and a half years, beginning in 1961, he was associated with the Planetary Circulation Project at the Massachusetts Institute of Technology, meanwhile receiving his master's degree in meteorology from M.I.T. From 1964 to 1966 he was research scientist at the Royal Netherlands Meteorological Institute in De Bilt, and during this period he received his Ph.D. from the University of Utrecht. The emphasis of his laboratory's work is on numerical modeling of the circulation in the atmosphere and the oceans. "This fall," he writes, "we hope to complete a more or less definitive study of the 'normal' circulation in the Northern Hemisphere, with statistics for each month of the year. This compilation will be the basis for our further studies of the natural variability of these statistics by comparing individual years." Oort is the son of the well-known astronomer Jan H. Oort.

GEORGE M. WOODWELL ("The Energy Cycle of the Biosphere") is senior ecologist at the Brookhaven National Laboratory and holds an adjunct appointment at Yale University as a lecturer. His original field of study was botany; he received an undergraduate degree in that subject at Dartmouth College in 1950 and master's and doctor's degrees from Duke University in 1956 and 1958 respectively. From 1957 to 1962, when he joined the Brookhaven staff, he taught at the University of Maine. Woodwell is the author of two earlier articles in SCIENTIFIC AMERICAN: "The Ecological Effects of Radiation" in June, 1963, and "Toxic Substances and Ecological Cycles" in March, 1967.

H. L. PENMAN ("The Water Cycle") is head of the physics department at the Rothamsted Experimental Station in Britain. Since receiving his doctorate from the University of Durham in 1937 he has investigated agricultural and botanical problems, being particularly concerned with transpiration and the irrigation of crops. He joined the Rothamsted staff in 1955. In 1962 he was elected a Fellow of the Royal Society and was awarded the Order of the British Empire.

PRESTON CLOUD and AHARON GIBOR ("The Oxygen Cycle") are respectively professor of biogeology and professor of biology at the University of California at Santa Barbara. Cloud writes that he "escaped the Depression by serving in the U.S. Navy from 1930 to 1933." As a result he was 26 before he obtained his bachelor's degree at George Washington University in 1938. He received his Ph.D. two years later from Yale University. From 1942 to 1961 he was a geologist with the U.S. Geological Survey. Before going to Santa Barbara he taught at the University of Minnesota and the University of California at Los Angeles. He is also involved in a number of other activities, including panels on space-science policy and Congressional panels dealing with resource and population problems. "I might add," he writes, "that I like to garden, fish, write doggerel, play chess, listen to baroque, blues and ethnic music, collect limericks and exchange ideas with people like Aharon Gibor." Gibor, who was born in Israel, was graduated from the University of California at Berkeley in 1950 and received his master's degree there in 1952. He obtained his Ph.D. in biology from Stanford University in 1955. He has worked at the Weizmann Institute of Science, the Alaska Department of Fish and Game and Rockefeller University.

BERT BOLIN ("The Carbon Cycle") is professor of meteorology at the University of Stockholm and director of the



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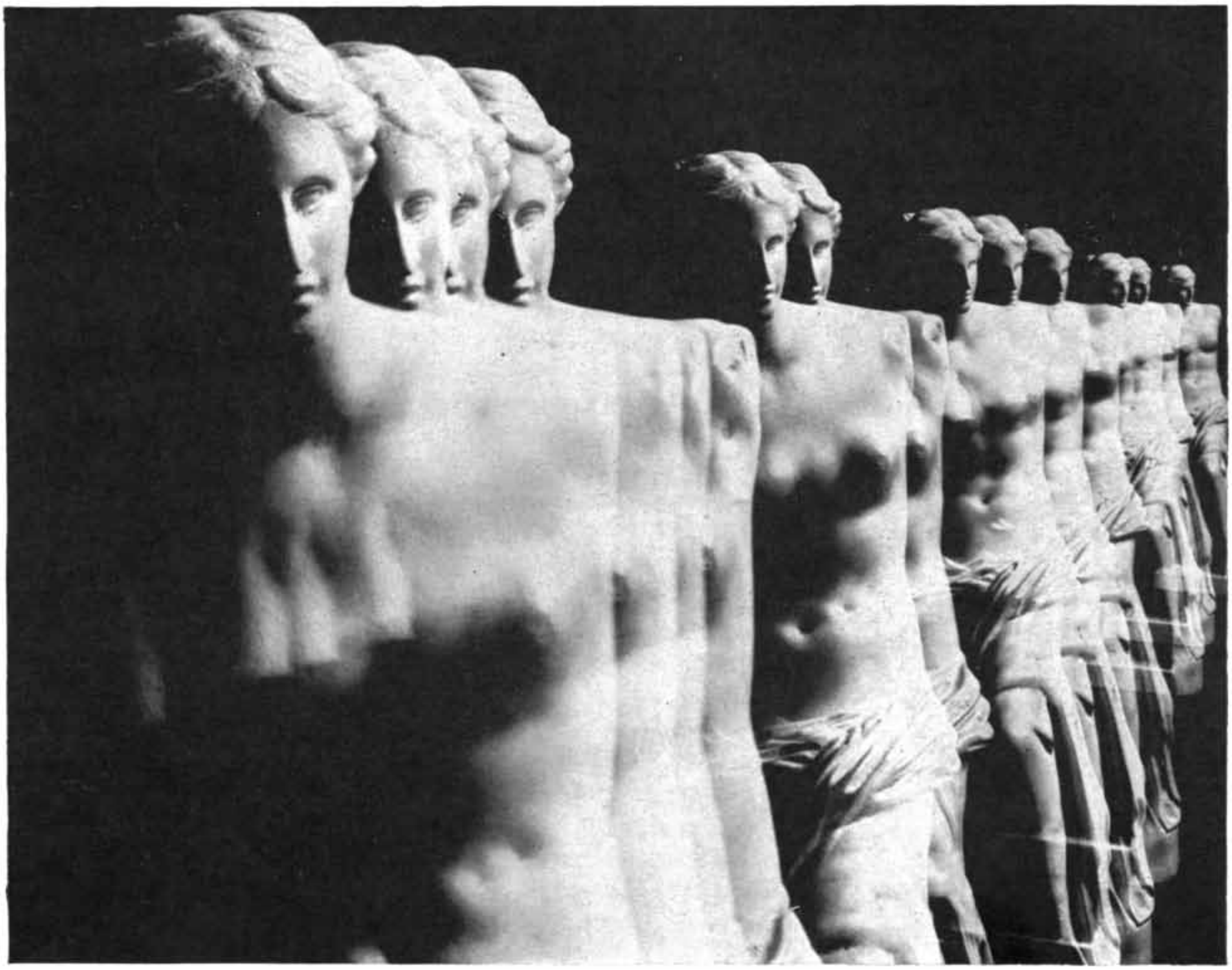

A new style in "dolly" shots : accelerate or slow down zooming speed while actually zooming.

Making it into the 1980's.

Not long ago, Dick Martin told Dan Rowan on the Laugh-In that man's most important goal in the 1970's was "to live into the 1980's". It is of no little significance that, shortly thereafter, this remark was being quoted to some 3000 Bell System engineers assembled in the Convention Center in Winston-Salem, N. C.

What is significant is that the problem to which the remark referred has become so urgent a part of our national consciousness that the 3000 engineers could well - if not gracefully - accept the possibility of our not making it into the 1980's. It was in this context that the theme of this year's National Engineer's Week was "Engineering-Environmental Design for the 1970's." Sponsored by Western Electric and Bell Telephone Laboratories, the Winston-Salem symposium was one of many such programs organized by the company to come to grips with problems of the environment.

Western Electric makes communications equipment for the Bell System. Because of the nature of our products we do not produce much pollution, and what we do we are making a strong, and encouragingly successful, effort to eliminate. We neither wish for nor deserve particular credit for this. We wish only to emphasize that it was the spirit of the times—a sense of urgency relevant to the entire problem rather than to a specific corporate problem—that prompted our co-sponsorship of the symposium.

The engineers who attended, from Southern Bell as well as from Western Electric and Bell Labs, heard three principal speakers. A.T.&T. Vice-President Walter W. Straley described the work of the Bell System's new Department of Environmental Affairs, of which he is head. Dr. George E. Symons, editor of the magazine Water and Wastes Engineering and an international consultant on conservation resources, spoke on the theme "Ten Years from Today Is Now." (It was Dr. Symons who quoted Dick Martin's remark, and considering his theme it was an apt quotation indeed.) And Dr. Lee DuBridge, science adviser to President Nixon discussed the question "Who Manages the Environment?"

None of the speakers, of course, could give complete answers to any environmental problems. The purpose of the symposium was not, however, to present answers. It was, rather, to heighten the sense of urgency; to encourage the participation in the search for answers; and to underline the message implicit in the theme of this year's Engineer's Week: that it is the nation's engineers who are uniquely favored to find solutions to the problems which they, in all honesty, did as much as anyone to create.

From the reaction of the 3000 engineers assembled, we are confident that we accomplished this purpose.

Western Electric

International Meteorological Institute in Stockholm. He has held the latter position since 1956 except for two years (1965–1967) when he was scientific director of the European Space Research Organization in Paris. Bolin was graduated from the University of Uppsala in 1946 and obtained his master's and doctor's degrees from the University of Stockholm in 1950 and 1956 respectively. His areas of research have included methods of numerical weather prediction, problems related to the circulation and transfer of carbon dioxide and studies of the large-scale circulation of the ocean using tracers. Bolin initiated and organized the first sounding-rocket experiments in Sweden. He is chairman of the Swedish Space Research Committee and of the Joint Organizing Committee for a Global Atmospheric Research Program.

C. C. DELWICHE ("The Nitrogen Cycle") is at the University of California at Davis, where he is chairman of the Graduate Group in Ecology, professor of geobiology and biochemist in the experiment station. He did his undergraduate work at the University of Wisconsin, receiving his bachelor's degree in biochemistry in 1940. After military service during World War II he obtained his Ph.D. in comparative biochemistry from the University of California at Berkeley. Delwiche has recently been designated as program coordinator for an integrated research program on the biology and ecology of nitrogen under the U.S. national committee for the International Biological Program.

EDWARD S. DEEVEY, JR. ("Mineral Cycles"), is Killam Professor of Biology at Dalhousie University in Halifax, Nova Scotia, where he went in 1968 after 22 years on the faculty at Yale University. He was graduated from Yale in 1934 and took his Ph.D. there in 1938. He then taught biology at Rice Institute for four years and was a research associate in biology at the Woods Hole Oceanographic Institution for three years before returning to Yale. He was professor of biology at Yale from 1957 to 1968 and director of the Geochronometric Laboratory from 1951 to 1962.

LESTER R. BROWN ("Human Food Production as a Process in the Biosphere") is a senior fellow with the Overseas Development Council. In the preface to his recent book *Seeds of Change* he writes: "Born and reared on a farm in southern New Jersey, I organized, at the age of 14, a commercial tomato-growing operation with my younger brother, an operation that was to see me through college. Six months spent living in Indian villages in 1956 broadened my interest in global agriculture by exposing me to a way of life typical of the vast majority of mankind, the peasant farmers in the poor countries." With a bachelor's degree in agricultural science from Rutgers University in 1955 and a master's degree in economics from the University of Maryland in 1959, Brown joined the U.S. Department of Agriculture in 1959 and remained there for 10 years. In 1962 he obtained the degree of master of public administration from Harvard University. From 1964 to 1968 Brown was special adviser to the Secretary of Agriculture on foreign agricultural policy, and for part of that period he was administrator of the Agricultural Development Service.

S. FRED SINGER ("Human Energy Production as a Process in the Biosphere") is Deputy Assistant Secretary of the Interior, with responsibility for the scientific programs of the U.S. Department of the Interior. Born in Vienna, he came to the U.S. in 1940 and was graduated from Ohio State University in 1943, taking his master's and doctor's degrees in physics at Princeton University in 1944 and 1948 respectively. He has held a number of academic and governmental appointments, including 11 years on the faculty of the University of Maryland, three years as dean of the School of Environmental Sciences at the University of Miami and two years as director of the National Weather Satellite Center of the U.S. Department of Commerce. He took up his present position in 1967. In addition to extensive work on environmental quality he has been interested in the origin of the moon and the early history of the earth, in cosmic rays, meteorites, radiation belts, meteorology and oceanography.

HARRISON BROWN ("Human Materials Production as a Process in the Biosphere") is professor of geochemistry and of science and government at the California Institute of Technology, where he has been a member of the faculty since 1951. He is also foreign secretary of the National Academy of Sciences and vice-president of the International Council of Scientific Unions. Brown was graduated from the University of California at Berkeley in 1938 and obtained his Ph.D. from Johns Hopkins University in 1941. Before going to Cal Tech he was associated with the U.S. atomic energy program.

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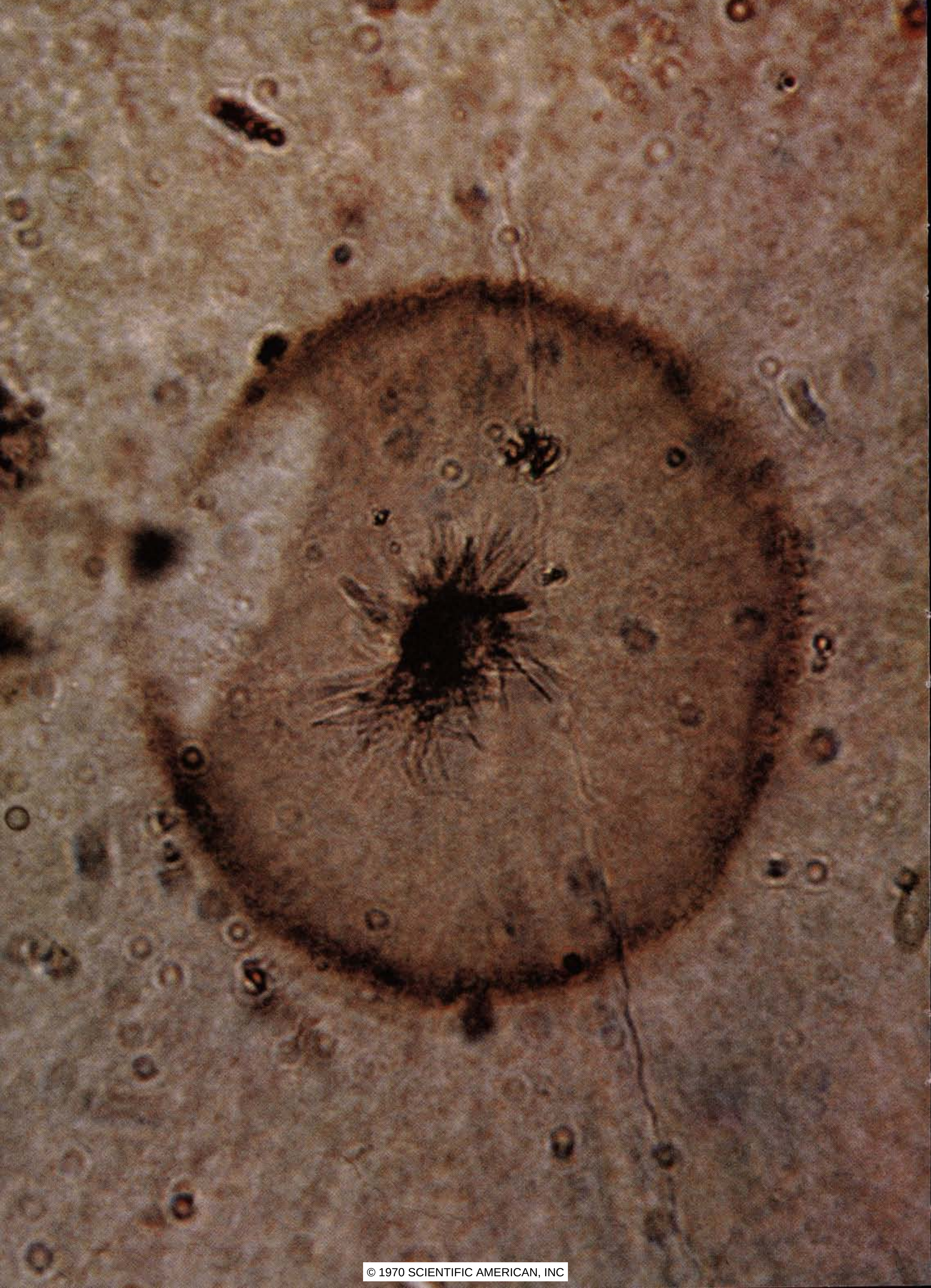

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The Biosphere

Introducing an issue on how the earth's thin film of living matter is sustained by grand-scale cycles of energy and chemical elements. All of these cycles are presently affected by the activities of man

by G. Evelyn Hutchinson

The idea of the biosphere was introduced into science rather casually almost a century ago by the Austrian geologist Eduard Suess, who first used the term in a discussion of the various envelopes of the earth in the last and most general chapter of a short book on the genesis of the Alps published in 1875. The concept played little part in scientific thought, however, until the publication, first in Russian in 1926 and later in French in 1929 (under the title *La Biosphère*), of two lectures by the Russian mineralogist Vladimir Ivanovitch Vernadsky. It is essentially Vernadsky's concept of the biosphere, developed about 50 years after Suess wrote, that we accept today. Vernadsky considered that the idea ultimately was derived from the French naturalist Jean Baptiste Lamarck, whose geochemistry, although archaically expressed, was often quite penetrating.

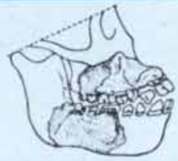
The biosphere is defined as that part of the earth in which life exists, but this definition immediately raises some problems and demands some qualifications. At considerable altitudes above the earth's surface the spores of bacteria and fungi can be obtained by passing air through filters. In general, however, such "aeroplankton" do not appear to be engaged in active metabolism. Even on the surface of the earth there are areas too dry, too cold or too hot to support metabolizing organisms (except technically equipped human explorers), but in such places also spores are commonly found. Thus as a terrestrial envelope the biosphere obviously has a somewhat irregular shape, inasmuch as it is surrounded by an indefinite "parabiospheric" region in which some dormant forms of life are present. Today, of course, life can exist in a space capsule or a space suit far outside the natural biosphere. Such artificial environments may best be regarded as small volumes of the biosphere nipped off and projected temporarily into space.

What is it that is so special about the biosphere as a terrestrial envelope? The answer seems to have three parts. First, it is a region in which liquid water can exist in substantial quantities. Second, it receives an ample supply of energy from an external source, ultimately from the sun. And third, within it there are interfaces between the liquid, the solid and the gaseous states of matter. All three of these apparent conditions for the existence of a biosphere need more detailed study and discussion.

All actively metabolizing organisms consist largely of elaborate systems of organic macromolecules dispersed in an aqueous medium. The adaptability of organisms is so great that even in some deserts or in the peripheral parts of the antarctic ice sheet there may be living beings that contain within themselves the only liquid water in the immediate neighborhood. Although such xerophytic (literally "dry plant") organisms may be able to conserve internal supplies of water for a long time, however, they still need some occasional dew or rain. (The hottest deserts appear to be formally outside the biosphere, although they may be parabiospheric in the sense explained above.) In the immediate past this kind of situation had a certain intellectual interest, since it seemed for a time that organisms might exist on Mars, in an almost waterless environment, by retaining water in their tissues. The most recent studies, however, seem to make any kind of biosphere on Mars quite unlikely.

The energy source on which all terrestrial life depends is the sun. At present the energy of solar radiation can enter the biological cycle only through the photosynthetic production of organic matter by chlorophyll-bearing orga-

REVOLUTION IN THE BIOSPHERE is symbolized by the fossilized blue-green alga in the photomicrograph on the opposite page. The cell, which is one of a variety of similar fossils found in the Gunflint geological formation in southern Ontario by Stanley A. Tyler and Elso S. Barghoorn of Harvard University, is estimated to be approximately two billion years old. The Gunflint algae are the oldest known photosynthetic and nitrogen-fixing organisms. As such they contributed to the original oxygenation of the earth's atmosphere and so prepared the way for all higher forms of plant and animal life in the biosphere.

YEARS BEFORE PRESENT	EVENT	GEOLOGICAL FORMATION	FOSSIL
0	OLDEST HOMINID	SIWALIK HILLS (INDIA)	*RAMAPITHECUS* 
	OLDEST LAND PLANT	LUDLOVIAN SERIES, UPPER SILURIAN (BRITAIN)	*COOKSONIA* 
	OLDEST METAZOAN ANIMAL	EDIACARA HILLS (AUSTRALIA)	*SPRIGGINA* 
1 BILLION			
	OLDEST EUCARYOTIC CELLS	UPPER BECK SPRING DOLOMITE (CALIFORNIA)	UNNAMED 
	FORMATION OF OXIDIZING ATMOSPHERE		
2 BILLION	OLDEST PHOTOSYNTHETIC AND NITROGEN-FIXING ORGANISM	GUNFLINT FORMATION (ONTARIO)	*GUNFLINTIA* 
3 BILLION	OLDEST KNOWN ORGANISM	FIGTREE FORMATION (SOUTH AFRICA)	*EOBACTERIUM* 
	FIRST ROCKS IN EARTH'S CRUST; FORMATION OF OCEAN		
4 BILLION	DIFFERENTIATION OF EARTH'S CRUST, MANTLE AND CORE; CRUST MELTED BY RADIOACTIVE HEATING		
4.5 BILLION	FORMATION OF EARTH		

ROUGH CHRONOLOGY OF THE BIOSPHERE as represented in the fossil record is given on this page, along with the geological formations in which the fossils were found and some other major events in the history of the earth. Data are from various sources.

nisms, namely green and purple bacteria, blue-green algae, phytoplankton and the vast population of higher plants. Such organisms are of course confined to the part of the biosphere that receives solar radiation by day. That includes the atmosphere, the surface of the land, the top few millimeters of soil and the upper waters of oceans, lakes and rivers. The euphotic, or illuminated, zone may be only a few centimeters deep in a very turbid river, or well over 100 meters deep in the clearest parts of the ocean. The biosphere does not end where the light gives out; gravity continues the energy flow downward, since fecal pellets, cast skins and organisms dead and alive are always falling from the illuminated regions into the depths.

The plant life of the open ocean, on which most of the animals of the sea depend for food, is planktonic, or drifting, in a special sense that is often misunderstood. Most of the cells composing a planktonic association are slightly denser than seawater, and under absolutely quiet conditions they would slowly sink to the bottom. That the upper layers are not depleted of plant cells and so of the capacity to generate food and oxygen is attributable entirely to turbulence. The plant cells sink at a speed determined by their size, shape and excess density; as they sink they divide and the population in the upper waters is continually replenished from below by turbulent upwelling water.

The sinking of the phytoplankton cells is in itself the simplest way by which a cell can move from a small parcel of water it has depleted of the available nutrients into a parcel still containing these substances. The mechanism can of course only operate when there is an adequate chance of a lift back to the surface for the cell and some of its descendants. The cellular properties that determine sinking rates, interacting with turbulence, are doubtless as important in the purely liquid part of the biosphere as skeletal and muscular structures, interacting with gravity, are to us as we walk about on the solid-gaseous interface we inhabit. Although this point of view was worked out some 20 years ago, largely through the efforts of the oceanographer Gordon A. Riley, it still seems hardly recognized by many biologists.

In addition to the extension of the biosphere downward, there is a more limited extension upward. On very high mountains the limit above which chlorophyll-bearing plants cannot live appears to be about 6,200 meters (in the Himalayas); it is partly set by a lack of liquid water, but a low carbon dioxide pressure, less than half the pressure at sea level, may also be involved. At still higher altitudes a few animals such as spiders may be found. These probably feed on springtails and perhaps mites that in turn subsist on pollen grains and other organic particles, blown up into what the high-altitude ecologist Lawrence W. Swan calls the aeolian zone.

The rather special circumstances that have just been recognized as needed for the life of simple organisms in the free liquid part of the biosphere emphasize how much easier it is to live at an interface, preferably when one side of the interface is solid, although quite a lot of microorganisms do well at the air-water interface in quiet pools and swamps. It is quite possible, as J. D. Bernal suggested many years ago, that the surface properties of solid materials in contact with water were of great importance in the origin and early development of life.

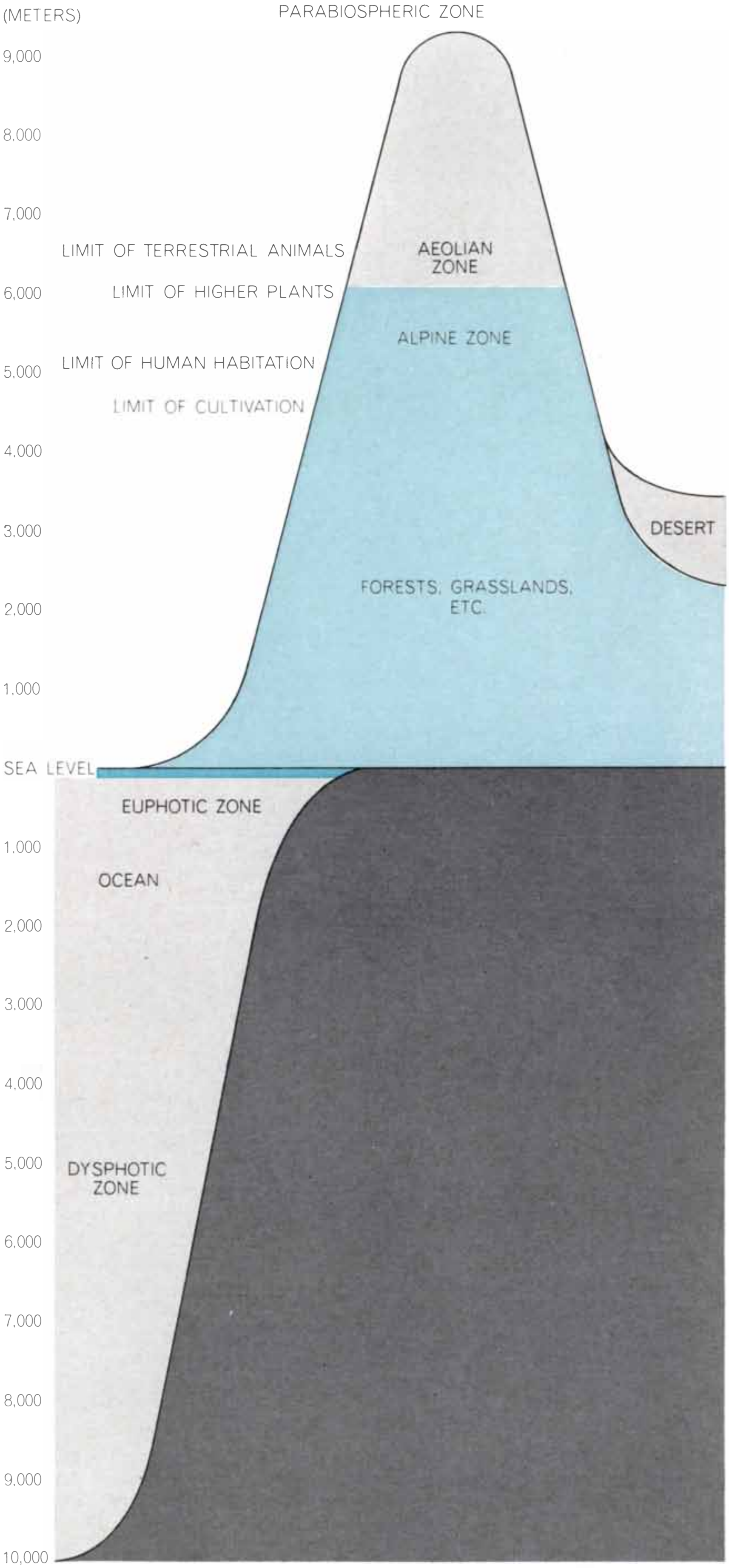
Studies of photosynthetic productivity show that often the plants that can produce the greatest organic yield under conditions of natural illumination are those that make the best of all three possible states, with their roots in sediments under water and their leaves in the air. Sugarcane and the ubiquitous reed *Phragmites communis* provide striking examples. The substances needed by such plants are (1) water, which is taken up by the roots but is maintained at a fairly constant pressure by the liquid layer over the sediments; (2) carbon dioxide, which is most easily taken up from the gaseous phase where the diffusion rate at the absorptive surface is maximal; (3) oxygen (by night), which is also more easily obtained from the air than from the water, and (4) a great number of other elements, which are most likely to be available in solution in the pore water of the sediment.

The present energetics of the biosphere depend on the photosynthetic reduction of carbon dioxide to form organic compounds and molecular oxygen. It is well known, however, that this process is only one of several of the form: $n\mathrm{CO_2} + 2n\mathrm{H_2}A + \text{energy} \rightarrow (\mathrm{CH_2O})_n + nA_2 + n\mathrm{H_2O}$. In this reaction the hydrogen donor $\mathrm{H_2}A$ may be hydrogen sulfide (H_2S), as in the case of the photosynthetic sulfur bacteria, water (H_2O), as in the case of the blue-green algae and higher green plants, or various other organic compounds, as in the case of the nonsulfur purple bacteria. (The last-mentioned case presents a paradox: Why be photosynthetic when there is plenty of metabolizable organic matter in the immediate neighborhood of the photosynthesizing cell?) The actual patterns of the possible reactions are extremely complicated, with several alternative routes in some parts of the process. For the purposes of this discussion, however, the important fact is probably that any set of coupled reactions so complex would take a good deal of mutation and selection to evolve.

The overall geochemical result of photosynthesis is to produce a more oxidized part of the biosphere, namely the atmosphere and most of the free water in which oxygen is dissolved, and a more reduced part, namely the bodies of organisms and their organic decomposition products in litter, soils and aquatic sediments. Some sediments become buried, producing dispersed organic carbon and fossil fuels, and there is a similar loss of oxygen by the oxidation of eroding primary rock. The quantitative relation of the fossilization of the organic (or reduced) carbon and the inorganic (or oxidized) carbon clearly bears on the history of the earth but so far involves too many uncertainties to produce unambiguous answers. From the standpoint of the day-to-day running of the biosphere what is important is the continual oxidation of the reduced part, living or dead, by atmospheric oxygen to produce carbon dioxide (which can be employed again in photosynthesis) and a certain amount of energy (which can be used for physical activity, growth and reproduction). The production of utilizable fossil fuels is essentially an accidental imperfection in this overall reversible cycle, one on which we have come to depend too confidently.

It is necessary to maintain a balance in our attitude by stressing the fragility and inefficiency of the entire process. If one considers a fairly productive lake, for example, it is usual to find about 2.5 milligrams of particulate organic matter under an average square centimeter of lake surface. Assuming that this organic matter is all phytoplankton, with a water content of 90 percent, there are about 25 cubic millimeters of photosynthetic organisms per 100 square millimeters of lake surface. If this were all brought to the surface, it would form a green film a quarter of a millimeter thick. Both assumptions undoubtedly exaggerate the thickness, which may well be no more than a tenth of a millimeter, or the thickness of a sheet of paper.

The total photosynthetic material of the open ocean can hardly be greater and



may well be much less. Similarly, when one looks up from the floor of a broad-leaved forest, there is obviously some overlap of leaves, but five leaves, one above the other, would usually remove almost all the available energy. Moreover, in this case much of the organic material is in the form of skeletal cellulose, which provides support and control of evaporation; as a result there is an even less economical use of the volume of the plant than in the case of the phytoplankton. The machinery by which energy enters the living world is clearly quite tenuous.

Estimates of the efficiency of the photosynthetic process are quite variable and depend greatly on the circumstances. Under conditions of optimum cultivation an annual utilization of several percent of the incoming visible radiation is easily achieved on land, the limit probably being set by the carbon dioxide content of the air, but the overall efficiency of land surfaces as a whole seems to lie between .1 and .3 percent. In water, under special circumstances aimed at maximum yield, very high levels of production, apparently approaching the theoretical quantum efficiency of the photosynthetic process, seem possible, but again in nature as a whole efficiencies of the order of a few tenths of a percent are usual. On land much of the radiant energy falling on a tall plant is not wasted but is needed to maintain the stream of water being transpired from the leaves.

The movement of material through living organisms involves many more elements than those contained in water and carbon dioxide. In addition to carbon, oxygen and hydrogen, all organisms use nitrogen, phosphorus, sulfur, sodium, potassium, calcium, magnesium, iron, manganese, cobalt, copper, zinc and probably chlorine, and some certainly use for special functions aluminum, boron, bromine, iodine, selenium, chromium, molybdenum, vanadium, silicon,

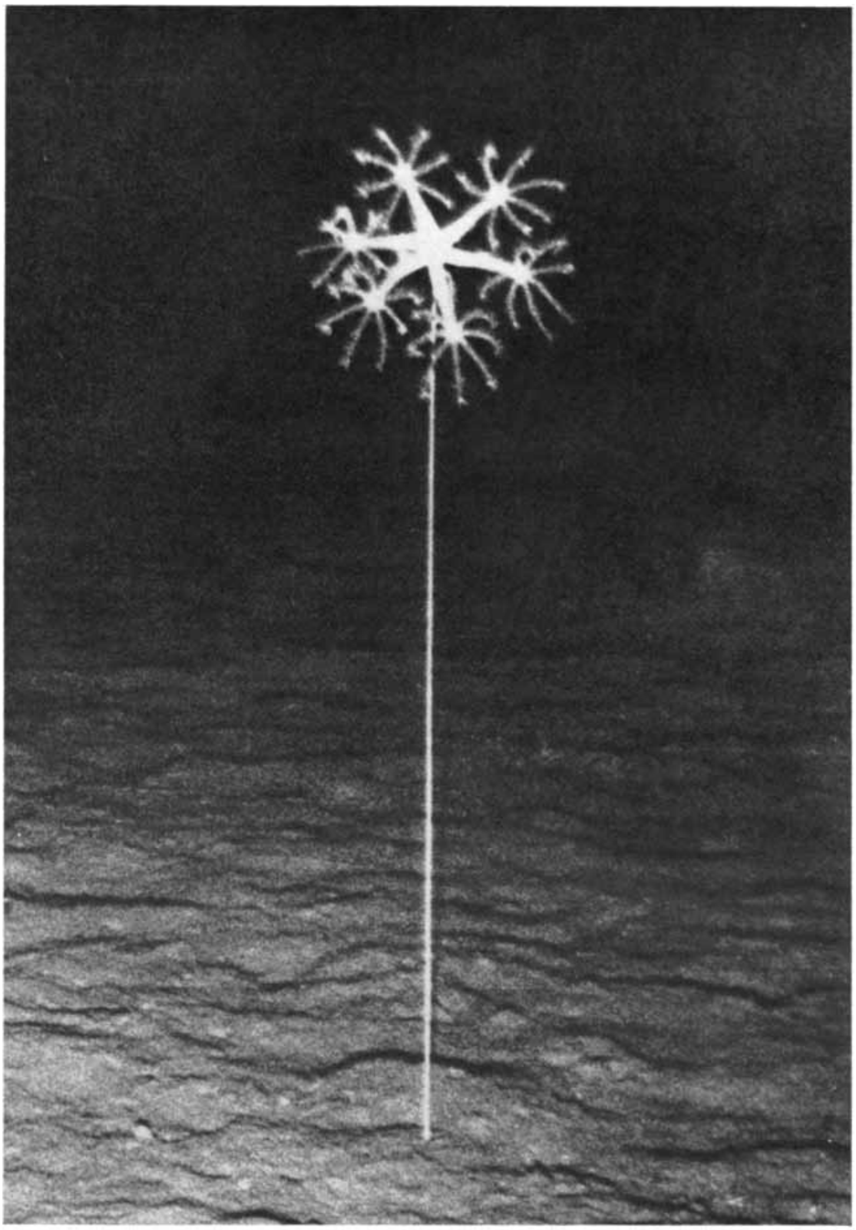
VERTICAL EXTENT of the biosphere is depicted schematically in the illustration at the left. As a terrestrial envelope the biosphere has a somewhat irregular shape inasmuch as it is surrounded by an indefinite "parabiospheric" region in which some dormant forms of life, such as the spores of bacteria and fungi, are present. The euphotic, or illuminated, zone of aqueous bodies may be only a few centimeters deep in a very turbid river or well over 100 meters deep in the clearest parts of the ocean.

strontium, barium and possibly nickel. A few elements that occur fairly regularly in specific compounds or situations, such as cadmium in the vertebrate kidney or rare earths in the hickory leaf, are obviously of interest even if they are not functional. Some of the elements now known to be significant only in a particular group of organisms, such as boron in plants, iodine in many animals, chromium in veretebrates or selenium in some plants, birds and mammals, may ultimately prove to be universally essential. A few more functional elements, germanium perhaps being a good candidate, may remain to be discovered. Even the rarer trace elements, when they are unquestionably functional, are present in metabolically versatile tissues, such as those of the liver, in quantities on the order of a million atoms per cell. Very little substitution of one element by another is possible, although some bacteria and algae can use rubidium in place of potassium with no adverse effects other than a slowed growth rate. We all know that certain elements are highly toxic (lead, arsenic and mercury are obvious examples), whereas many of the functional elements are poisonous when high levels of intake are induced by local concentrations in the environment. This means that the detailed geochemistry of each element, particularly in the process of crossing the solid-liquid interface, is of enormous biological importance.

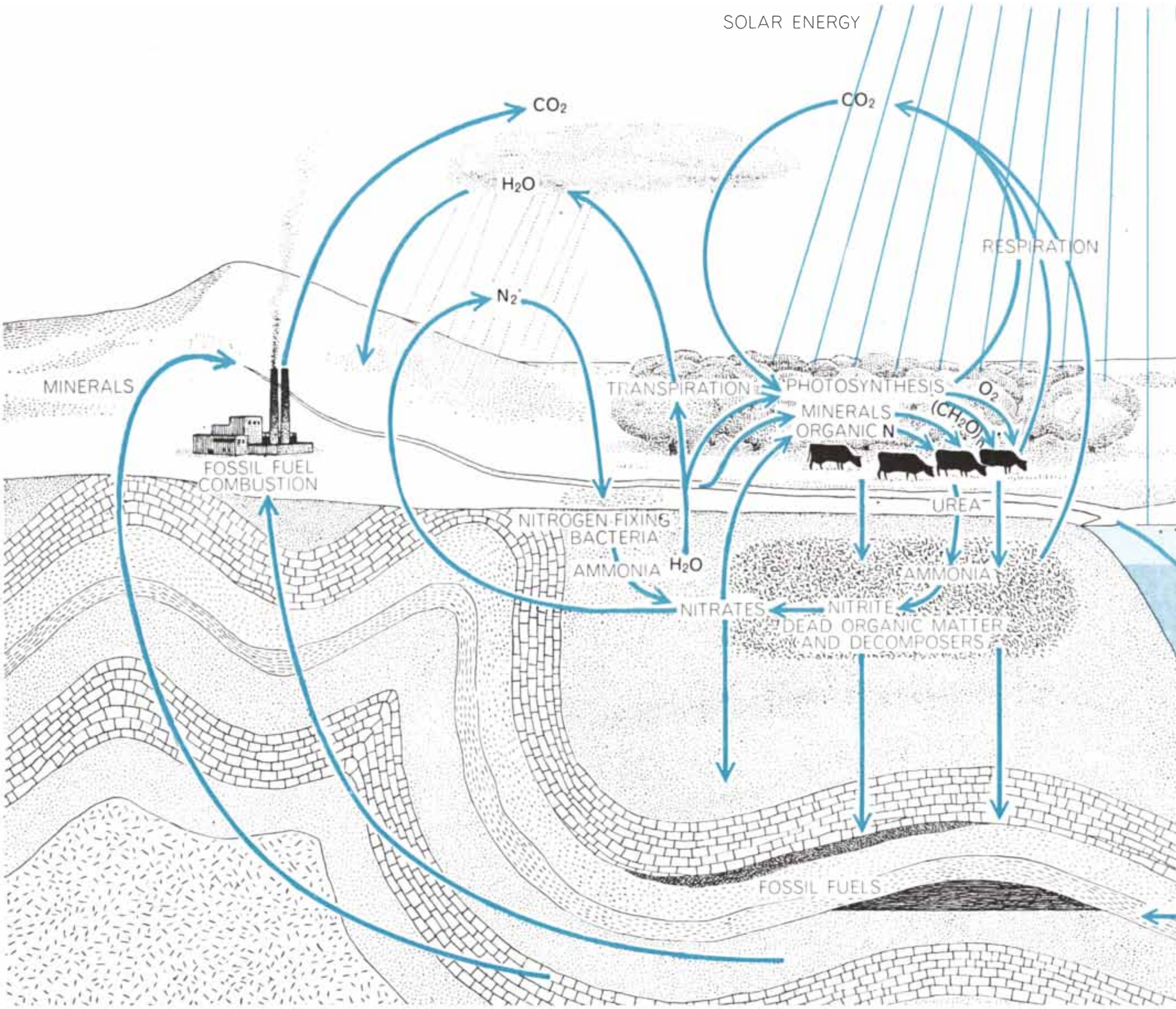
Often the possibility of an element's migrating from the solid state to an ionic form in an aqueous phase (from which an organism can obtain a supply of the element) depends on the state of oxidation at the solid-liquid boundary. Under reducing conditions iron and manganese are freely mobile as divalent (doubly ionized) ions, whereas under oxidizing conditions iron, except when it is complexed organically, is essentially insoluble, and manganese usually precipitates as manganese dioxide. Chromium, selenium and vanadium, all of which are required in minute quantities by some organisms, migrate most easily in an oxidized state as chromate, selenate and vanadate, and so behave in a way opposite from iron. The extreme insolubility of the sulfides of iron, copper, zinc and some other heavy metals may limit the availability of these elements when reduction is great enough to allow hydrogen sulfide to be formed in the decomposition of proteins or by other kinds of bacterial action. Phenomena of this kind mean that under different chemical conditions different materials determine how much living matter can be present.

Expanding this 19th-century agriculturist's idea of limiting factors a little, it is evident that in a terrestrial desert hydrogen and oxygen in the form of water determine the amount of life. In the blue waters of the open ocean the best results indicate that a deficiency of iron is usually limiting, the element probably being present only as dispersed ferric hydroxide, which can be used by phytoplankton cells if it becomes attached to their cell wall. In an intermediate situation, as in a natural terrestrial soil in a fairly humid region, or in a lake or coastal sea, phosphorus is probably the most usual limiting element.

The significance of phosphorus in controlling the quantity of living organisms in nature is due not only to its great biological importance but also to the fact that among the light elements it is relatively scarce. As an element of odd atomic number it is almost two orders of magnitude rarer in the universe than its neighbors in the periodic table, silicon and sulfur. Moreover, in iron meteorites



LIFE AT THE FRINGE of the biosphere is represented by this strange-looking creature photographed recently by an automatic camera lowered to a depth of 15,900 feet from the U.S. Naval oceanographic vessel *Kane*, which at the time was situated in the South Atlantic some 350 miles off the coast of Africa. The plantlike organism is actually an animal: a polyp of the family Umbellulidae. The stem on which its food-gathering tentacles are mounted is approximately three feet long and is leaning toward the camera at an angle of 30 degrees.

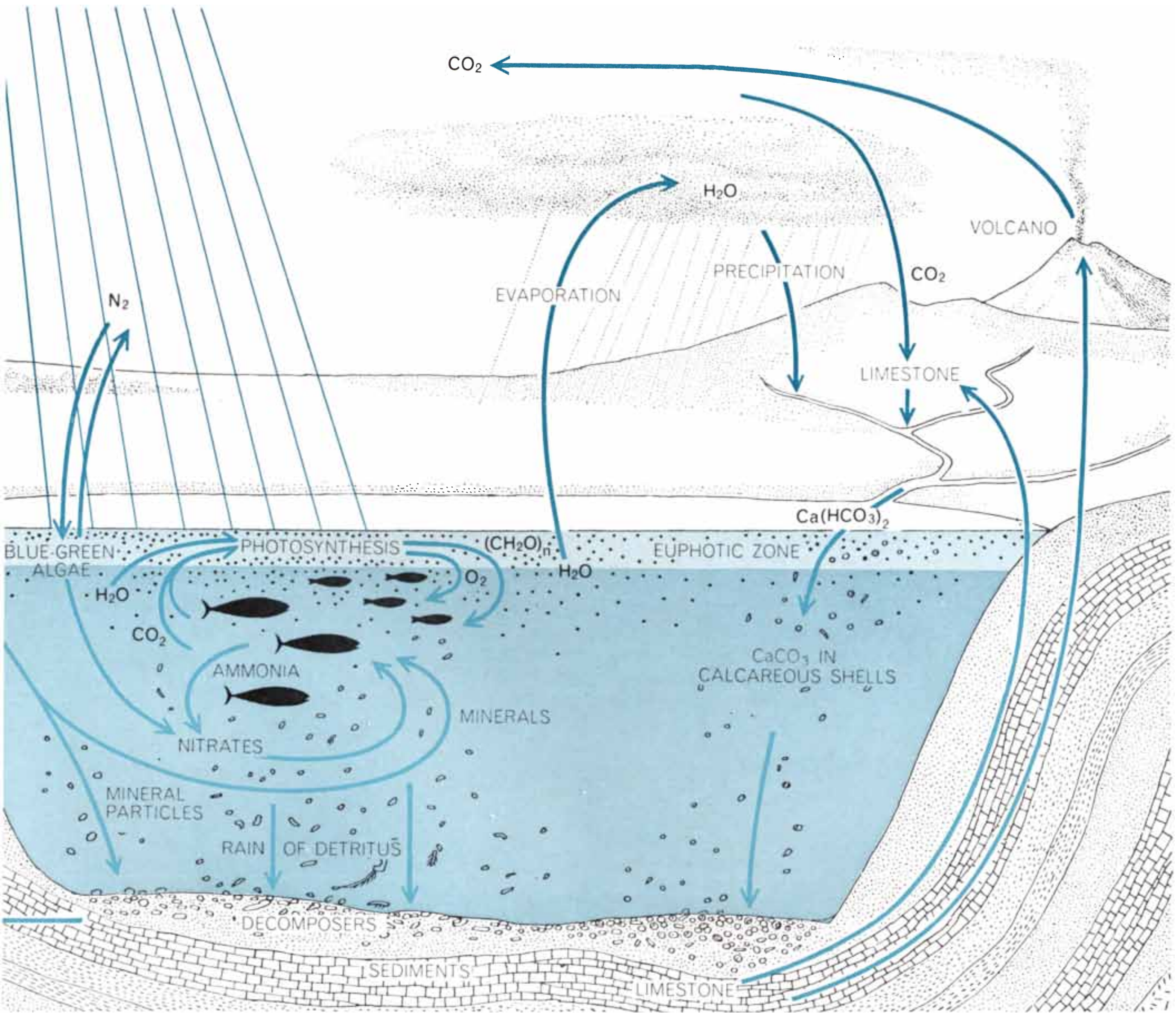


MAJOR CYCLES OF THE BIOSPHERE are indicated in a general way in the illustration on these two pages; more detailed versions of specific cycles accompany the succeeding articles in this issue. In brief, the operation of the biosphere depends on the utili-

phosphorus is found to be enriched in the form of the iron-nickel phosphide schreibersite, so that it is not unlikely that a good part of the earth's initial supply of the element is locked up in the metallic core of our planet. The amount of phosphorus available is thus initially limited by cosmogenic and planetogenic processes. In the biosphere the element is freely mobile under reducing but not too alkaline conditions; since the supply of reduced iron is nearly always much in excess of the phosphorus, oxidation precipitates not only the iron but also the phosphorus as the very insoluble ferric phosphate.

In many richly productive localities where phosphorus is reasonably accessible the quantity of combined nitrogen evidently builds up by biological fixation, so that the ratio of the two elements in water or soil will tend to be about the same as it is in living organisms. In such circumstances both the phosphorus and the nitrogen are limiting; the addition of either one alone produces little or no increase in living matter in a bottle of water or in any other system isolated from the environment, whereas the addition of both often leads to a great increase. Where nitrogen alone is limiting it may be the result of a disturbance of the ecological balance between the nitrogen-fixing organisms (mainly blue-green algae in water and bacteria in soil) and the other members of the biological association. Limitation by nitrogen is never due to a dearth of the element as such, since it is the commonest gas in the atmosphere, but rather depends on the level of activity of the special biological mechanisms, chemically related to photosynthesis but retained only by primitive organisms, for dissociating the two atoms of molecular nitrogen (N_2) and forming from them the amino ($-NH_2$) groups of proteins and other organic compounds.

If the biosphere is to continue in running order, the biologically important materials must undergo cyclical changes so that after utilization they are put back, at the expense of some solar energy, into a form in which they can be reused. The rate at which this happens is quite variable. The rate of circulation of the organic matter of terrestrial organisms, derived from the carbon dioxide of the atmosphere, is measured in decades. In



zation of solar energy for the photosynthetic reduction of carbon dioxide (CO_2) from the atmosphere to form organic compounds on the one hand $(CH_2O)_n$ and molecular oxygen (O_2) on the other. The cycling of certain other vital elements is also indicated.

the case of calcium, which is carried from continental rocks in rivers as calcium bicarbonate ($Ca(HCO_3)_2$) and precipitated as calcium carbonate ($CaCO_3$) in the open ocean largely in the form of the tiny shells of foraminifera, most of the replacement must be due to the movement of the ocean floors toward coastal mountain-building belts; presumably the rate of cyclical replacement would be measured in hundreds of millions of years. Phosphorus would behave rather like calcium, nitrogen more like carbon, although the atmospheric reservoir of nitrogen is of course much larger and the biological fixation of the element is less widespread and energetically more expensive.

At present the artificial injection of some elements in a mobile form into the ocean and atmosphere is occurring much faster than it did in preindustrial days; new cycles have come into being that may distribute very widely and in toxic quantities elements such as lead and mercury, as well as fairly stable new compounds such as insecticides and defoliants. It should be obvious that the possible action of all such substances on the tenuous and geochemically inefficient green mantle of the earth demands intense study if life is to continue in the biosphere.

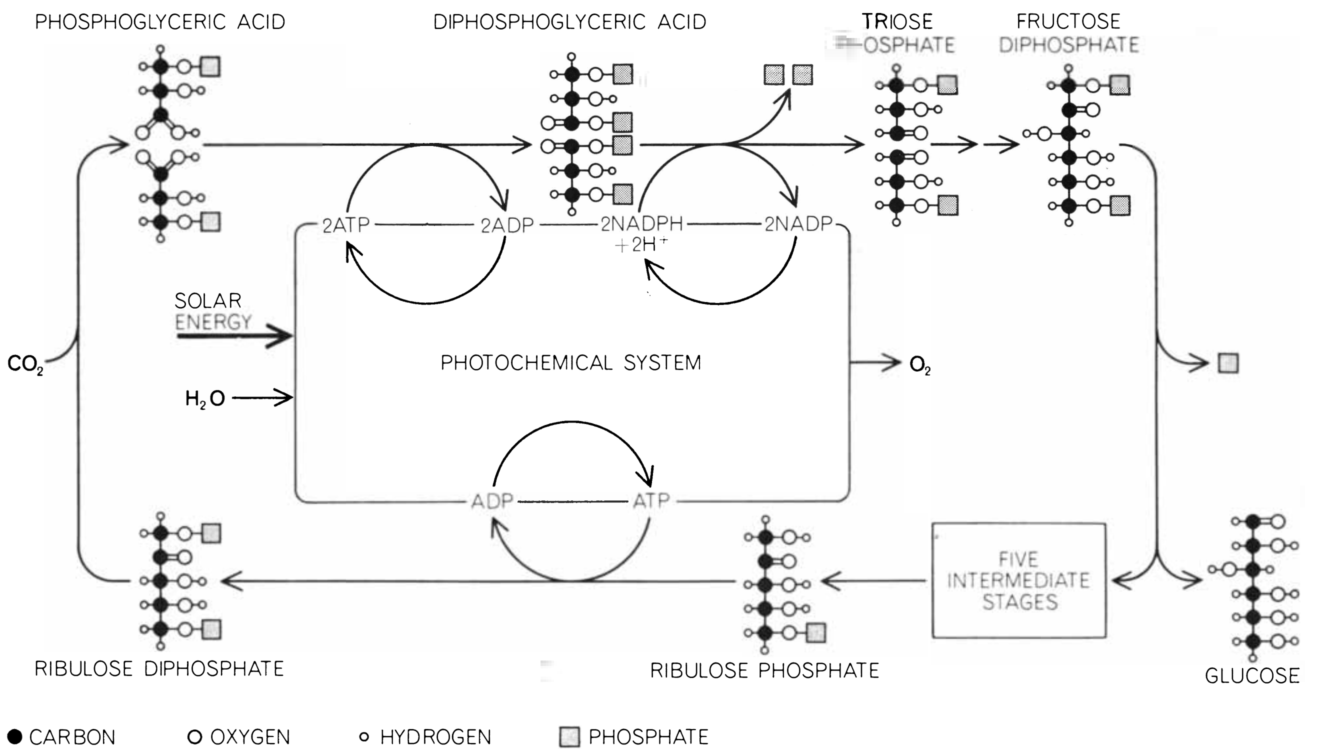
How did the system we have been examining come into being? There are now a few facts that seem clear and a few inferences that are reasonable. We know that the present supply of atmospheric oxygen is continually replenished by photosynthesis, and that if it were not, it would slowly be used up in the process of oxidation of ferrous to ferric iron and sulfides to sulfates in weathering. All the evidence points to the atmosphere of the earth's being secondary. The extreme rarity of the cosmically abundant but chemically inert gas neon compared with water vapor, which has almost the same molecular weight, shows (as Harrison Brown pointed out 25 years ago) that only gases that could be held in combination in the solid earth were available for the formation of the secondary atmosphere. The slow production of oxygen by the photolysis (literally "splitting by light") of water and by the thermal dissociation of water with the loss of hydrogen into space is possible even in the early atmosphere, but nearly everyone agrees that this would merely lead to a little local oxidation of material at or near the earth's crust.

Some mixture of water vapor, methane, carbon monoxide, carbon dioxide, ammonia and nitrogen presumably initiated the secondary atmosphere. We know from laboratory experiments that when an adequate energy source (such as ultraviolet light or an electric discharge) is available, many organic compounds, including practically all the building blocks of biological macromolecules, can be formed in such an atmosphere. We also know from studies of meteorites that such syntheses have occurred under extraterrestrial conditions, but that a good many substances not of biological significance were also formed. It is just possible that ultimately exploration of the asteroids may produce evidence of the kind of environment on a disrupted planet in which these kinds of prebiological organic syntheses took place.

However that may be, we can be reasonably confident that a great deal of prebiological organic synthesis occurred on the earth under reducing conditions at an early stage in our planet's history. The most reasonable energy source would be solar ultraviolet radiation. Since some of the most important compounds are not only produced but also destroyed by the wavelengths available in the absence of an oxygen screen, it is probable that the processes leading to production of the first living matter took place under specific structural conditions. Syntheses may have occurred in the water vapor and gases above a primitive system of pools or a shallow ocean, while at the bottom of the latter, somewhat shielded by liquid water, polymerization of some of the products on clay particles or by other processes may have taken place.

The first hint that organisms had been produced is the presence of bacteria-like structures in the Figtree geological formation of South Africa; these fossils are believed to be a little more than three billion years old. Carbon-containing cherts from Swaziland that are older than that have been examined by Preston Cloud of the University of California at Santa Barbara, who did not find any indication of biological objects. The oldest really dramatic microflora are those described by Stanley A. Tyler and Elso S. Barghoorn of Harvard University from the Gunflint formation of Ontario, which is about two billion years old [*see illustration on page 44*]. Sedimentary rocks from that formation seem to contain genuine filamentous blue-green algae that were doubtless both photosynthetic and nitrogen-fixing. Cellular structures that were probably components of blue-green algal reefs certainly occurred a little earlier than two billion years ago. The most reasonable conclusion that can be drawn from the work of Barghoorn, Cloud and others, who are at last giving us a real Precambrian paleobiological record, is that somewhere around three billion years ago biochemical evolution had proceeded far enough for discrete heterotrophic organisms to appear.

These organisms (which, as their name implies, draw their nourishment from externally formed organic molecules) could utilize the downward-diffusing organic compounds in fermentative metabolism, but they lived at sufficient depths of water or sediment to be shielded from the destructive effect of the solar ultraviolet radiation. After somewhat less than another billion years procaryotic

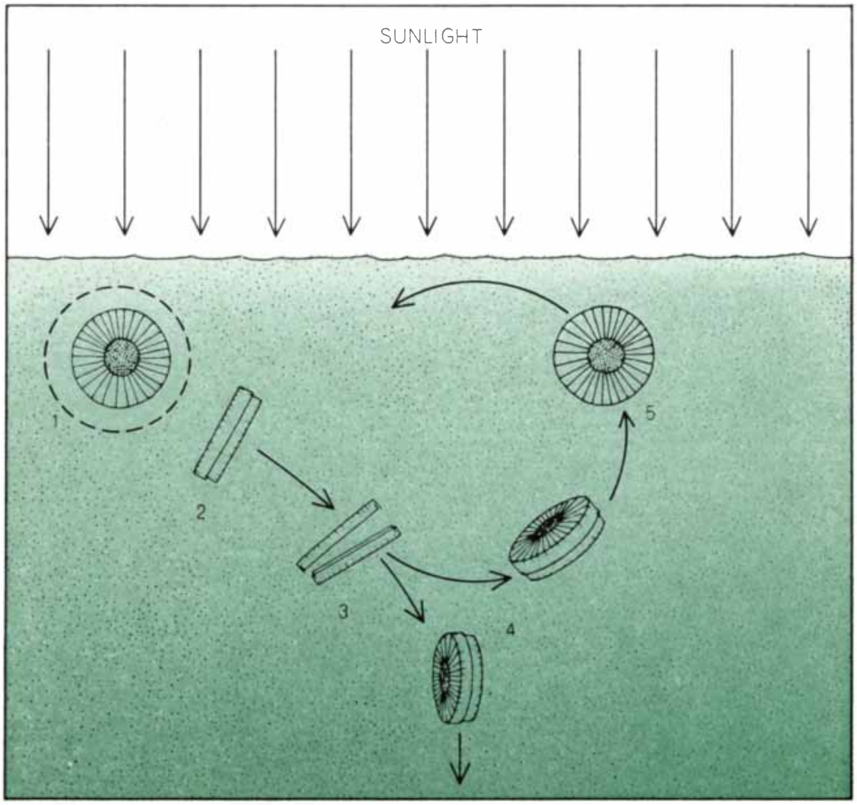


PHOTOSYNTHESIS, the fundamental process for sustaining life on the earth, is accomplished by plants on land, by freshwater algae and by phytoplankton in the sea. Utilizing the energy contained in sunlight, they convert carbon dioxide and water into some form of carbohydrate (for example glucose), releasing oxygen as a waste product. This simplified diagram shows the cyclical process by which a molecule of carbon dioxide is attached to a five-carbon molecule, ribulose-1,5-diphosphate, previously assembled from five molecules of carbon dioxide. The photochemical system packages part of the incoming solar energy by converting adenosine diphosphate (ADP) to adenosine triphosphate (ATP) and by converting nicotinamide adenine dinucleotide phosphate (NADP) to its reduced form (NADPH). Two molecules of NADPH and three of ATP are required to fix one molecule of carbon dioxide. Carbon atoms from CO_2 can be incorporated into a variety of compounds and removed at various points in the cycle.

cells—cells without a fully developed mitotic mechanism for cell division and without mitochondria—had already started photosynthesis. The result of these developments would have ultimately been the complete transformation of the biosphere from the old heterotrophic fermentative regime to the new autotrophic (self-nourishing), respiratory and largely oxidized condition. How fast the change took place we do not know, but it was certainly the greatest biological revolution that has occurred on the earth. The net result of this revolution was no doubt the extermination of a great number of inefficient and primitive organisms that could not tolerate free oxygen and their replacement by more efficient respiring forms.

Cloud and his associates have recently found evidence of eucaryotic cells—cells with a fully developed mitotic mechanism and with mitochondria—some 1.2 to 1.4 billion years old. It is reasonable to regard the rise of the modern eucaryotic cell as a major consequence of the new conditions imposed by an oxygen-containing atmosphere. Moreover, Lynn Margulis of Boston University has assembled most convincingly the scattered but extensive evidence that this response was of a very special kind, involving a multiple symbiosis between a variety of procaryotic cells and so constituting an evolutionary advance quite unlike any other known to have occurred.

If the first eucaryotes arose 1.2 to 1.4 billion years ago, there would be about half of this time available for the evolution of soft-bodied multicellular organisms, since the first fossil animal skeletons were deposited around 600 million years ago at the beginning of the Cambrian period. Although most of the detailed history consists of a series of blanks, we do have a time scale that seems sensible.



PHYTOPLANKTON CELL is slightly denser than seawater and under absolutely quiet conditions would slowly sink to the bottom. In this way the cell can move from a small parcel of water (*broken circle*) from which it has removed all the available nutrients (*black dots*) into a parcel still containing these substances. As the cell sinks it divides, and losses from the population in the surface waters that constitute the euphotic zone are continually made good by upward turbulence, which returns some of the products of cell division to the surface layer. The particular phytoplankton shown is a diatom of the genus *Coscinodiscus*.

Without taking too seriously any of the estimates that have been made of the expectation of the life of the sun and the solar system, it is evident that the biosphere could remain habitable for a very long time, many times the estimated length of the history of the genus *Homo,* which might be two million years old. As inhabitants of the biosphere, we should regard ourselves as being in our infancy, particularly when we throw destructive temper tantrums. Many people, however, are concluding on the basis of mounting and reasonably objective evidence that the length of life of the biosphere as an inhabitable region for organisms is to be measured in decades rather than in hundreds of millions of years. This is entirely the fault of our own species. It would seem not unlikely that we are approaching a crisis that is comparable to the one that occurred when free oxygen began to accumulate in the atmosphere.

Admittedly there are differences. The first photosynthetic organisms that produced oxygen were probably already immune to the lethal effects of the new poison gas we now breathe. On the other hand, our machines may be immune to carbon monoxide, lead and DDT, but we are not. Apart from a slight rise in agricultural productivity caused by an increase in the amount of carbon dioxide in the atmosphere, it is difficult to see how the various contaminants with which we are polluting the biosphere could form the basis for a revolutionary step forward. Nonetheless, it is worth noting that when the eucaryotic cell evolved in the middle Precambrian period, the process very likely involved an unprecedented new kind of evolutionary development. Presumably if we want to continue living in the biosphere we must also introduce unprecedented processes.

Vernadsky, the founder of modern biogeochemistry, was a Russian liberal who grew up in the 19th century. Accepting the Russian Revolution, he did much of his work after 1917, although his numerous philosophic references were far from Marxist. Just before his death on January 6, 1945, he wrote his friend and former student Alexander Petrunkevitch: "I look forward with great optimism. I think that we undergo not only a historical, but a planetary change as well. We live in a transition to the noosphere." By noosphere Vernadsky meant the envelope of mind that was to supersede the biosphere, the envelope of life. Unfortunately the quarter-century since those words were written has shown how mindless most of the changes wrought by man on the biosphere have been. Nonetheless, Vernadsky's transition in its deepest sense is the only alternative to man's cutting his lifetime short by millions of years. The succeeding articles in this issue of *Scientific American* may contain useful hints as to how this alternative may be brought to fruition.

The Energy Cycle of the Earth

The solar energy absorbed by the earth is eventually reradiated into space as heat. Meanwhile it is distributed over the surface of the earth by the circulation of the atmosphere and the oceans

by Abraham H. Oort

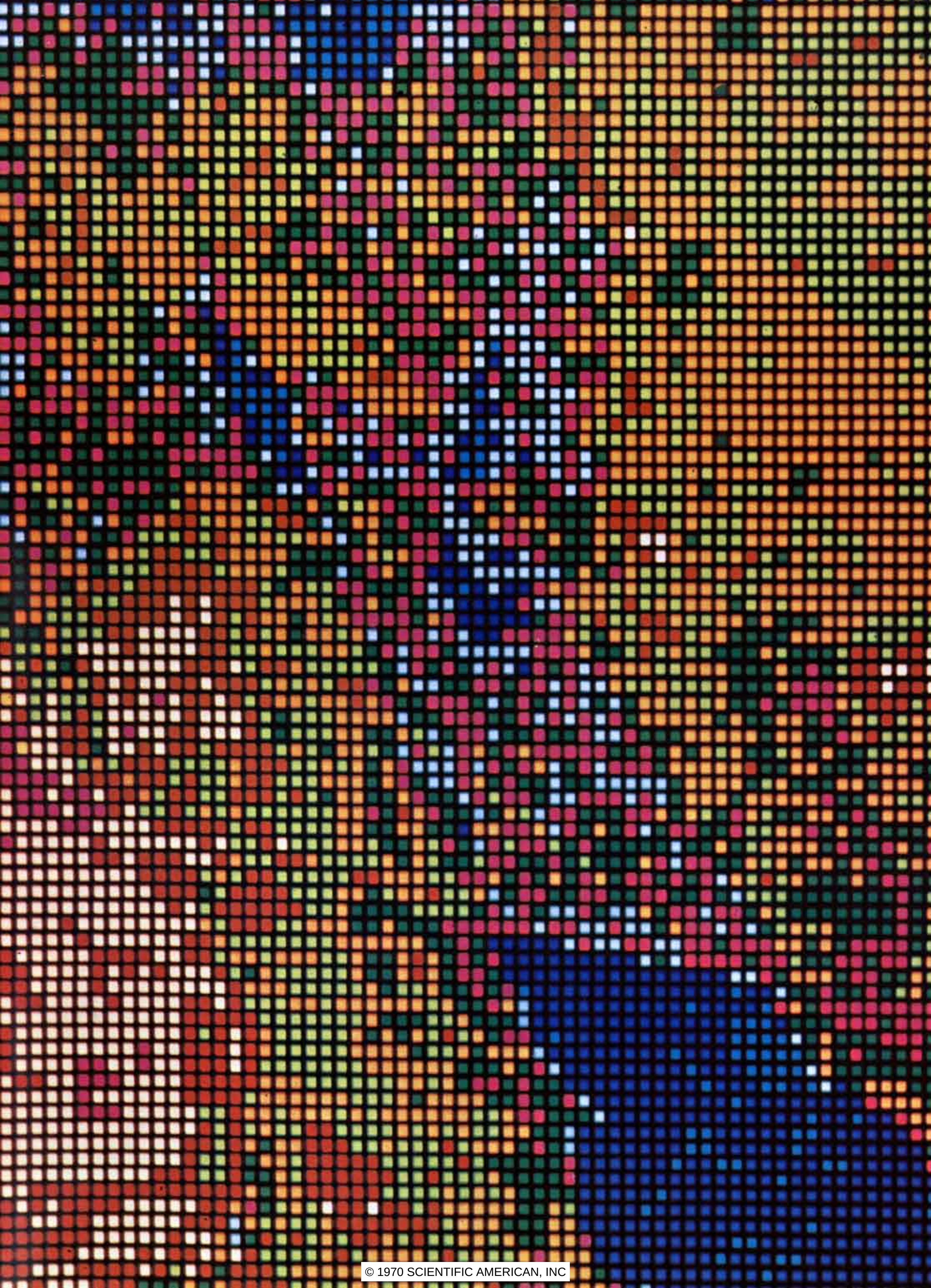
All life on the earth is of course ultimately powered by the sun, and accordingly it is strongly affected by variations of the incoming solar radiation over the globe. The distribution of sunlight with latitude determines to a great extent the location of the major climatic zones—tropical, temperate and polar—and these zones in turn set broad geographic limits to the different forms of terrestrial life.

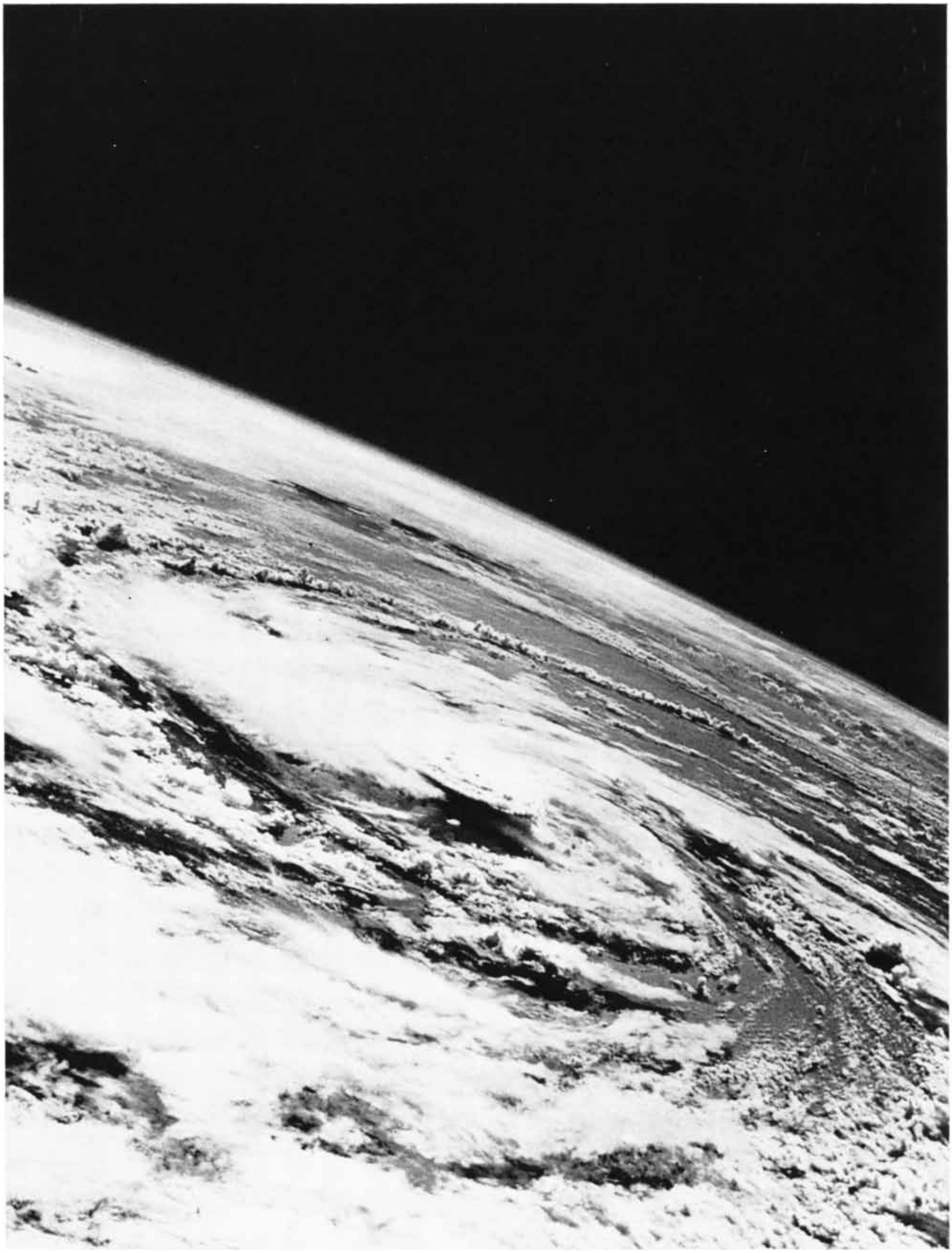
What is less familiar is the central function of the atmosphere and the oceans in redistributing the incoming solar energy and hence in determining the "macroclimate" of the earth. The importance of the circulation of the atmosphere and the oceans to the operation of the biosphere becomes apparent when one considers that present forms of life could not endure the harsh climate that would exist if conditions of radiative equilibrium were to prevail at all latitudes (that is, if the incoming solar radiation to a zone were exactly balanced by the outgoing terrestrial radiation from that zone). This article is devoted not only to an examination of the character of the incoming short-wave radiation and the outgoing long-wave radiation but also to an attempt to trace the cycle of the solar energy from the time it enters the atmosphere as sunlight until it finally finds its way back into space as heat. At the end of the article I shall take up the question of the possible effects of man's intervention in these vast energy processes.

When the sun is over the Equator on March 21 and September 23 (the equinoxes), a maximum amount of solar radiation is received at the Equator [*see illustration on page 58*]. On the same dates the radiation received at the north and south poles is practically zero. This symmetrical decrease of radiation with latitude toward both poles only occurs, however, during the transition seasons, spring and fall. In the summer hemisphere, for example, there is almost no meridional (north-south) heating gradient. Even more surprising is the fact that the 24-hour average sunshine has a maximum value at the summer pole, not at the subsolar point in the Tropics! This of course is owing to the permanent daylight at the summer pole. From a consideration of these factors alone one would expect significant differences in the large-scale circulation between the summer and the winter hemispheres. In addition one would expect climatic effects related to the variation of incoming radiation with local time in each hemisphere [*see illustration on page 59*]. Diurnal changes (that is, changes with a period of 24 hours) in the wind, temperature and humidity are only important, however, close to the ground and at high levels in the atmosphere. Locally the interaction of land and sea breeze effects may also play a role, but the overall atmospheric circulation cannot respond well to such short-period phenomena. This is even truer of the oceanic circulation. In addition to the imposed diurnal and annual periodicities in the incoming solar radiation, one finds a slight semiannual variation of insolation in the Tropics, where the sun passes overhead twice during the year.

How is the solar energy transmitted and transformed once it enters the top of the atmosphere? Averaged over the globe about 30 percent of the radiation is either scattered back by the constituents of the atmosphere or directly reflected by clouds or the earth's surface. This portion of the solar energy is lost into space and cannot be used to generate atmospheric motions. About 50 percent of the incoming radiation finally reaches the ground or ocean, where it is absorbed as heat. The properties of the surface determine the thickness of the layer over which the available heat is distributed. In the case of an ocean surface wave motions are quite effective in distributing the heat through a thick layer, sometimes extending down to a depth of 100 meters. The diurnal variation in temperature of the ocean surface itself

MOSAIC OF COLORED SQUARES on the opposite page is actually a "map" showing the relative infrared reflectance of various land and water surfaces in a region of the Middle East. The data used to construct the map were obtained at noon on May 4, 1969, by means of a high-resolution scanning infrared radiometer on board the unmanned artificial earth satellite *Nimbus 3*. The data were digitized, adjusted for differences in sun angle and displayed in a format in which the color of each square represents a range of relative reflectance. In assigning different colors to each range an attempt was made to render the scene in "natural" colors. Thus the lowest ranges of relative reflectance, which correspond generally to water surfaces, are represented by different shades of blue. Areas of intermediate reflectance, corresponding roughly to vegetated regions, are green. Highly reflective desert areas are beige. The large body of water at lower right is the Red Sea. At its northern end the reflectance is modified by haze, obscuring much of the gulfs of Suez and Aqaba, which flank the Sinai Peninsula. The blue area at top left is the Mediterranean Sea. The triangular green area adjacent to it is the Nile delta. The string of green squares at bottom left represents the lake forming in the Nile River valley as a result of the construction of the Aswan Dam. The map was produced as part of a study conducted by Norman H. MacLeod of the National Aeronautics and Space Administration in an effort to develop a quantitative technique for observing the earth in terms of the relative reflectance of its parts.





HURRICANE GLADYS was photographed by the *Apollo 7* astronauts as it approached the west coast of Florida on the morning of October 17, 1968. The view is toward the southeast with Cuba in the distant background. The lack of the usual high cloud cover made it possible to view the spiral lower cloud structure of this cyclonic storm in considerable detail. Traveling cyclones (of which hurricanes are a particularly violent form) contribute to the net poleward transport of heat in the middle latitudes and thus help to moderate the harsh climate that would exist on the earth if conditions of radiative equilibrium were to prevail at all latitudes.

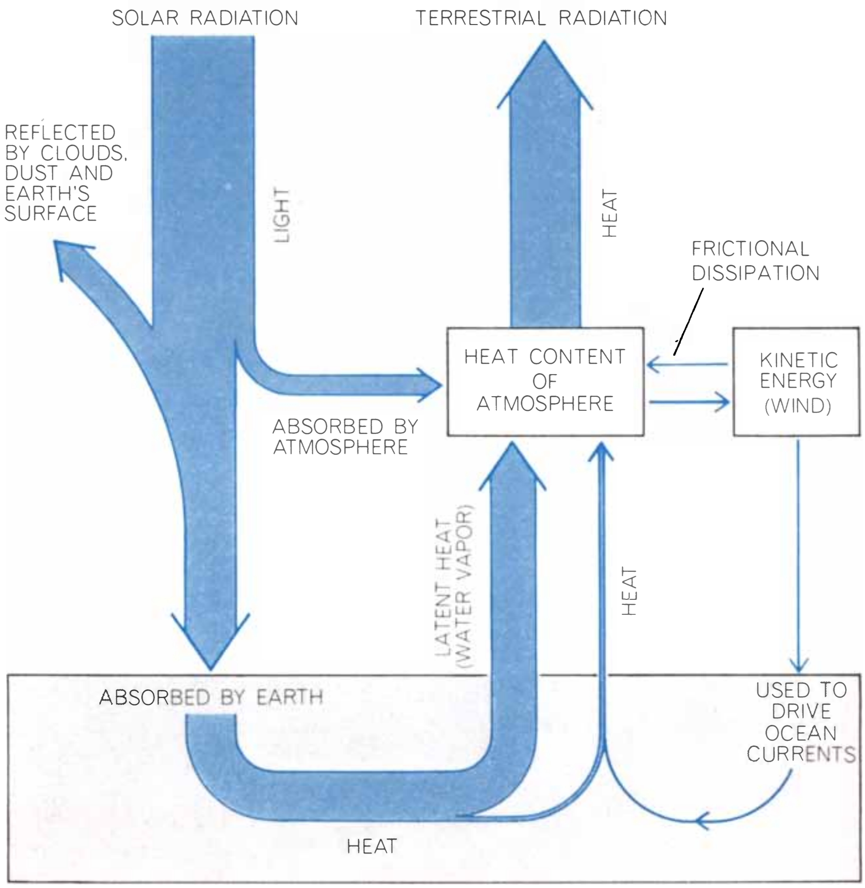
is thus generally less than 1 degree Celsius. The situation on land depends not only on the diurnal amplitude of the incoming radiation but also on the properties of the soil (for example its wetness) and the presence or absence of vegetation. The energy transfer down into the ground occurs through the slow process of molecular heat conduction. Over bare ground the diurnal temperature range at the surface can amount to several tens of degrees Celsius, but the temperature change is hardly noticeable below a depth of half a meter.

What happens to the remaining 20 percent of the incoming solar radiation that is apparently absorbed on its path through the atmosphere? Here it is necessary to consider the spectrum of the incoming and outgoing radiation [*see top illustration on page 60*]. The emission spectrum of the sun roughly resembles that of a "black body" radiating at a temperature of 6,000 degrees Kelvin. (A black body is defined as one that absorbs all the radiation falling on it.) In the visible portion of the spectrum (wavelengths between .4 and .7 micron), where the maximum influx of solar energy takes place, the radiation can penetrate almost without loss down to the earth's surface except where clouds are present. High in the atmosphere ordinary oxygen (O_2) and ozone (O_3) molecules absorb an estimated 1 to 3 percent of the incoming radiation. This absorption occurs in the ultraviolet portion of the spectrum and effectively limits the penetrating radiation to wavelengths longer than .3 micron. Although this effect is relatively small, it is important because it is the main source of energy for the circulation above 30 kilometers [see "The Circulation of the Upper Atmosphere," by Reginald E. Newell; SCIENTIFIC AMERICAN, March, 1964]. Moreover, the absorption at these levels shields the biosphere from the damaging effects of ultraviolet radiation. At wavelengths longer than one micron most of the atmospheric absorption is due to water vapor, dust and water droplets in clouds. This process operates in the lower troposphere and involves most of the remaining 20 percent of the total incoming radiation.

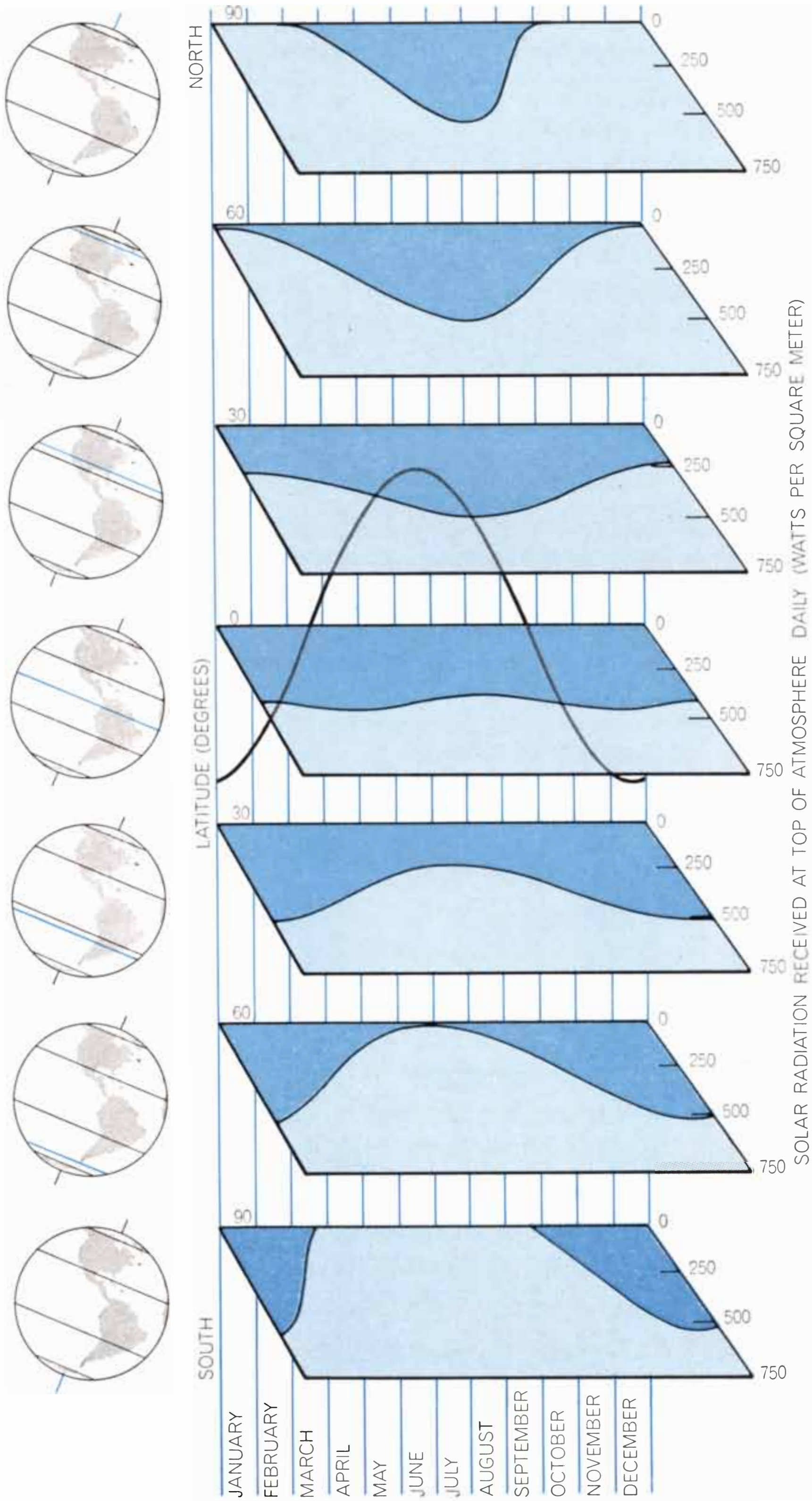
In spite of certain long-term climatic changes climatological records do not show an appreciable net heating or cooling of the earth and its atmosphere. Therefore the earth must emit an amount of radiation equal to the radiation absorbed. A characteristic shift to longer wavelengths does take place, however, since the earth radiates at an effective black-body temperature of about 255 degrees K., a very low value compared with the sun's black-body temperature of 6,000 degrees. The earth's emission occurs throughout a broad range of wavelengths with a flat maximum at about 12 microns. In this range of the spectrum the atmosphere is not transparent. Water vapor, ozone and carbon dioxide absorb significant amounts of long-wave radiation.

If one now calculates the vertical transfer of solar and terrestrial radiation using the observed temperature and humidity structure, one finds that the atmosphere is not in local radiative equilibrium. The net effect due to solar and terrestrial radiation alone would be an intense heating of the earth's surface and a cooling of the atmosphere at the rate of up to two degrees C. per day, depending on the height. In reality the air is prevented from cooling by the vertical transfer of heat directly from the earth's surface and by the release of heat through the condensation of water vapor. It is at this point that the dynamics of the atmosphere begin to play an important role.

The transport of energy upward into the atmosphere forms the major energy supply for the atmospheric heat engine. A large portion of this energy, however, is "latent" (that is, in the form of water vapor), and it is used to raise the atmospheric temperature only when condensation takes place. Close to the surface the energy transport occurs through evaporation of water, through heat conduction and through the transfer of long-wave radiation. At a certain height above the surface turbulent eddies mix the water vapor and heat further upward. The scale of the effective eddies increases with distance from the surface, finally growing to convective clouds of the cumulus type in the free atmosphere. This upward transfer of energy from the surface compensates for the radiative cooling of the atmosphere. A schematic diagram of the average energy cycle in the atmosphere reveals the important



ATMOSPHERIC HEAT ENGINE is averaged over the entire atmosphere in this diagram. The thickness of the arrows indicates approximately the strength of the various energy flows and conversion rates. As the diagram shows, the earth's surface acts as an indirect source of energy for the circulation in the atmosphere. Estimates of the efficiency of the atmospheric heat engine differ widely, depending on the energy inputs and outputs used to define efficiency. By one definition (the amount of energy used to generate ocean currents divided by the incoming solar energy) the efficiency of the system is less than 1 percent.



INCOMING SOLAR RADIATION (*dark color*) **is shown in this three-dimensional chart at seven different latitudes as a function of month of the year. A large difference in the meridional (north-south) heating gradient exists between the winter and the summer hemispheres. In winter the gradient is very large, whereas in summer it practically disappears. The annual cycle in declination of the sun between 23 degrees north latitude (the Tropic of Cancer) and 23 degrees south latitude (the Tropic of Capricorn) is indicated by the solid black curve in the latitude plane (*background*). The radiation is averaged over all hours of the day. Data are from the Smithsonian Meteorological Tables, compiled by Robert J. List.**

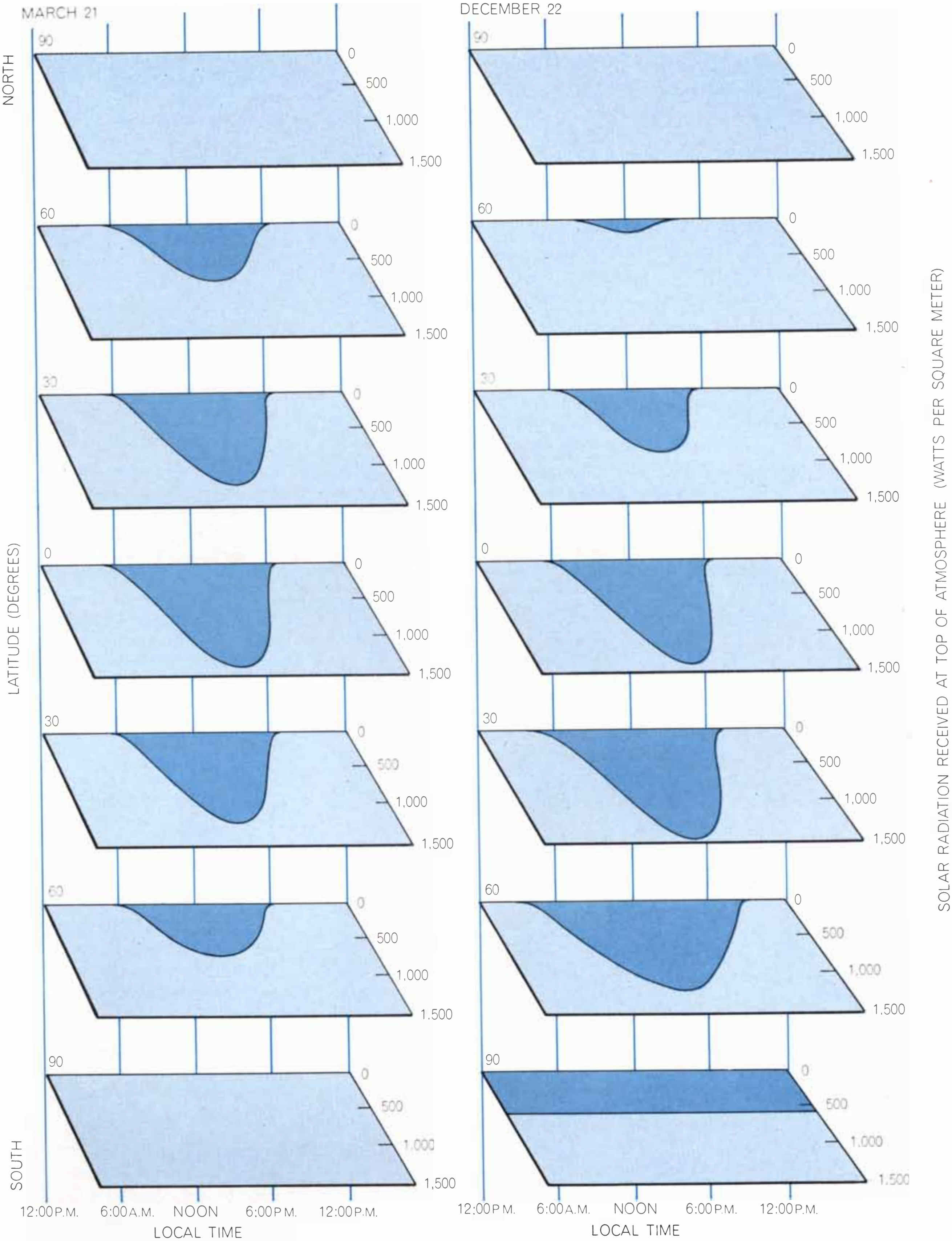
role of the earth's surface as the source of latent heat and sensible heat [*see illustration on preceding page*].

There is a significant difference in the character of the heating for the ocean and for the atmosphere. In the ocean the heating is applied at the top, which leads to stable conditions, whereas in the atmosphere the heating is applied at the bottom, giving rise to vigorous convection. The ocean currents, which are driven mainly by the winds, redistribute the absorbed solar heat horizontally and thereby influence in turn the pattern of the heat supply to the atmosphere that finally closes the cycle. The oceans and the atmosphere are strongly coupled systems and cannot very well be treated separately. The final circulation pattern is determined by the interaction of the two systems, each system influencing the other in a complicated cycle of events.

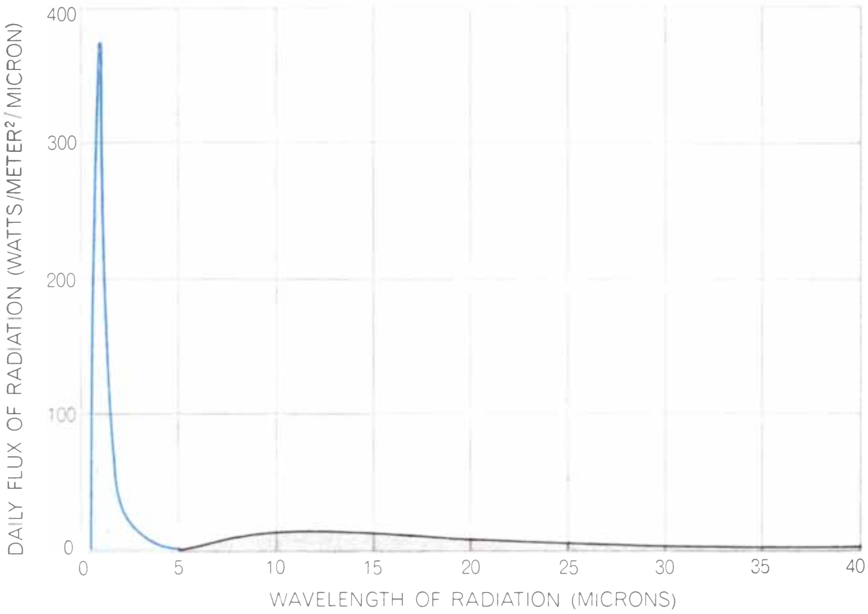
The effects of radiation and convection alone tend to maintain the proper energy balance for the earth as a whole, but the atmospheric and oceanic circulation must be considered if one wishes to explain the observed north-south temperature distribution [*see bottom illustration on page 60*]. The fact that the incoming solar radiation drops off more rapidly toward the winter pole than the outgoing terrestrial radiation does means that there is an excess in radiational heating in the summer hemisphere and a deficit near the winter pole. The storage of heat in the ocean during summer and the release of a large portion of this heat during winter has a moderating effect on the climate. Without an efficient north-south transfer of heat, however, the earth would still become very hot in the summer hemisphere and extremely cold at high latitudes in the winter hemisphere. The heating gradient constitutes the major driving force for the large-scale atmospheric currents and ultimately also for the oceanic currents. Judging from the existing temperature gradient, these circulations must be quite effective agents for transporting energy toward the winter pole.

What type of atmospheric and oceanic circulation patterns would develop as a consequence of such an imposed heating gradient? Let us limit the discussion for the time being to the winter situation. It is in this season that the north-south gradient in the solar heating is strongest and that the differences between the radiative equilibrium temperature and the observed temperature are at a maximum. What simple mechanism would suffice to transport heat poleward?

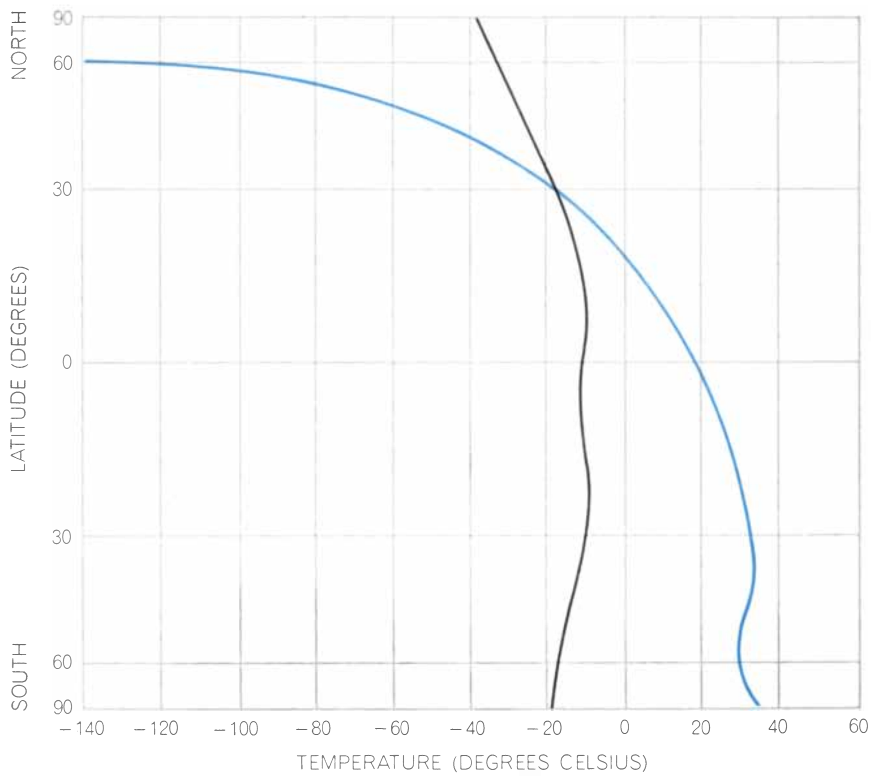
Let us first consider a model atmo-



DIURNAL INSOLATION as a function of latitude varies widely according to the date. At the time of the equinoxes (around March 21 and September 23) the poleward decrease in the amount of incoming solar radiation with latitude is symmetrical with respect to the Equator and practically no radiation is received at either the North Pole or the South Pole (*chart at left*). At the solstices (around June 21 and December 22) the latitudinal differences in diurnal insolation between the two hemispheres are extreme (*chart at right*); the summer pole (*bottom*) receives sunlight 24 hours a day, whereas the winter pole (*top*) receives no sunlight at all.



APPROXIMATE EMISSION SPECTRA of the sun (*colored curve*) and the earth (*black curve*) are represented in this graph under the assumption that they radiate as "black bodies" with temperatures of 6,000 degrees and 250 degrees Kelvin respectively. The solar curve is corrected for the distance between the sun and the earth, for the fact that only one side of the earth is illuminated by the sun at any instant and finally for the mean albedo (reflectance) of 30 percent for the earth. The areas under the two curves are equal; in other words, the earth emits as much radiation as it absorbs. The important change in the character of this radiation from the short-wave to the long-wave part of the spectrum is evident.



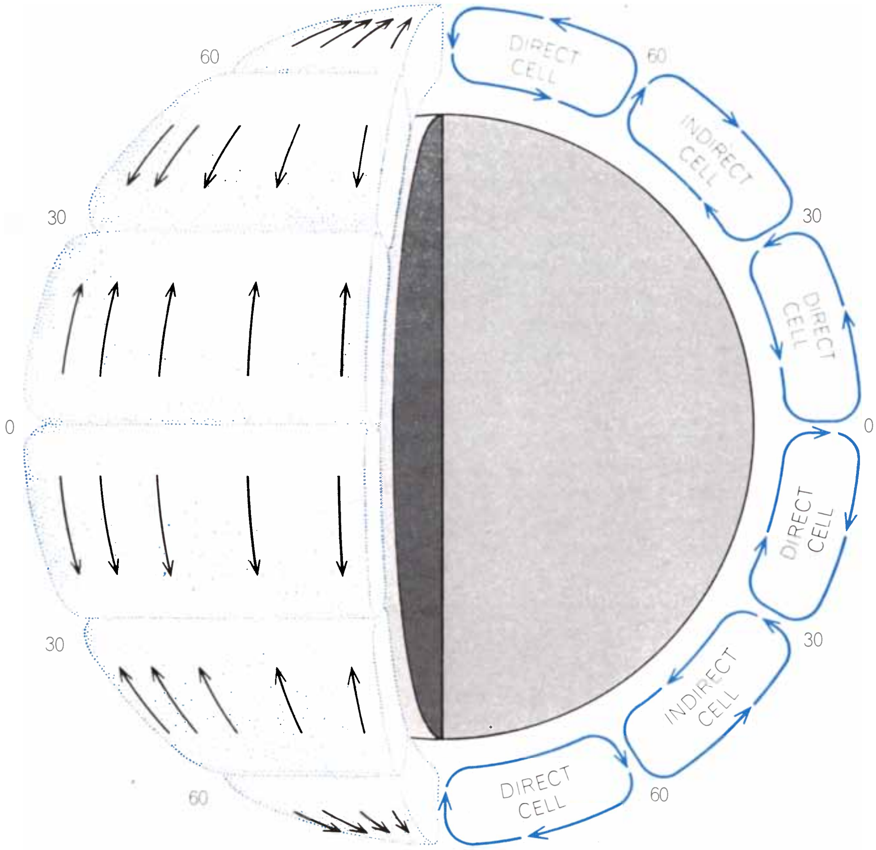
IMPORTANCE OF ATMOSPHERIC DYNAMICS in moderating the earth's climate is demonstrated by this graph, which compares the calculated radiative-equilibrium temperature for a "black" earth (*colored curve*) with the observed vertical mean temperature (*black curve*) as a function of latitude during January. At this time no sunshine reaches the earth north of the Arctic Circle; neglecting any lag effects due to the storage of heat, the radiative-equilibrium temperature in the polar cap would go down to absolute zero (–273.2 degrees Celsius), while the summer hemisphere would tend to become extremely hot.

sphere that has a uniform temperature and rotates at the same rate as the earth. If one starts to heat the air at low levels on the summer side of the Equator, the local temperature will rise and the air column will expand mainly in the vertical direction. This process will create at the upper levels a relatively high-pressure belt located over the "thermal" Equator. Next the north-south pressure gradient will force the equatorial air at all longitudes to move toward the low-pressure zone, mainly into the winter hemisphere, where initially vertical contraction occurred as a result of radiational cooling. The air will then slowly start to sink over a wide region in the winter hemisphere and will return to the Equator at low levels. The cycle will be closed finally through a rise of the air after it has arrived in the vicinity of the thermal Equator.

A simple cellular circulation of this kind, called a mean meridional circulation, would be completely symmetrical with respect to the earth's axis of rotation. The existence of one such cell in each hemisphere with rising warm air near the Equator and sinking cold air near the poles was originally postulated by the English meteorologist George Hadley in 1735. Such a cell is called a direct cell since it releases potential energy and converts it into kinetic energy. Later investigators, notably the 19th-century American meteorologist William Ferrel, showed that one actually needs three cells in each hemisphere to explain the important climatological features at the earth's surface [*see illustration on opposite page*]. This picture has been confirmed by many observational and theoretical studies and seems to represent rather well the annual mean conditions in the atmosphere. Recent and more detailed observations, however, have shown that only during the transition months in fall and spring is such an idealized circulation symmetrical with respect to the Equator realized. The asymmetry in heating during most of the year appears to favor the development of only one strong cell in the Tropics: the one in the winter hemisphere. This cell circulates on the average about 2×10^8 metric tons of air per second. At the same time the "summer" Hadley cell has shrunk to an insignificant size [*see illustration on pages 62 and 63*].

Let us consider in somewhat greater detail what energy transformations take place in the tropical Hadley cell. In its lower branch subtropical air flows close to the earth's surface toward the summer hemisphere with an average velocity of one or two meters per second. During the long journey equatorward heat and moisture are absorbed from the warm underlying ocean. This is the region of the trade winds. Near the Equator the air starts to rise in a fairly narrow region called the intertropical convergence zone, where intense precipitation occurs. In that zone a powerful conversion from sensible and latent heat into potential energy occurs as the air expands and the water vapor condenses, the net effect being a cooling of the equatorial atmosphere.

The upper branch of the Hadley cell now transports the air, which has become relatively cold but which has a high potential energy, into the winter hemisphere. In the rather wide downward branch in the subtropics the subsiding cold air is strongly heated by compression, and the potential energy supplied to the air in the equatorial convergence zone is converted back into heat. One would expect that the sinking air in the subtropics would be dry, since almost all the moisture was rained out in the upward branch of the Hadley cell. That expectation is confirmed by the location of the continental deserts and the small amount of rainfall over the oceans in this latitude.



CELLULAR MODEL of atmospheric circulation was first proposed by the English meteorologist George Hadley in 1735 and was modified by the American meteorologist William Ferrel in the 19th century. The pattern has a rotational symmetry around the earth's axis. The two tropical cells are called Hadley cells; two mid-latitude cells are called Ferrel cells.

The large overturning in each hemisphere of the kind Hadley envisioned is not adequate to transport enough energy poleward to counteract the externally imposed heating gradient. In such a situation temperatures near the Equator would start to rise above the observed values, and near the Pole they would start to drop. This would continue until a critical value of the north-south temperature gradient was reached, at which point zonal (east-west) asymmetries would start to develop (this process is called baroclinic instability). Theoretical models indicate that the maximum instability would tend to develop with atmospheric waves a few thousand kilometers long. In the middle latitudes, where the strong meridional temperature gradients are found, these waves can grow very fast and can take over the task of transporting energy poleward from the Hadley cell.

The familiar traveling cyclones and anticyclones, which can be found on every weather map in the middle latitudes, are a manifestation of this instability process. They form an extension of the large waves in the middle and upper troposphere. These systems mix heat in an efficient way through horizontal processes. At the same level one finds warm, humid air flowing poleward and cold, dry air flowing equatorward. On the average these flows are equivalent to a net poleward transport of sensible and latent heat. Waves with lengths of a few thousand kilometers and with time scales of a few days to a week appear to be mainly responsible for the transfers. The typical "variable" climate of middle latitudes is determined to a great extent by such large-scale waves. These waves are more intense and frequent in winter than they are in summer, since they generally develop in regions of strong horizontal temperature contrasts.

In middle and high latitudes the mean meridional circulation is weak. One can probably interpret the reverse, mid-latitude Ferrel cell as a circulation that is being driven, or forced, by the atmospheric waves. The net effect of this "indirect" cell is the sinking of relatively warm air and the rising of cold air! At high latitudes near the Pole there is some suggestion of a direct polar cell; in the Northern Hemisphere this cell is very weak. The slow rising motion between roughly 50 and 60 degrees north latitude is connected with the upward branches of the Ferrel and polar cells, and its effects are evident in the climatological records. In this belt one finds a second maximum in rainfall. The precipitation, however, occurs at irregular intervals and is mainly determined by the frequency of the weather systems passing by.

In summer the mean meridional circulation appears to be disorganized and weak at all latitudes. Asymmetries connected with the distribution of continents and oceans dominate the circulation. The land generally acts as a heat source and the colder water at middle and high latitudes as a heat sink. One apparent asymmetry is the Asian monsoon, which carries warm and humid air far north into the Asian continent. At most other longitudes in the northern part of the Tropics the air still moves equatorward. In this season studying the asymmetries in the circulation is probably more relevant than studying the mean meridional circulation, which has rotational symmetry around the earth's axis.

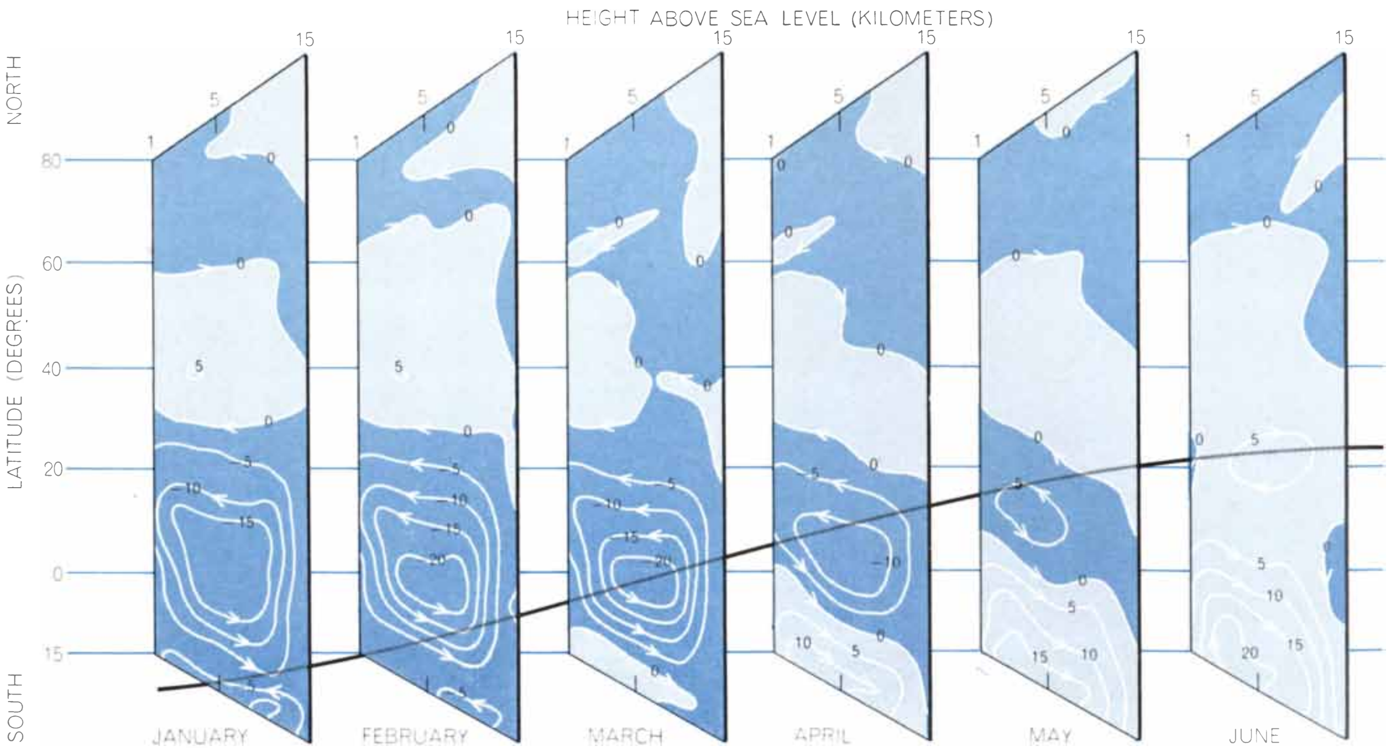
Up to this point I have discussed only some mean features of the climate as they have been derived from the observations of the past 20 to 30 years. Paleontological and even meteorological records show that the climate has changed slowly but significantly in the past and probably is changing now. On the other hand, it appears unlikely that either the total influx of solar energy or the rotation rate of the earth have changed drastically during the period in which life developed on the earth. Therefore it is probably safe to assume that the basic circulation regime has not changed. However, relatively minor changes in the strength of the north-south energy exchange, through either the mean meridional circulations at low latitudes or the large-scale horizontal waves at middle latitudes, can cause deviations from the present climate. Needless to say, any such deviations could be very significant as far as the living organisms are concerned.

The most likely way the climate could be influenced by either natural or artificial means seems to be through a trigger mechanism that ultimately changes the radiation balance. For example, if the cloud cover or dust content of the air were changed at high latitudes, the amount of reflected radiation would increase and consequently less solar radiation would be available to heat the atmosphere and the earth's surface at these latitudes. The resulting increase in the north-south heating gradient would presumably lead to more violent and more frequent disturbances in the middle latitudes. These circulations would in turn affect the original cloud cover. From that point on it seems hopeless to predict with any degree of certainty what the additional effects on the climate would be.

Changes in the reflectivity or absorptivity of the earth's surface can also alter the climate. It has been suggested that if the snow and ice fields near the North Pole were to be covered with black carbon, the Arctic Ocean might become ice-free through the increased absorption of solar radiation in summer. Again the present radiation balance and the climate over the earth would be affected. Still another possibility would be a change in the relative proportion of the atmospheric gases. For example, the measured slow increase in the carbon dioxide content of the air due to the burning of fossil fuels would presumably lead to more absorption of long-wave terrestrial radiation in the atmosphere and consequently to extra heating. One can think of many other ways in which changes in the earth's macroclimate might occur.

One must also consider the possibility of external influences such as natural variations in the amount and the spectral distribution of the incident solar radiation itself associated with variations in the level of solar activity. For instance, during periods of high solar activity the solar output mainly increases in the ultraviolet portion of the spectrum. Since most of that radiation is absorbed above 30 kilometers, one would expect to find the largest dynamic response at those levels. It is still an open question whether or not such variations in solar emission—either in the form of increased ultraviolet radiation or possibly also in the form of showers of energetic particles—affect the weather deep down in the atmosphere. The meteorological evidence for direct climatic variations caused by such changes in solar output is inconclusive, but variations of this kind certainly cannot be ruled out.

As an example one can imagine that through a change in the radiation balance the general regime of atmospheric and oceanic circulation could be brought to settle in a new quasi-equilibrium state that would be slightly different from the state it is in now. According to some recent studies conducted by M. I. Budyko in the U.S.S.R. and William D. Sellers in the U.S., even the present state of the atmosphere might not be as stable as one would like to think; these authors suggest that comparatively small changes in the present state can lead to a new ice age. Another consideration is that an initial disturbance of the circulation might, if maintained for a long enough time, ex-



ANNUAL CYCLE in the mean meridional circulation of the Northern Hemisphere was investigated by the author and Eugene M. Rasmusson using data from an extensive radiosonde network. They found that while the Hadley cell on the winter side of the Equator grows in strength and even expands across the Equator, the summer Hadley cell tends to weaken and finally almost disappears. Thus in contrast to the Hadley-Ferrel model there appears to be little symmetry in the tropical circulation with respect to the Equator, except

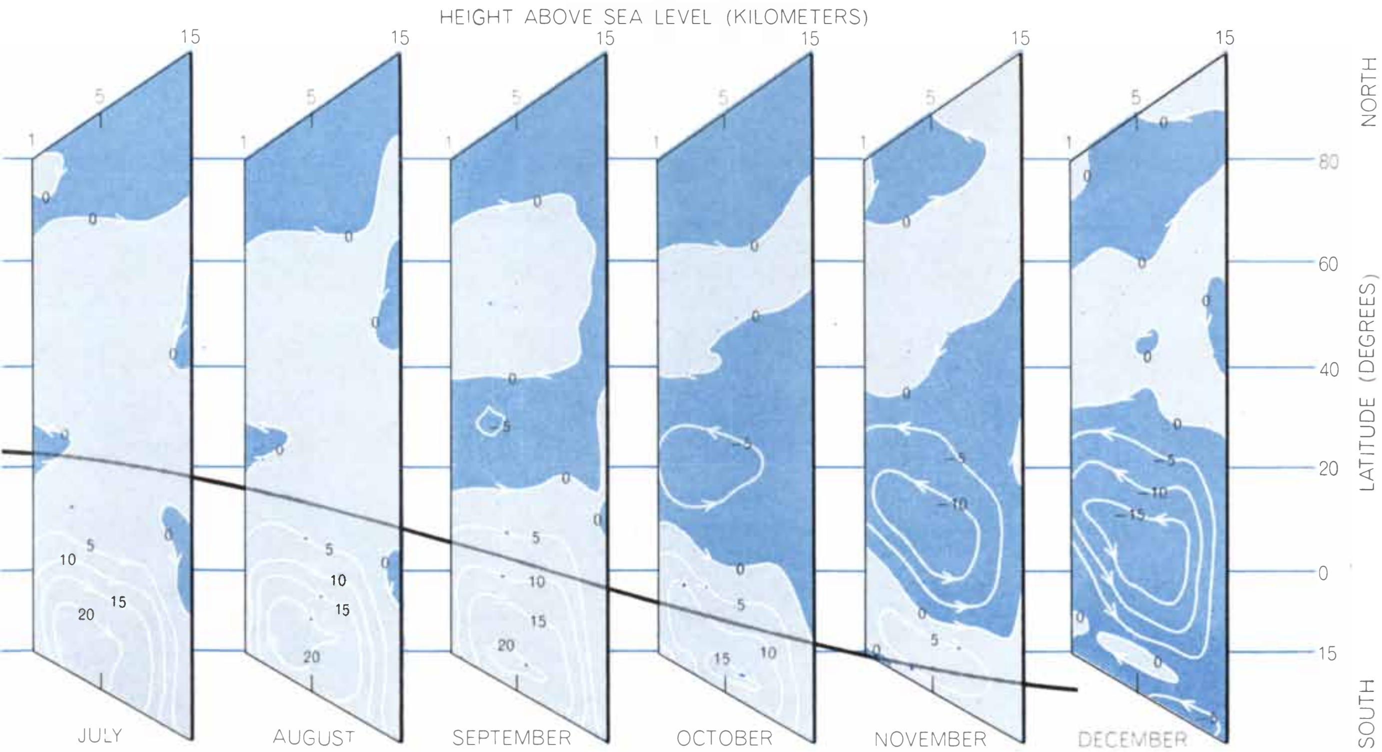
cite a long-term climatic fluctuation. The period of this fluctuation would probably be related to the natural turnover time of the oceans (of the order of a century or more) because of their capacity to store large amounts of heat.

Some reassurance that our present climate is not too unstable may be gained from the fact that during the past few centuries the climate has not fluctuated widely. An important complicating factor is the highly interactive nature of the different processes that operate in the ocean and the atmosphere. This makes it practically impossible to deduce through simple reasoning or even by using a simple model what would happen if one could bring about a slight, but more or less permanent, change in the radiation budget.

A high-priority task in the examination of these problems is to establish from observations how the present general circulation in both the ocean and the atmosphere is maintained. Here important contributions have been made in the past 20 years by three groups, one led by Victor P. Starr of the Massachusetts Institute of Technology, the second by Jacob Bjerknes of the University of California at Los Angeles and the third by Erik H. Palmén of the University of Helsinki. The next tasks are to determine whether or not slow changes in the general circulation are taking place, and to try to establish possible cause-and-effect relations. The limited records and the tremendous job of reducing the observations to meaningful parameters, however, severely restrict this direct approach.

With the arrival of large electronic computers a powerful new method for studying the climate has been developed. The thermal structure and the dynamics of the atmosphere are simulated through numerical integration in time of the equations that govern the behavior of the atmosphere. The basic equations are the equations of radiative energy transfer, the equations of motion and the thermodynamic equation. Starting from certain initial conditions (for example a uniform-temperature atmosphere at rest), the integration is carried out in time steps of the order of 10 minutes, and new values for the meteorological parameters (wind components, temperature, pressure and humidity) are calculated at each point in a three-dimensional grid covering the global atmosphere. The most realistic numerical experiments to date have been conducted at the Geophysical Fluid Dynamics Laboratory of the Environmental Science Services Administration by Joseph Smagorinsky, Syukuro Manabe and Kirk Bryan, Jr. In their experiments the number of grid points in space is of the order of 50,000 (about 10 vertical levels and a horizontal grid distance of about 300 kilometers). After the atmosphere has settled down and recovered from the unrealistic initial conditions, the relevant general circulation statistics are calculated in the same way they would be for the real atmosphere. With the present grid the large-scale weather systems seem to be rather well resolved.

On the other hand, the smaller-scale phenomena such as cumulus convection cannot be simulated explicitly. They have to be incorporated in a different way. In spite of these uncertainties and others (such as the lack of knowledge of how to properly incorporate the exchange processes near the earth's surface), the results so far are encouraging. Although the ability to forecast the exact location and intensity of the important weather systems degrades rather quickly in the course of a week, the predicted statistics of the average behavior taken over a much longer period appear to reproduce the observed statistics rather well. The numerical experiments seem to be the most promising road to a better understanding of the present climate. In addition they provide a powerful tool for evaluating the effects on the climate of natural or man-made disturbances.



possibly in the spring and fall. Outside the Tropics they found only a weak, indirect circulation in middle latitudes and a very weak, direct circulation near the Pole. In both middle and high latitudes asymmetric "weather" systems dominate the circulation and the mean meridional circulation is almost negligible. Contour units indicate the total mass transport of air (times 10^7 tons per second) integrated both horizontally along the latitude circle and vertically from the earth's surface up to the height of the contour.

The Energy Cycle of the Biosphere

Life is maintained by the finite amount of solar energy that is fixed by green plants. An increasing fraction of that energy is being diverted to the direct support of one living species: man

by George M. Woodwell

The energy that sustains all living systems is solar energy, fixed in photosynthesis and held briefly in the biosphere before it is reradiated into space as heat. It is solar energy that moves the rabbit, the deer, the whale, the boy on the bicycle outside my window, my pencil as I write these words. The total amount of solar energy fixed on the earth sets one limit on the total amount of life; the patterns of flow of this energy through the earth's ecosystems set additional limits on the kinds of life on the earth. Expanding human activities are requiring a larger fraction of the total and are paradoxically making large segments of it less useful in support of man.

Solar energy has been fixed in one form or another on the earth throughout much of the earth's 4.5-billion-year history. The modern biosphere probably had its beginning about two billion years ago with the evolution of marine organisms that not only could fix solar energy in organic compounds but also did it by splitting the water molecule and releasing free oxygen.

The beginning was slow. Molecular oxygen released by marine plant cells accumulated for hundreds of millions of years, gradually building an atmosphere that screened out the most destructive of the sun's rays and opened the land to exploitation by living systems [see "The Oxygen Cycle," by Preston Cloud and Aharon Gibor, page 110]. The colonization of the land began perhaps 400 million years ago. New species evolved that derived more energy from a more efficient respiration in air, accelerating the trend.

Evolution fitted the new species together in ways that not only conserved energy and the mineral nutrients utilized in life processes but also conserved the nutrients by recycling them, releasing more oxygen and making possible the fixation of more energy and the support of still more life. Gradually each landscape developed a flora and fauna particularly adapted to that place. These new arrays of plants and animals used solar energy, mineral nutrients, water and the resources of other living things to stabilize the environment, building the biosphere we know today.

The actual amount of solar energy diverted into living systems is small in relation to the earth's total energy budget [see "The Energy Cycle of the Earth," by Abraham H. Oort, page 54]. Only about a tenth of 1 percent of the energy received from the sun by the earth is fixed in photosynthesis. This fraction, small as it is, may be represented locally by the manufacture of several thousand grams of dry organic matter per square meter per year. Worldwide it is equivalent to the annual production of between 150 and 200 billion tons of dry organic matter and includes both food for man and the energy that runs the life-support systems of the biosphere, namely the earth's major ecosystems: the forests, grasslands, oceans, marshes, estuaries, lakes, rivers, tundras and deserts.

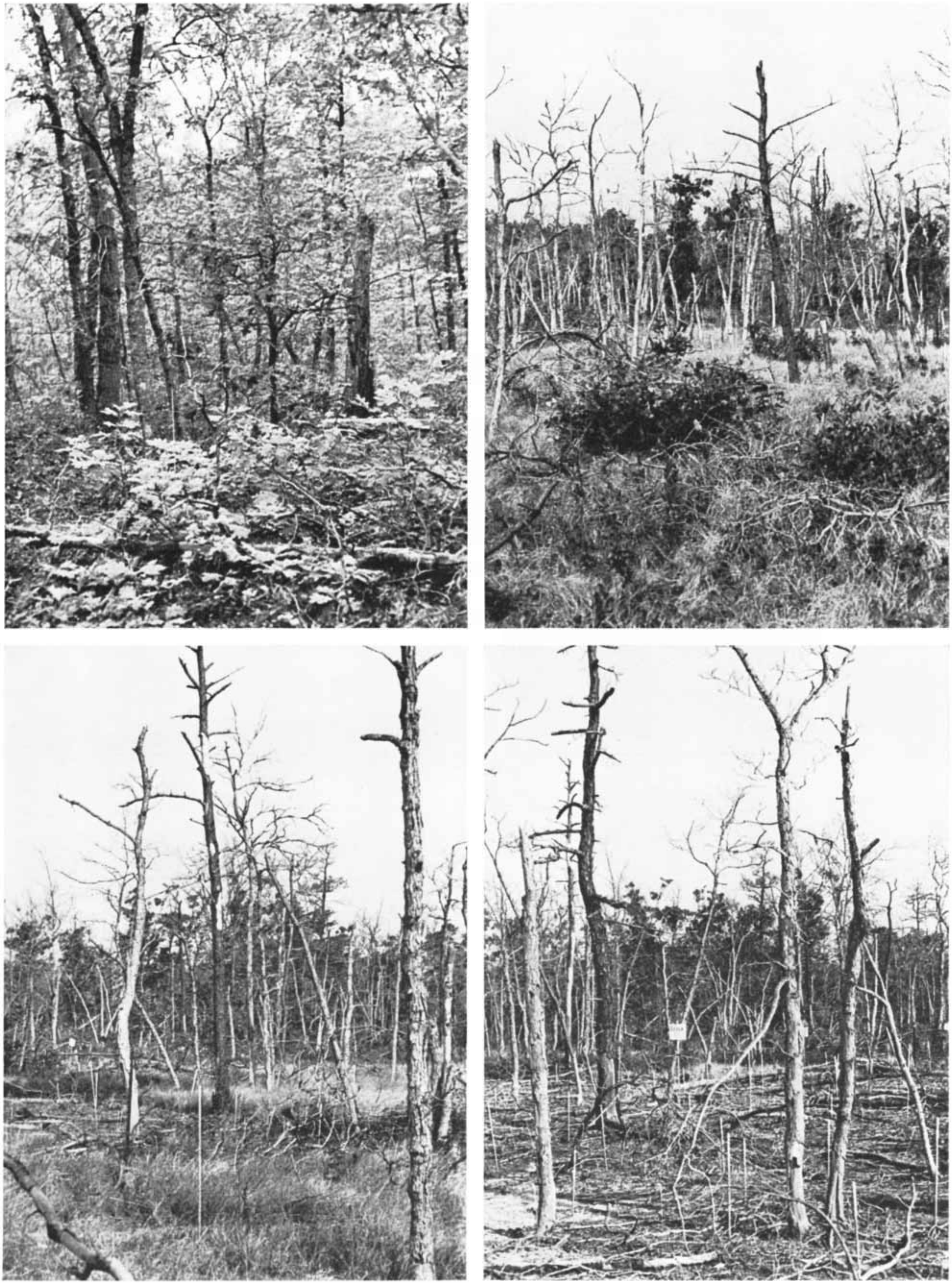
The complexity of ecosystems is so great as to preclude any simple, single-factor analysis that is both accurate and satisfying. Because of the central role of energy in life, however, an examination of the fixation of energy and its flow through ecosystems yields understanding of the ecosystems themselves. It also reveals starkly some of the obscure but vital details of the crisis of environment.

More than half of the energy fixed in photosynthesis is used immediately in the plant's own respiration. Some of it is stored. In land plants it may be transferred from tissues where it is fixed, such as leaves, to other tissues where it is used immediately or stored. At any point it may enter consumer food chains.

There are two kinds of chain: the grazing, or browsing, food chains and the food chains of decay. Energy may be stored for considerable periods in both kinds of chain, building animal populations in the one case and accumulations of undecomposed dead organic matter and populations of decay organisms in the other. The fraction of the total energy fixed that flows into each of these chains is of considerable importance to the biosphere and to man. The worldwide increase in human numbers not only is shifting the distribution of energy within ecosystems but also requires that a growing fraction of the total energy fixed be diverted to the direct support of man. The implications of such diversions are still far from clear.

Before examining the fixation and flow of energy in ecosystems it is important to consider the broad pattern of their development throughout evolution. If one were to ascribe a single objective to evolution, it would be the perpetuation of life. The entire strategy of evolution is focused on that single end. In realizing it evolution divides the resources of any

GREEN PLANTS are the "primary producers" of the biosphere, converting solar energy into organic compounds that maintain the plants and other living things. Forests, which cover about a tenth of the earth's surface, fix almost half of the biosphere's total energy. The photograph on the opposite page, which was made in the Mazumbai forest in Tanzania, illustrates the rich diversity typical of a relatively mature ecosystem, with many species arranged in a structure that apportions the available solar energy as effectively as possible.

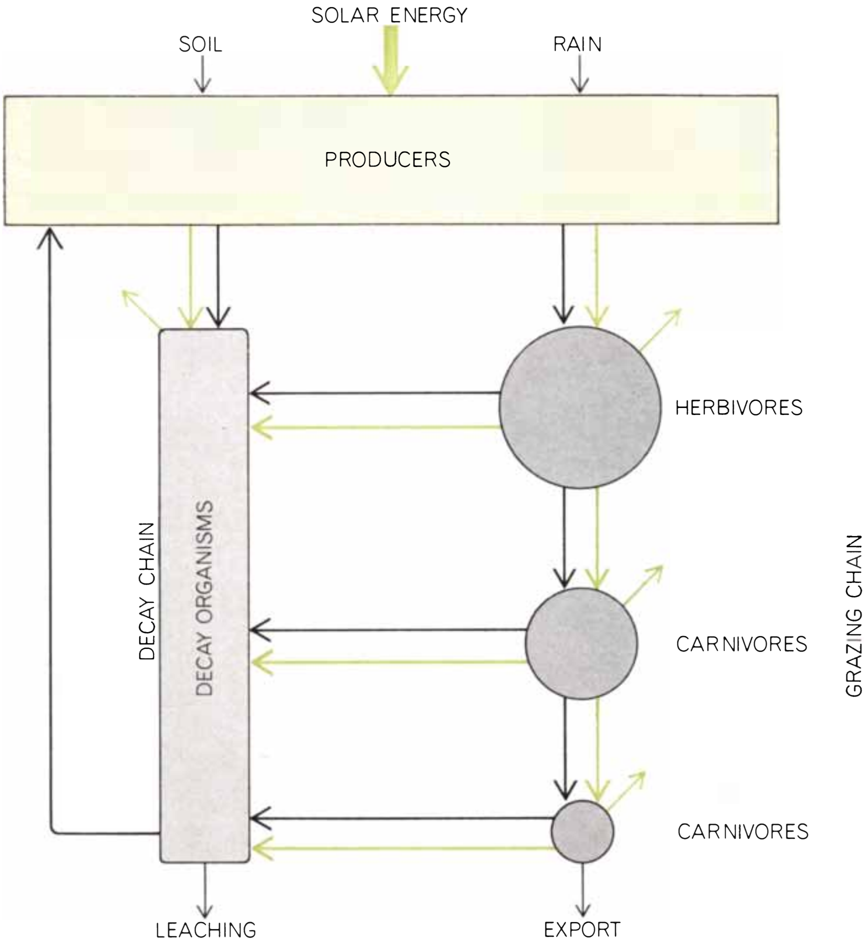


STRUCTURE OF FORESTS changes with disturbance according to well-defined patterns. The photographs show the loss of structure in an oak-pine forest at the Brookhaven National Laboratory as a result of continued exposure to gamma radiation. Exposure of the intact forest (*top left*) to radiation first destroys pine trees and then other trees, leaving tree sprouts, shrubs and ground cover (*top right*). Longer exposure kills shrubs (*bottom left*) and finally the sedge, grasses and herbs of the ground cover (*bottom right*).

location, including its input of energy, among an ever increasing number of different kinds of users, which we recognize as plant and animal species.

The arrangement of these species in today's ecosystems is a comparatively recent event, and the ecosystems continue to be developed by migration and continuing evolution. Changes accrue slowly through a conjoint evolution that is not only biological but also chemical and physical. The entire process appears to be open-ended, continuous, self-augmenting and endlessly versatile. It builds on itself, not merely preserving life but increasing the capacity of a site to support life. In so doing it stabilizes the site and the biota. Mineral nutrients are no longer leached rapidly into watercourses; they are conserved and recirculated, offering opportunities for more evolution. Interactions among ecosystems are exploited and stabilized, by living systems adapted to the purpose. The return of the salmon and other fishes from years at sea to the upper reaches of rivers is one example; impoverished upland streams are thus fertilized with nutrients harvested in the ocean, opening further possibilities for life.

The time scale for most of these developments, particularly in the later stages when many of the species have large bodies and long life cycles, is very long. Such systems are for all practical purposes stable. These are the living systems that have shaped the biosphere. They are self-regulating and remarkably resilient. Now human activities have become so pervasive as to affect these systems all over the world. What kinds of change can we expect? The answers depend on an understanding of the patterns of evolution and on a knowledge of the structure and function of ecosystems. And the fixation and flow of energy is at the core.



NET FLOW OF ENERGY (*colored arrows*) and nutrients (*black arrows*) through a natural community is diagrammed in simplified form. In a mature community all the energy fixed by the primary producers, the plants, is dissipated as heat in the respiration of the plants, the consumers (herbivores and successive echelons of carnivores) and decay organisms. Almost all nutrients are eventually recycled, however, to renew plant and animal populations.

Much of our current understanding of ecosystems has been based on a paper published in *Ecology* in 1942 by Raymond L. Lindeman, a young colleague of G. Evelyn Hutchinson's at Yale University. (It was Lindeman's sixth and last paper; his death at the age of 26 deprived ecology of one of its most outstanding intellects.) Lindeman drew on work by earlier scholars, particularly Arthur G. Tansley and Charles S. Elton of England and Frederick E. Clements and Victor E. Shelford of the U.S., to examine what he called the "trophic-dynamic aspect" of ecology. He called attention to the fixation of energy by natural ecosystems and to the quantitative relations that must exist in nature between the different users of this energy as it is divided progressively among the various populations of an ecosystem.

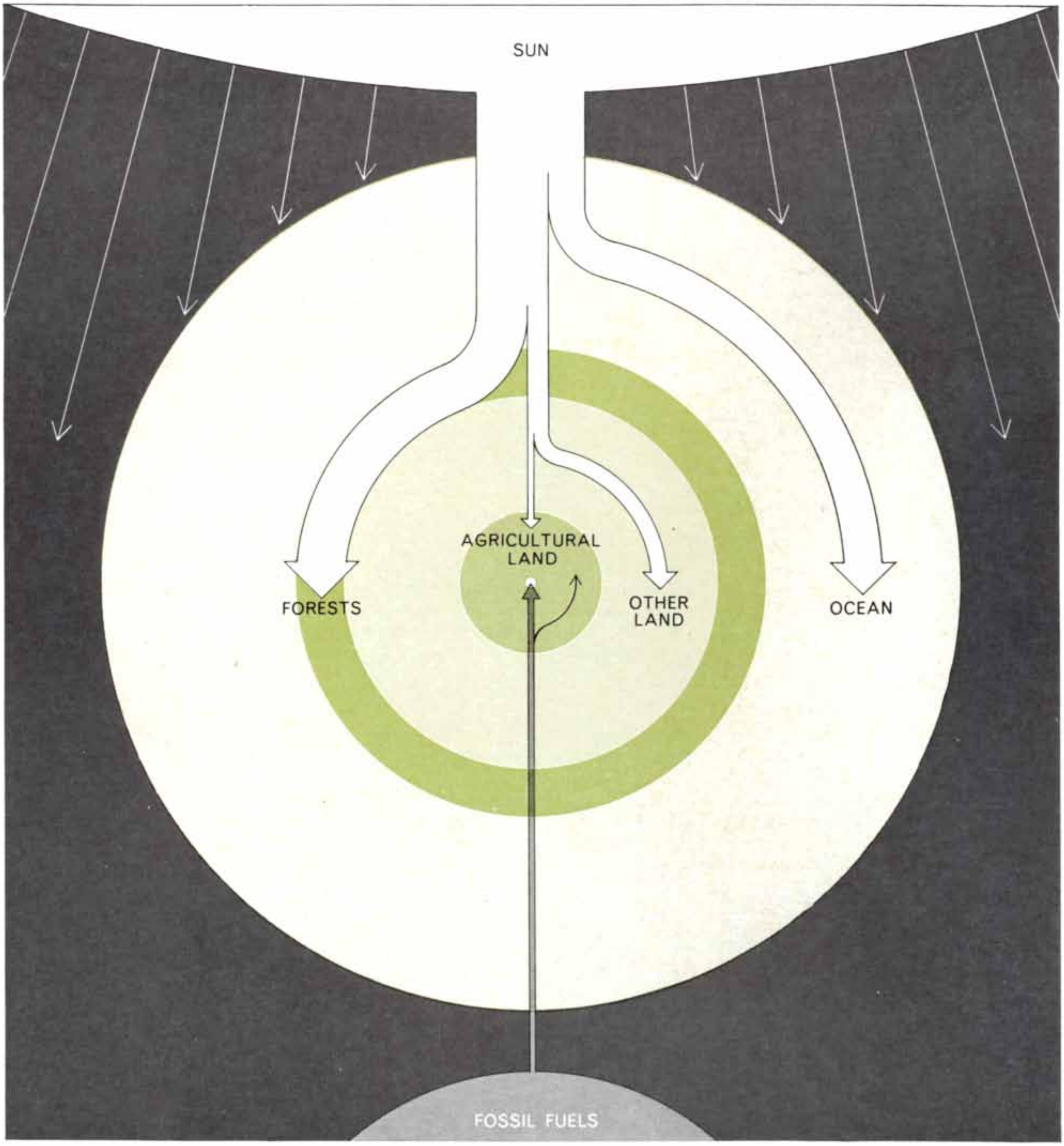
Lindeman's suggestions were provocative. They stimulated a series of field and laboratory studies, all of which strengthened his synthesis. One of the most useful generalizations of his approach, sometimes called "the 10 percent law," simply states that in nature some fraction of the energy entering any population is available for transfer to the populations that feed on it without serious disruption of either. The actual amount of energy transferred probably varies widely. It seems fair to assume that in the grazing chain perhaps 10 to 20 percent of the energy fixed by the plant community can be transferred to herbivores, 10 to 20 percent of the energy entering the herbivore community can be transferred to the first level of carnivores and so on. In this way what is called a mature community may support three or four levels of animal populations, each related to its food supply quantitatively on the basis of energy fixation.

No less important than the grazing food chains are the food chains of decay. On land these chains start with dead organic matter: leaves, bits of bark and branches. In water they originate in the remains of algae, fecal matter and other organic debris. The organic debris may be totally consumed by the bacteria, fungi and small animals of decay, releasing carbon dioxide, water and heat. It may enter far more complex food webs, potentially involving larger animals such as mullet, carp, crabs and ultimately higher carnivores, so that although it is convenient to think of the grazing and decay routes as being distinct, they usually overlap.

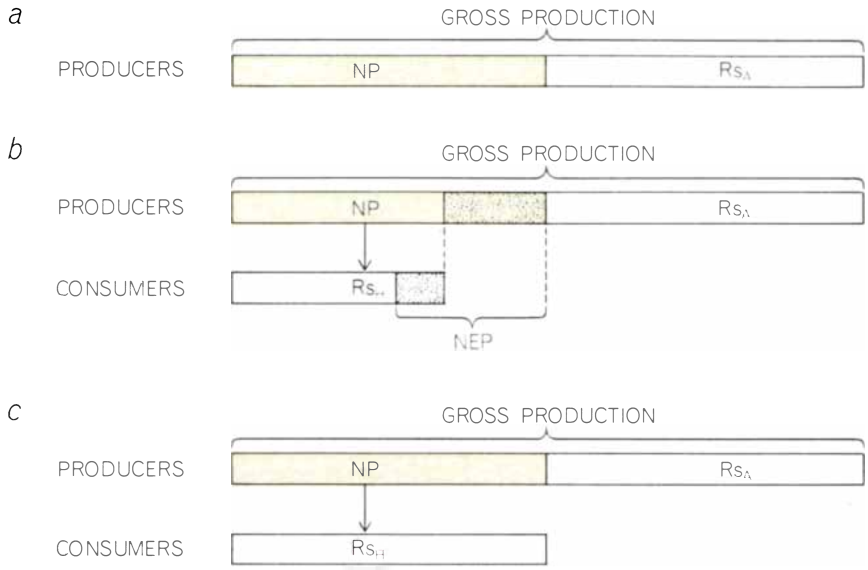
The decay food chain does not always function efficiently. Under certain circumstances it exhausts all the available oxygen. Decay is then incomplete; its products include methane, alcohols, amines, hydrogen sulfide and partially decomposed organic matter. Its connections to the grazing food chain are reduced or broken, with profound effects on living systems. Such shifts are occurring more frequently in an increasingly man-dominated world.

How much energy is fixed by the major ecosystems of the biosphere? The question is more demanding than it may appear because measuring energy fixation in such diverse vegetations as forests, fields and the oceans is most difficult. Rates of energy fixation vary from day to day—even from minute to minute—and from place to place. They are affected by many factors, including light and the concentration of carbon dioxide, water and nutrients.

In spite of the difficulties in obtaining unequivocal answers several attempts have been made to appraise the total amounts of energy fixed by the earth's ecosystems. Most recently Robert H.



ENERGY FIXED by the earth's primary producers is equivalent to about 164 billion metric tons of dry organic matter a year, according to Robert H. Whittaker and Gene E. Likens of Cornell University. About 5 percent of the energy is fixed by agricultural ecosystems and is utilized directly by man, one species among millions. Man also draws annually on fossil fuel reserves for about the same amount of energy. In this anthropocentric view of the biosphere the area of the concentric rings is proportional to the major ecosystems' share of the surface area of the earth (indicated in millions of square kilometers). The width of the arrows is proportional to the amount of energy fixed in each ecosystem and contributed by fossil fuels (indicated in billions of metric tons of dry matter per year). The intensity of the color in each ring suggests the productivity (production per unit area) of each ecosystem.



ENERGY IS UTILIZED by producers and consumers as shown here. In the case of a single green plant (*a*) some of the total energy fixed, or gross production, is expended in the plant's own respiration (Rs_A) and the rest goes into net production (NP), or new tissue. In a successional plant-and-animal community (*b*) some of the net production is stored as growth, contributing to net ecosystem production (NEP); the rest is used by consumers, which expend most of it in respiration (Rs_{II}) and store some as growth, adding to net ecosystem production. In a mature community (*c*) all the energy fixed is used in respiration.

Whittaker and Gene E. Likens of Cornell University have estimated that in all the earth's ecosystems, both terrestrial and marine, 164 billion metric tons of dry organic matter is produced annually, about a third of it in the oceans and two-thirds of it on land. This "net production" represents the excess of organic production over what is required to maintain the plants that fixed the energy; it is the energy potentially available for consumers.

Virtually all the net production of the earth is consumed annually in the respiration of organisms other than green plants, releasing carbon dioxide, water and the heat that is reradiated into space. The consumers are animals, including man, and the organisms of decay. The energy that is not consumed is either stored in the tissues of living organisms or in humus and organic sediments.

The relations between the producers and the consumers are clarified by two simple formulas. Consider the growth of a single green plant, an "autotroph" that is capable of fixing its own solar energy. Some of the energy it fixes is stored in organic matter that accumulates as new tissue. The amount of the new tissue, measured as dry weight, is the net production. This does not, however, represent all the energy fixed. Some energy is required just to support the living tissues of the plant. This is energy used in respiration.

The total energy fixed, then, is partitioned immediately within the plant according to the equation $GP - Rs_A = NP$. The total amount of energy fixed is gross production (GP); Rs_A is the energy used in the respiration of the autotrophic plant, and the amount of energy left over is net production (NP). The growth of a plant is measurable as net production, which can be expressed in any of several different ways, including energy stored and dry weight.

The same relations hold for an entire plant community and for the biosphere as a whole. If we consider not only the plants but also the consumers of plants and the entire food web, including the organisms of decay, we must add a new unit of respiration without adding any further producers. That is what happens as an ecosystem matures: consumer populations increase substantially, adding to the respiration of the plants the respiration (Rs_{II}) of the heterotrophs, the organisms that obtain their energy from the photosynthesizing plants. For an ecosystem (the total biota of any unit of the earth's surface) NEP equals $GP - (Rs_A + Rs_{II})$. NEP is the net ecosystem production, the net increase in energy stored within the system. $Rs_A + Rs_{II}$ is the total respiration of the ecosystem.

This last equation establishes the important distinction between a "successional," or developmental, ecosystem and a "climax," or mature, one. In the successional system the total respiration is less than the gross production, leaving energy (NEP) that is built into structure and adds to the resources of the site. (A forest of large trees obviously has more space in it, more organic matter and probably a wider variety of microhabitats than a forest of small trees.) In a climax system, on the other hand, all the energy fixed is used in the combined respiration of the plants and the heterotrophs. NEP goes to zero: there is no energy left over and no net annual storage. Climax ecosystems probably represent a most efficient way of using the resources of a site to sustain life with minimum impact on other ecosystems. It is of course such ecosystems that have dominated the biosphere throughout recent millenniums.

These general relations are clarified if one asks, with regard to a specific ecosystem, how much energy is fixed and how it is used, and how efficient the ecosystem is in harvesting solar energy and supporting life. The answers are found by solving the simple production equations, but in order to solve them one must measure the metabolism of an entire unit of landscape. Such studies are being attempted in many types of ecosystem under the aegis of the International Biological Program, a major research effort designed to examine the productivity of the biosphere. The example I shall give is drawn from research in an oak-pine forest at the Brookhaven National Laboratory.

The research has spanned most of a decade and has involved many contributors. A most important contribution was made by Whittaker, who collaborated with me in completing a detailed description of the structure of the forest, including the total amount of organic matter, the weight and area of leaves, the weight of roots and the amount of net production. The techniques developed in that work are now being used in many similar studies. Such data are necessary to relate other measurements, including measurements of the gas exchange between leaves and the atmosphere, to the entire forest and so provide an additional measurement of net production and respiration.

A major problem was measuring the forest's total respiration. We used two techniques. First, Winston R. Dykeman and I took advantage of the frequent inversions of temperature that occur in central Long Island and used the rate of accumulation of carbon dioxide during these inversions as a direct measurement of total respiration. The inversions are nocturnal; this eliminates the effect of photosynthesis, which of course proceeds only in daylight.

During an inversion the temperature of the air near the ground is (contrary to the usual daytime situation) lower than that of the air at higher elevations. Since the cooler air is denser, the air column remains vertically stable for as much as several hours; the carbon dioxide released by respiration accumulates, and its buildup at a given height is an index of the rate of respiration at that height. The calculation of the buildup during more than 40 inversions in the course of a year provided one measure of total respiration [*see top illustration on page 72*]. A second measurement came from a detailed study of the rates of respiration of various segments of the forest (including the branches and stems of trees) and the soil.

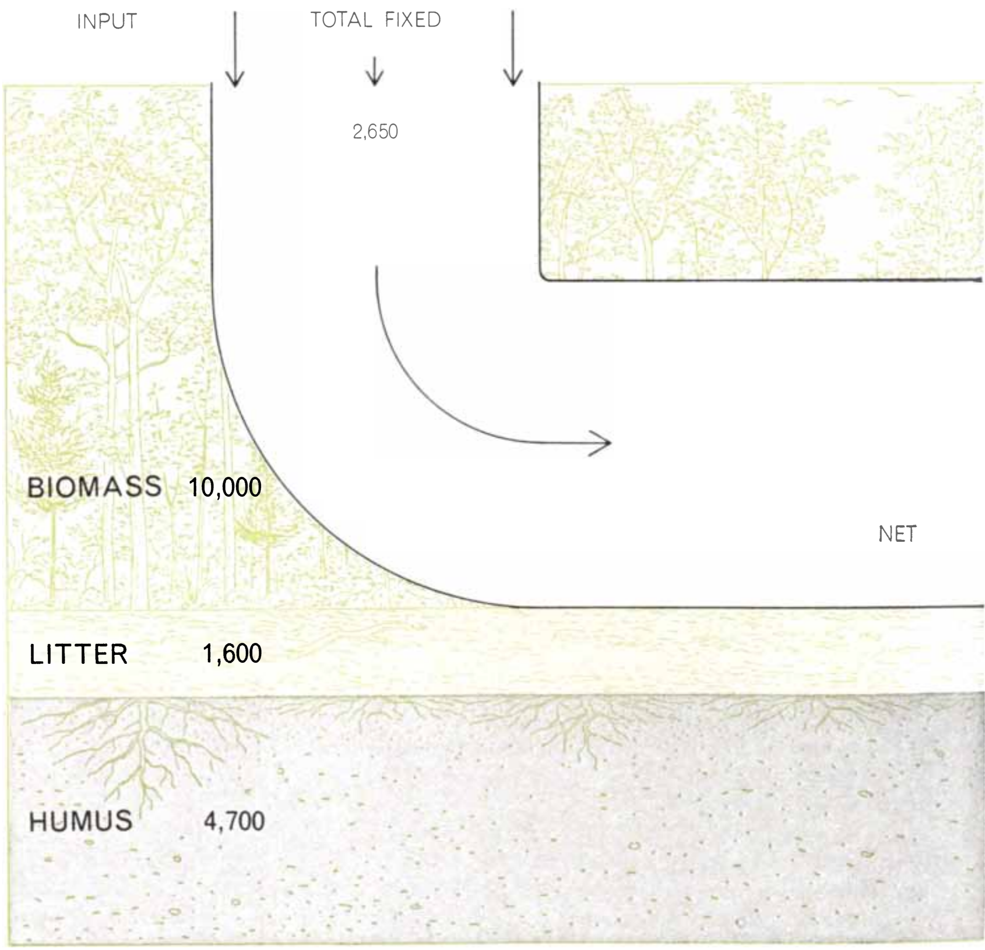
The estimates available from these studies and others are converging on the following solution of the production equations, all in terms of grams of dry organic matter per square meter per year: The gross production is 2,650 grams; the net production, 1,200 grams; the net ecosystem production, or net storage, 550 grams, and the total respiration, or energy loss, 2,100 grams, of which Rs_A is 1,450 and Rs_H is 650 [*see illustration on these two pages*]. The forest is obviously immature in the sense that it is still storing energy (NEP) in an increased plant population. The ratio of total respiration to gross production (2,100/2,650) suggests that the forest is at about 80 percent of climax and confirms other studies that show that the forest is "late successional."

The net production of the Brookhaven forest of 1,200 grams per square meter per year is in the low middle range for forests and is typical of the productivity of small-statured forests. The efficiency of this forest in using the annual input of solar energy effective in photosynthesis is about .9 percent. Large-statured forests (moist forests of the Temperate Zone, where nutrients are abundant, and certain tropical rain forests) have a net productivity ranging up to several thousand grams per square meter per year. They may have an efficiency approaching 3 percent of the usable energy available throughout the year at the surface of the ground, but usually not much more.

Sugarcane productivity in the Tropics has been reported as exceeding 9,000 grams per square meter per year. The new strains of rice that are contributing to the "green revolution" have a maximum yield under intensive triple-cropping regimes that may approach 2,000 grams of rice per square meter per year. Over large areas the yield is much lower, seldom exceeding 350 to 400 grams of milled rice per square meter per year. These yields are to be compared with corn yields in the U.S., which approach 500 grams. (The rice and corn yields are expressed as grain, not as total net production as we have been discussing it. Net production including the chaff, stems, leaves and roots is between three and five times the harvest of grain. Thus the net production of the most productive agriculture is 6,000 to 10,000 grams, probably the highest net production in the world. Most agriculture, however, has net production of 1,000 to 3,000 grams, the same range as most forests.)

The high productivities of agriculture are somewhat misleading in that they are bought with a contribution of energy from fossil fuels: energy that is applied to cultivate and harvest the crop, to manufacture and transport pesticides and fertilizers and to provide and control irrigation. The cost accounting is incomplete; these systems "leak" pesticides, fertilizers and often soil itself, injuring other ecosystems. It is clear, however, that the high yields of agriculture are dependent on a subsidy of energy that was fixed as fossil fuels in previous ages and is available now (and for some decades to come) to support large human populations. Without this subsidy or some other source of power, yields would drop. They may suffer in any case as it becomes increasingly necessary to reduce the interactions between agriculture and other ecosystems. One sign is the progressive restriction in the use of insecticides because of hazards far from where they are applied. Similar restraint may soon be necessary in the use of herbicides and fertilizers.

The oceans appear unproductive compared with terrestrial ecosystems. In separate detailed analyses of the fish production of the world's oceans William E. Ricker of the Fisheries Research Board of Canada and John H. Ryther of the Woods Hole Oceanographic Institution recently emphasized that the oceans are far from an unlimited resource. The net production of the open ocean is about



ENERGY RELATIONSHIPS were worked out for an oak-pine forest at the Brookhaven National Laboratory. Of the annual gross production of 2,650 grams of dry matter per

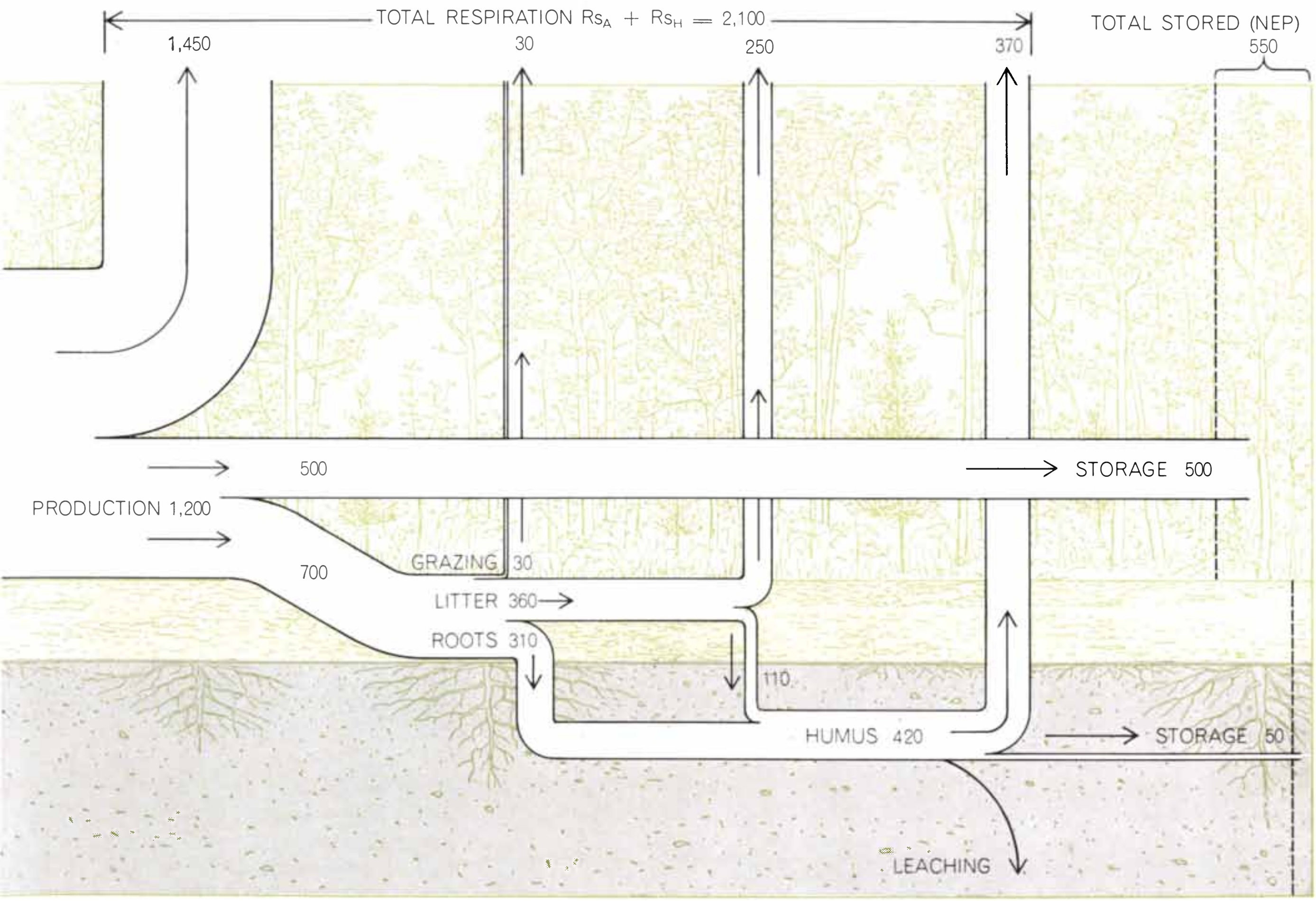
50 grams of fixed carbon per square meter per year. Areas of very high productivity, including coastal areas and areas of upwelling where nutrients are abundant, do not average more than 300 grams of carbon. The mean productivity of the oceans, according to this analysis, would be about 55 grams of carbon, equivalent to between 120 and 150 grams of dry organic matter.

Inasmuch as the highest productivity of enriched areas of the ocean barely approaches that of diminutive forests such as Brookhaven's, the oceans do not appear to represent a vast potential resource. On the contrary, Ryther suggests on the basis of an elaborate analysis of the complex trophic relations of the oceans that "it seems unlikely that the potential sustained yield of fish to man is appreciably greater than 100 million [metric] tons [wet weight]. The total world fish landings for 1967 were just over 60 million tons, and this figure has been increasing at an average rate of about 8 percent per year for the past 25 years.... At the present rate, the industry can expand for no more than a decade." Ricker comes to a similar conclusion. Neither he nor Ryther appraised the effects on the productivity of the oceans of the accumulation of toxic substances such as pesticides, of industrial and municipal wastes, of oil production on the continental shelves, of the current attempts at mining the sea bottom and of other exploitation of the seas that is inconsistent with continued harvesting of fish.

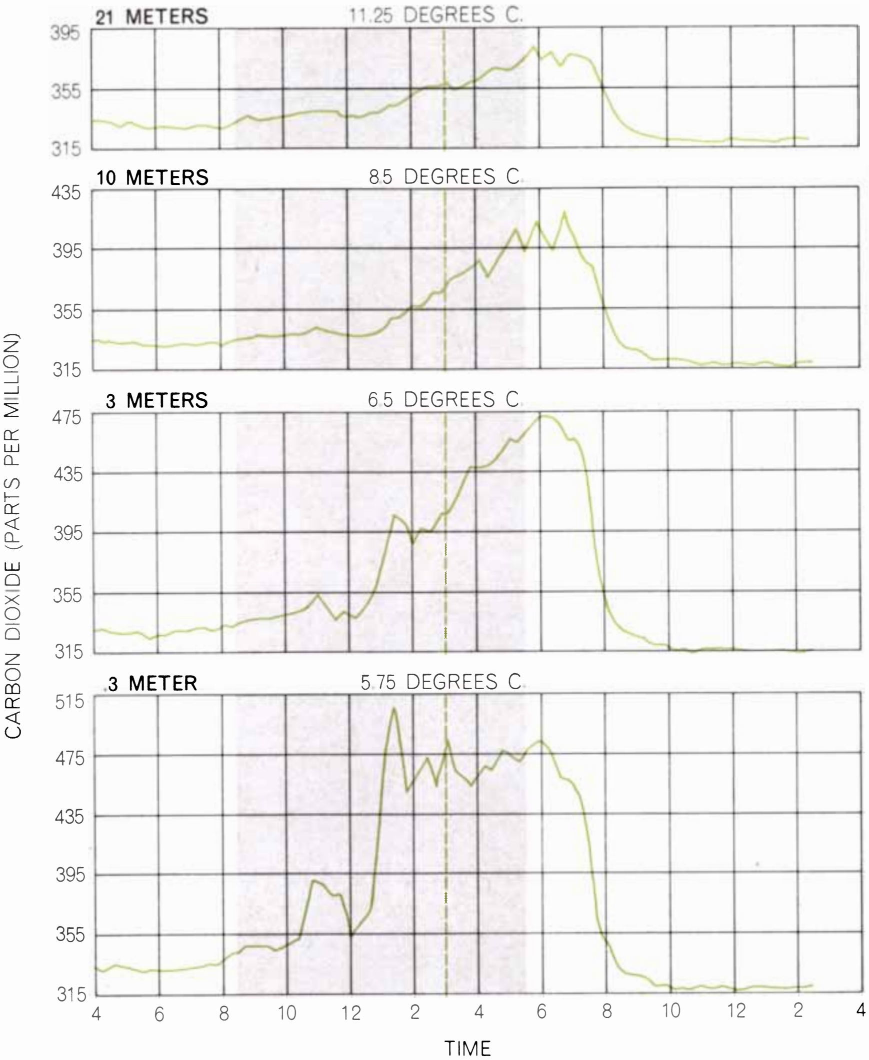
The available evidence suggests that, in spite of the much larger area of the oceans, by far the greater amount of energy is fixed on land. The oceans, even if their productivity can be preserved, do not represent a vast unexploited source of energy for support of larger human populations. They are currently being exploited at close to the maximum sustainable rate, and their continued use as a dump for wastes of all kinds makes it questionable whether that rate will be sustained.

A brief consideration of the utilization of the energy fixed in the Brookhaven forest will help to clarify this point. The energy fixed by this late-successional forest is first divided between net production and immediate use in plant respiration, with about 55 percent being used immediately. (The ratio of 55 percent going directly into respiration appears consistent for the Temperate Zone forests examined so far; the ratio appears to rise in the Tropics and to decline in higher latitudes.) The net production is divided among herbivores, decay and storage. In the Brookhaven forest herbivore populations have been reduced by the exclusion of deer, leaving as the principal herbivores insects and limited populations of small mammals.

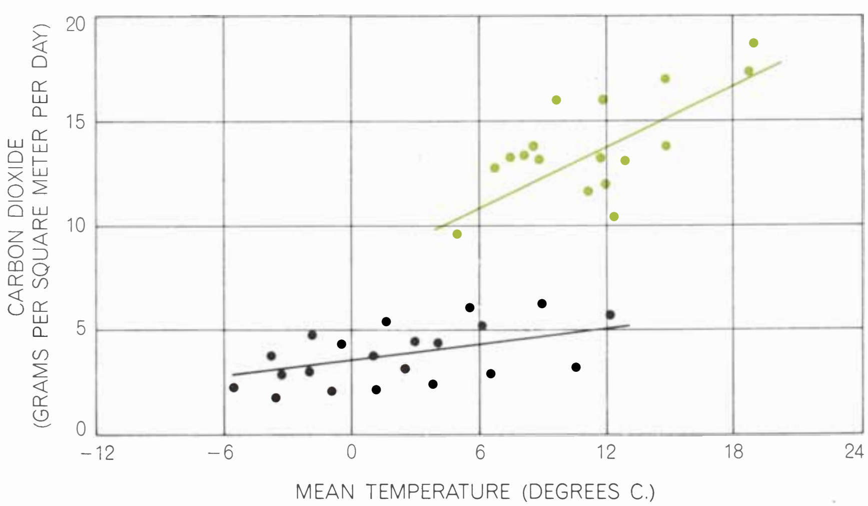
Our estimates indicate that only a few percent of the net production is consumed directly by herbivores (a low rate in comparison with other ecosystems). Practically all this quantity is consumed immediately in animal respiration, so that the animal population shows virtually no annual increase, or contribution to the net ecosystem production. The principal contribution to the net ecosystem production is the growth of the plant populations, which



square meter, some 2,100 grams are lost in respiration, leaving 550 stored as new plant growth, litter and humus. The animal population is not increasing appreciably. This is a "late successional" forest in which 80 percent of the production is expended in respiration.



RATE OF RESPIRATION of the forest was determined by measuring the rate at which carbon dioxide, a product of respiration, accumulated during nights when the air was still because of a temperature inversion. The curves give the carbon dioxide concentration at four elevations in the course of one such night. (Note that the temperature, recorded at 3:00 A.M., was lower near the ground than at greater heights.) The hourly increase in carbon dioxide concentration, which was calculated from these curves, yielded rate of respiration.



RESPIRATION of the forest, plotted against temperature, is seen to proceed at a higher rate in summer (*colored curve*) than in winter (*black curve*). Annual respiration was calculated in grams of carbon dioxide, then converted to yield the total respiration, 2,100 grams.

accounts for more than 40 percent of the net production. The remainder of the net production enters the food chains of decay, which are obviously well developed. Clearly the elimination of deer, combined with poorly developed herbivore and carnivore populations, has resulted in a diversion of energy from the grazing chain into the food chains of decay.

This is precisely what happens in aquatic systems as they are enriched with nutrients washed from the land; the shift to decay is also caused by the accumulation of any toxic substance, whether it affects plants or animals. Any reduction in populations of grazers shifts the flow of energy toward decay. Any effect on the plants shifts plant populations away from sensitive species toward resistant species that may not be food for the indigenous herbivores, thereby eliminating the normal food chains and also shifting the flow of energy into decay.

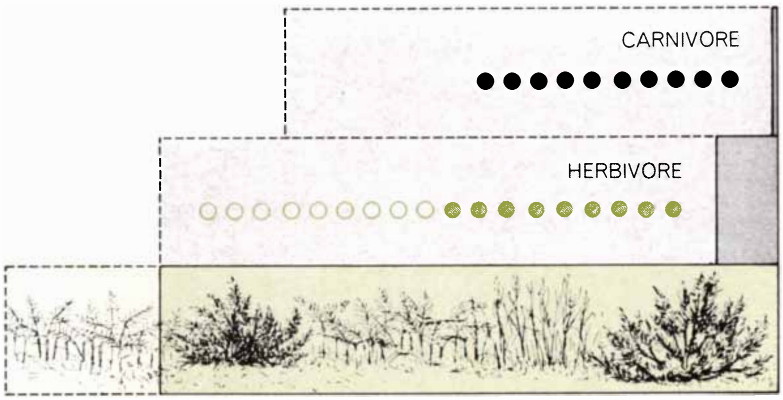
These observations simply show that the structure and function of major ecosystems are sensitive to many influences. Clearly the amount of living tissue that can be supported in any ecosystem depends on the amount of net production. Net production, however, is coupled to both photosynthesis and respiration, both of which can be affected by many factors. Photosynthesis is sensitive to light intensity and duration, to the availability of water and mineral nutrients and to temperature. It is also sensitive to the concentration of carbon dioxide; on a worldwide basis the amount of carbon dioxide in the atmosphere may exert a major control over rates of net production. Greenhouse men have recognized the sensitivity of photosynthesis to carbon dioxide concentration for many years and sometimes increase the concentration artificially to stimulate plant growth. Has the emission of carbon dioxide from the combustion of fossil fuels in the past 150 years caused a worldwide increase in net production, and if so, how much of an increase?

With equipment specially designed at Brookhaven, Robert Wright and I supplied air with enhanced levels of carbon dioxide to trees and determined the effect on net photosynthesis by measuring the uptake of the gas by leaves. The net amount of carbon dioxide that was fixed increased linearly with the increase in the carbon dioxide concentration in the air. Such small increases in carbon dioxide concentration have virtually no effect on rates of respiration. The data suggest that the increase of about 10 percent (30 parts per million) in the carbon dioxide concentration of the atmosphere since the middle of the 19th century caused by the industrial revolution may have increased net production by as much as 5 to 10 percent. This increase, if applicable worldwide and considered alone, would increase the total energy (and carbon) stored in natural ecosystems by an equivalent amount, and would result in an equivalent improvement in the yields of agriculture. The increase in net production also tends to stabilize the carbon dioxide content of the atmosphere by storing more carbon in living organic matter, particularly in forests, and in the nonliving organic matter of sediments and humus. Such changes have almost certainly occurred on a worldwide basis as an inadvertent result of human activities in the past 100 years or so.

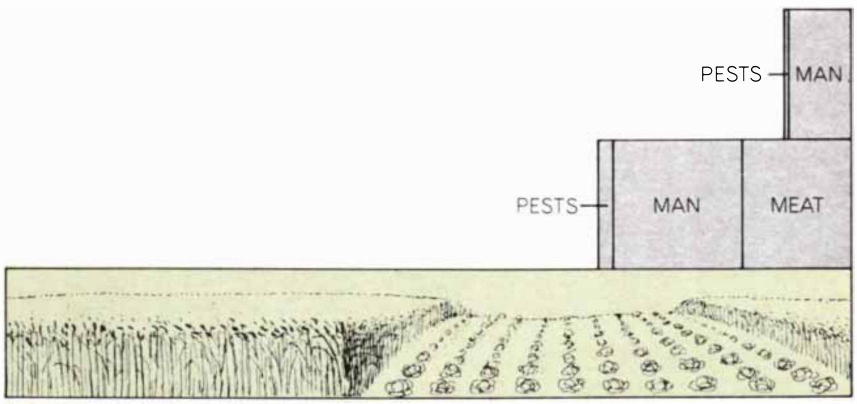
Such simple single-factor analyses of environmental problems, however, are almost always misleading. As the carbon dioxide concentration in the atmosphere has been increasing, many other factors have changed. There was a period of rising temperature, possibly due to the increased carbon dioxide concentration. More recently, however, there has been a decline in world temperatures that continues. This can be expected to reduce net production worldwide by reducing the periods favorable for plant growth. Added to the effects of changing temperature—and indeed overriding it—is the accumulation of toxic wastes from human activities. The overall effect is to reduce the structure of ecosystems. This in turn shortens food chains and favors (1) populations of small hardy plants, (2) small-bodied herbivores that reproduce rapidly and (3) the food chains of decay. The loss of structure also implies a loss of "regulation"; the simplified communities are subject to rapid changes in the density of these smaller, more rapidly reproducing organisms that have been released from their normal controls.

Local increases in water temperature also give rise to predictable effects. There is talk, for example, of warming the waters of the New York region with waste heat from reactors to produce a rich "tropical" biota, but such manipulation would produce a degraded local biota supplemented by a few hardy species of more southerly ecosystems. Such circumstances again favor productivity not by complex, highly integrated arrays of specialized organisms but by simple arrays of generalized ones. Energy then is funneled not into intricate food webs capped by tuna, mackerel, petrels, dolphins and other highly specialized carni-

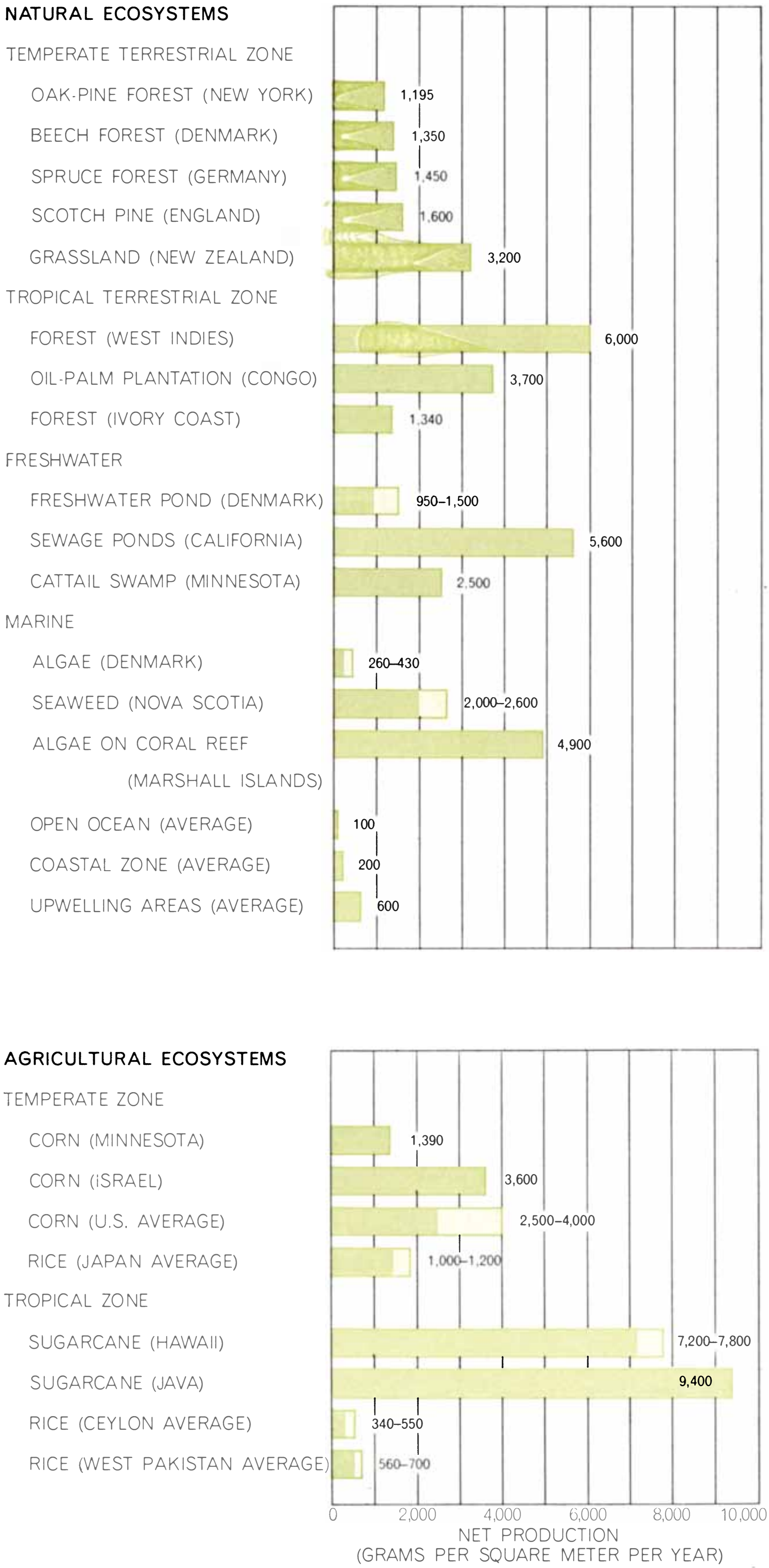
INTACT NATURAL ECOSYSTEM is exemplified by a mature oak-hickory forest that supports several stages of consumers in the grazing food chain, with from 10 to 20 percent of the energy in each trophic level being passed along to the next level. The symbols represent different herbivore and carnivore species. Complexity of structure regulates population sizes, maintaining the same pattern of energy distribution in the system from year to year.



DEGRADED ECOSYSTEM has a truncated grazing chain. The annual production of the sparse grasses, herbs and shrubs fluctuates (*shaded area*). So do populations of herbivores and carnivores, which are characterized by large numbers of individuals but few different species. Under extreme conditions most of the net production may be consumed, leading to the starvation of herbivores and accentuating the characteristic fluctuation in populations.



AGRICULTURAL ECOSYSTEM is a special case, yielding a larger than normal harvest of net production for herbivores, including man and animals that provide meat for man. Stability is maintained through inputs of energy in cultivation, pesticides and fertilizer.



NET PRODUCTION LEVELS of a number of natural and agricultural ecosystems are compared. (The total net production of U.S. corn and of rice is calculated from grain yields.)

vores but into simple food webs dominated by hardy scavengers such as gulls and crabs and into the food webs of decay. As the annual contribution to decay increases, these webs in water become overloaded; the oxygen dissolved in the water is used up and metabolism shifts from the aerobic form where oxygen is freely available to the much less efficient anaerobic respiration; organic matter accumulates, releasing methane, hydrogen sulfide and other noxious gases that only reinforce the tendency.

The broad pattern of these changes is clear enough. On the one hand, an increasing fraction of the total energy fixed is being diverted to the direct support of man, replacing the earth's major ecosystems with cities and land devoted to agriculture—the simplified ecosystems of civilization that require continuing contributions of energy under human control for their regulation. On the other hand, the leakage of toxic substances from the man-dominated provinces of the earth is reducing the structure and self-regulation of the remaining natural ecosystems. The trend is progressive. The simplification of the earth's biota is breaking down the insulation of large units of the earth's surface, increasing the interactions between terrestrial and aquatic systems, between upland and lowland, between river and estuary. The long-term trend of evolution toward building complex, integral, stable ecosystems is being reversed. Although the changes are rapid, accelerating and important, they do not mean that the earth will face an oxygen crisis; photosynthesis will continue for a long time yet, perhaps at an accelerated rate in certain places, stimulated by increased carbon dioxide concentrations in air and the availability of nutrients in water. A smaller fraction of the earth's fixed energy is easily available to man, however. The energy flows increasingly through smaller organisms such as the hardy shrubs and herbs of the irradiated forest at Brookhaven, the scrub oaks that are replacing the smog-killed pines of the Los Angeles basin, the noxious algae of eutrophic lakes and estuaries, into short food chains, humus and anaerobic sediments.

These are major man-caused changes in the biosphere. Many aspects of them are irreversible; their implications are poorly known. Together they constitute a major series of interlocking objectives for science and society in the next decade focused on the question: "How much of the energy that runs the biosphere can be diverted to the support of a single species: man?"

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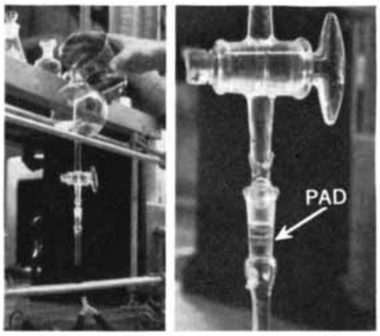
Occasional fish come in with the Lake Ontario water we use to make film . . .

Homogenized fish marinated in HNO_3 to keep mercury in solution as Hg^{++}.



Neutralized marinade is passed through pad of CdS-impregnated asbestos, which quantitatively precipitates Hg^{++}.

To prevent loss of mercury as vapor, all operations are at room temperature until oven is raised around tube containing pad, which then releases Hg vapor for atomic absorption photometry at 2537Å.

For evaluation by laboratories more directly involved than we in measuring mercury levels in biological material, working details on our method are available on request from Dept. 55W, Eastman Kodak Company, Rochester, N.Y. 14650.

A hypersensitivity to mercury

Mercury can act as a ruinously erratic photographic hypersensitizer. Long ago this induced in us a state of corporate hypersensitivity to that element. It extends even to the cosmetics our ladies wear. Wherever on earth we make film, we must keep track of Hg at the parts-per-billion level. The Kodak Research Laboratories in Coburg, Australia contributed in *Analytical Chemistry* for June, 1967 (p 790) a way of doing so with portable equipment containing a mercury resonance lamp such as in 1912 amused R. W. Wood, a man who spent a long, fabulous life proving that physics is fun. This device permits us to offer (merely for interest, not as a definitive survey) the following comparisons:

	Hg (including methylmercury) in parts per billion
Municipal water supply, Rochester, N. Y., May, 1970	0.01
Kodak offshore intake on Lake Ontario, May, 1970	0.03
World ocean average (*1*)	0.03
Niagara River (feeding Lake Ontario from Lake Erie), May, 1970	0.06
Intertidal-zone water, Gouldsboro Bay, Maine, June, 1970	0.06
Soft tissue of clams (*Mya arenaria*), Gouldsboro Bay, June, 1970	8.
Total tissue of silver bass (*Roccus chrysops*) from Kodak intake, May, 1970	2.
Total tissue of bullhead (*Ameiurus neblosus*) from Kodak intake, May, 1970	12.
Total tissue of alewife (*Alosa pseudoheringus*) from Kodak intake, June, 1970	215.
Total tissue of searun alewife (also *Alosa pseudoheringus*) from Mount Desert Island, Maine, June, 1970 (*2*)	10.
Total tissue of sculpin (*Myoxocephalus scorpius*), Maine coast, June, 1970 (*2*)	<2.
Total tissue of flounders (*Pseudopleuronectes americanus* and *Limanda ferruginea*), Maine coast, June, 1970 (*2*)	10.

(1) As quoted in *The Oceans*, Sverdrup, Johnson, and Fleming
(2) Collection kindly provided by Dept. of Sea and Shore Fisheries, State of Maine

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How about hot blueberry muffins for breakfast? Or a warm wedge of blueberry pie right now?

September is lowbush blueberry time. Last year nearly 20 million pounds were harvested with rakes like this:

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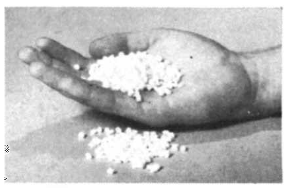

and differs from solder in emitting no lead fumes in the shop. Further differences, however, pose difficulties for an organization with lots of orders for blueberry rakes and few mechanical engineers available to develop the kind of production equipment where EASTMAN High Performance Adhesives really perform. Fed our product along with sheet metal and ⅛″-round tines, it would pour out at the other end in one day enough rakes to handle even a 40-million-pound blueberry year.

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Answer: (1) **inherent viscosity,** a measure of polymer molecular weight; (2) **glass transition temperature,** at which the noncrystalline portion of the polymer is transformed from a tough, rubbery material to a brittle, glasslike one; (3) **degree of crystallinity;** (4) **melting point.**

Our job is to control chemically the interrelationship of these four factors. That makes bond strength closely predictable for given conditions of service and fabrication. When our job is done hand-in-glove with the design of the applicator equipment, the result is more efficient assembly of metal parts—even dissimilar metals—than the older traditions hold decent.

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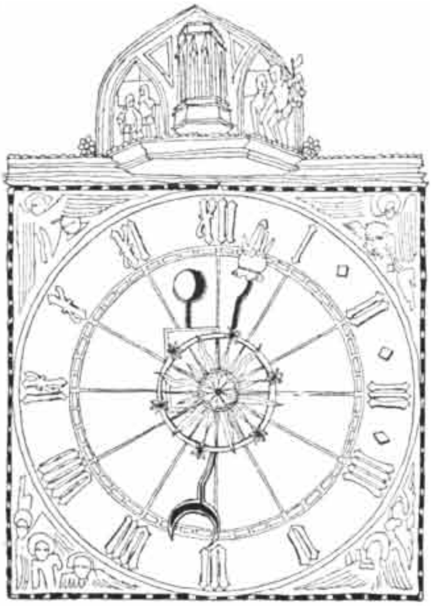
SCIENCE AND



The Side Effects of Man

Pollution, broadly defined as the unwanted side effects of human activity, is effecting global changes in the environment and causing a deterioration of the biosphere. The precise nature of these processes is obscure, however, and the amount of damage inflicted and the rate of increase in man's demands on the environment are still uncertain because of a lack of sufficient information. These are the overall conclusions of a group of scientists and other professional people who conducted a Study of Critical Environmental Problems during July. The study, sponsored by the Massachusetts Institute of Technology and directed by Carroll L. Wilson of M.I.T., was designed to focus attention on some of the issues that will be considered by the United Nations Conference on the Human Environment in 1972. It concentrated on broad problems of worldwide significance: on the indirect effects of pollution through changes in climate, ocean ecology and large terrestrial ecosystems rather than the direct local and regional effects of pollution. Its participants came from such disciplines as meteorology, atmospheric chemistry, oceanography, biology, ecology, geology, physics, engineering, economics, social sciences and the law. Their findings and recommendations were summarized in a preliminary report at the end of the study session and will be published later this year.

The major problems considered were the climatic effects of increasing loads of carbon dioxide and particles in the atmosphere (specifically emissions from supersonic aircraft) and the ecological effects of persistent pesticides, heavy metals, oil in the oceans and accumulations of nutrients in waterways. The group did not consider the management of radioactive wastes but called for an independent study of the subject.

A projected 18 percent increase by the year 2000 in atmospheric carbon dioxide from the burning of fossil fuels could raise the earth's average surface temperature half a degree Celsius, the study concluded; a doubling of the carbon dioxide might raise the temperature two degrees, leading to long-term warming of the planet. The direct climatic change in this century will probably be small, the group reported, but the long-term consequences may be profound. Careful estimates of fuel combustion, monitoring of atmospheric carbon dioxide and studies of its movement through the total biomass, the atmosphere and the oceans are required, and better computer models of worldwide atmospheric patterns should be developed. The level of fine particles in the atmosphere is increasing as man's activities release sulfates, nitrates and hydrocarbons, the group noted. The particles both reflect and absorb radiation, and not enough is known about their optical properties for one to say whether they tend to warm or cool the earth's surface. Again the group called for more research and monitoring.

Fine particles, carbon dioxide and water vapor will be introduced into the stratosphere by supersonic transports, according to the report. The carbon dioxide should not affect the climate, but a possible doubling of the fine-particle load and a 10 percent global stratospheric increase in water vapor could make a significant difference, raising the temperature of the stratosphere and increasing cloudiness. Expressing "genuine concern," the participants urged that "uncertainties about SST contamination and its effects be resolved before large-scale operation of SST's begins."

Pesticides have broad ecological effects, according to the report, because the reduction of one pest population may be accompanied by damage to a predator population that in turn allows the proliferation of new pests. Toxic, persistent pesticides such as DDT create special problems. The participants recommended "drastic reduction in the use of DDT as soon as possible." Taking account of the heavy dependence on DDT in many developing countries, they urged that subsidies be made available to enable such countries to switch to more expensive nonpersistent pesticides and biological controls. Like DDT, mercury and many other heavy metals are concentrated by marine and land organisms and are highly toxic. The use of mercury in pesticides should be drastically curtailed and industrial wastes should be better controlled.

A million and a half tons of oil are spread on the ocean every year and perhaps two or three times as much may be leaked away on land. The group recommended extensive research on the effects of oil in the ocean, restrictions on sources of oil spills and studies of the possibility of recycling oil used for lubrication.

Eutrophication of waters—enrichment through overfertilization with nitrogen and phosphorus—is having a broad ecological effect, the group found. The pollutants come largely from municipal wastes and from runoff from agricultural land. Detergents, which in the U.S. provide about 75 percent of the phosphorus in waste water, should be reformulated to eliminate the phosphorus, and nutrients should be reclaimed and recycled from sewage plants and feedlots.

Until recently, the report concluded, men have been absorbed with the "first-order effects of science and technology: the goods and services produced." The side effects were taken in stride. Now a shift in values is discernible: control of the side effects is getting a higher priority. Society will have to "make a more thorough and imaginative use of its resources of science and technology, its organizational skills and its financial resources" to achieve a balance between production and side effects. This will require new institutions for assessing the effects of new technologies and materials, monitoring the distribution of pollutants, identifying options and educating the public on those options.

Ambassadors to the Biosphere

A variety of proposals to create at least one agency, in or out of the Government, that would be able to deal with environmental problems on a broad basis is under consideration in the Administration and Congress. President Nixon took a step in that direction when he sent Congress a reorganization plan that would create an Environmental Protection Agency, which would take over the work that several Federal agencies are doing now in such areas as air and water pollution, the disposal of solid wastes, the control of pesticides and the establishment of standards of radiation. The Senate Public Works Committee plans to begin hearings this month on a bill to create the National Environmental Laboratories as an autonomous agency with close ties to the Federal Government; the status of the laboratories would resemble that of the Smithsonian Institution. During the hearings the committee intends to consider a number of other proposals, including one by the Ecological Society of America for an independent, nongovernmental National Institute of Ecology.

The proposal of the Ecological Society is based on the society's belief that much basic ecological information is not finding its way into the decision-making process, that multidisciplinary research is needed to clarify processes of renewability of resources, that the potential of ecology as a means of predicting environmental change has not been realized and that existing organizational arrangements for achieving these objectives are deficient. The society envisions an institution that would have close ties with governments, universities and industries and would have laboratory functions, conduct policy research, store data and mount an information program.

In Washington the expectation is that the Environmental Protection Agency will come into being, inasmuch as it involves mainly a new administrative arrangement for existing agencies. The fate of the other proposals is uncertain because opinion has not yet crystallized. The crucial question of footing the bill for large-scale efforts to reduce pollution remains unresolved. The precise role of the Federal Government in environmental activities is still a matter of debate involving state and local governments and industry as well as the Federal Government. A number of competing jurisdictions, involving both administrative agencies and Congressional committees, must be reconciled.

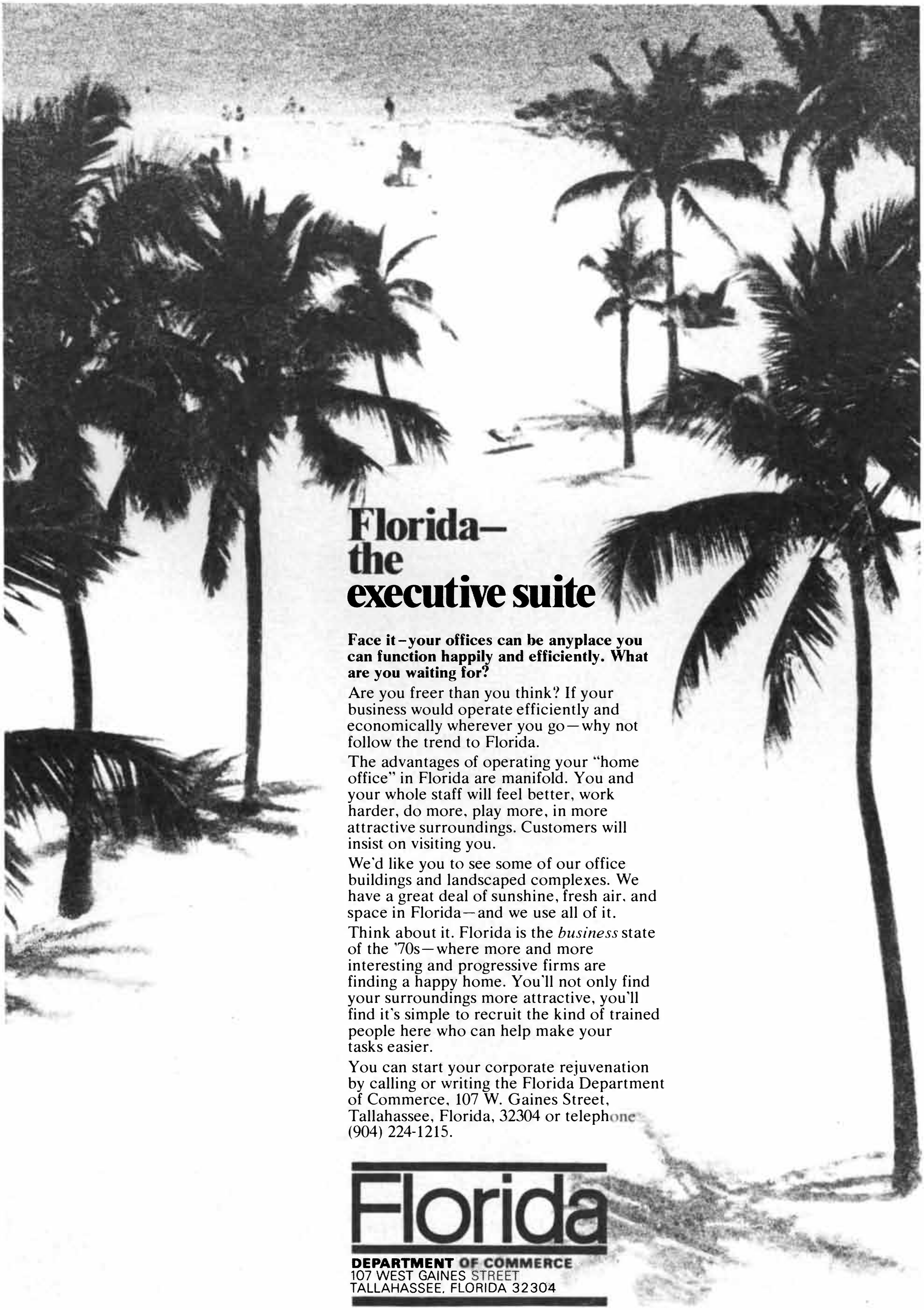
Martian Orbiters

Next year two Mariner spacecraft will be launched toward Mars carrying enough fuel (1,050 pounds each) for them to be slowed down on arrival and captured by the planet as satellites. From carefully selected orbits the Mariners will carry out a complex reconnaissance of the planet, including television photography, infrared radiometry, ultraviolet spectroscopy and mapping of the planet's gravity field. The new Mariners will be close copies of *Mariner 6* and *Mariner 7*, which took some 200 photographs of Mars last year.

The Martian orbit for Mission A, to be launched in May, will vary from a low point of about 1,800 kilometers to a high point of 17,000 kilometers, providing one trip around Mars every 12 hours. The orbit for Mission B, to be launched in November, may approach as close as 1,000 kilometers but will have a maximum altitude of 41,500 kilometers, which will entail an orbital period of 32.8 hours, or 1⅓ times the rotation rate of the planet. An approach closer than 1,000 kilometers has been ruled out to make sure that an accidental descent does not contaminate the Martian surface. The closest approach of the 1969 Mariners was 3,500 kilometers. The 1971 Mariners are each designed to operate for 90 days in orbit and to stay aloft for at least 20 years. By that time the surface of the planet will presumably have been examined in detail by future spacecraft.

The 1971 Mariners will carry cameras similar to those used in the 1969 missions: a wide-angle camera of 50-millimeter focal length and a narrow-angle, or telescopic, camera of 500-millimeter focal length. The two orbits have been selected to provide medium-resolution pictures of 70 percent of the planet's surface and high-resolution pictures of 5 percent of the surface within the narrow-angle views. It is expected that in three months of daily coverage significant changes will be observed in the planet's surface and in the atmosphere, including the appearance of clouds and dust storms.

There is particular interest in recording the "wave of darkening," the surface darkening that occurs near the receding polar caps with the coming of spring in each hemisphere. According to a hypothesis that dates back to the 19th century, the areas darken when Martian organisms of some kind begin growing in response to the rise in temperature and humidity. To test this hypothesis any changes seen in the television images will be correlated with data provided by infrared radiometry and spectroscopy. There are, of course, possible nonbiological explanations for the wave of darkening. According to one idea, the changing wind patterns of spring simply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redistribute dust and alter the reflectivity of the surface. Analyses of the various instrument readings should also settle once and for all whether the Martian polar caps are water ice or, as most interested workers now believe, frozen carbon dioxide.

Women's Liberation

In the 11 years between 1955 and 1966 the fraction of American men over 18 who smoked cigarettes declined from 56.9 percent to 50.7 percent. Simultaneously the fraction of women smokers increased from 28.4 to 32.9 percent. Because of the growth of population in the 11-year period, there were actually 1.3 million more men smokers in 1966 than in 1955. The number of women smokers increased by 5.5 million. These statistics are presented in *Changes in Cigarette Smoking Habits between 1955 and 1966*, published by the Department of Health, Education, and Welfare.

The report shows not only that more women are smoking than ever before but also that they are smoking at an earlier age. In the 1955 survey only 2.1 percent had started smoking by age 15; in the 1966 survey the percentage had quadrupled. Perhaps most surprising is that there has been a marked rise in smoking among women of every age; the older the age group, the greater the percentage increase. Whereas the increase in smoking among women of 18 to 24 was 4 percent, the increase among those 35 to 44 was 16 percent, and among those 55 and over it was 72 percent. Among men there was a decline ranging from 5 to 9 percent for every age group but one: among men 55 to 64 there was a slight (.9 percent) increase.

Upstart RNA

Biochemical investigations at the University of Wisconsin and the Massachusetts Institute of Technology support a radical genetic hypothesis: viruses whose genetic material is RNA can produce an enzyme capable of constructing DNA on an RNA template, and thereafter the DNA bearing the viral genetic message can be replicated along with the host cell's own DNA. In this way a cell could be forced to carry the seed of its own destruction. It had been a central postulate of molecular biology that DNA, the bearer of the genetic message in all cells, is the only material capable of serving as a template for the production of new DNA. Those viruses whose genetic message is coded in RNA can organize the replication of their own RNA (the postulate assumed) but have no capacity for translating viral RNA into DNA.

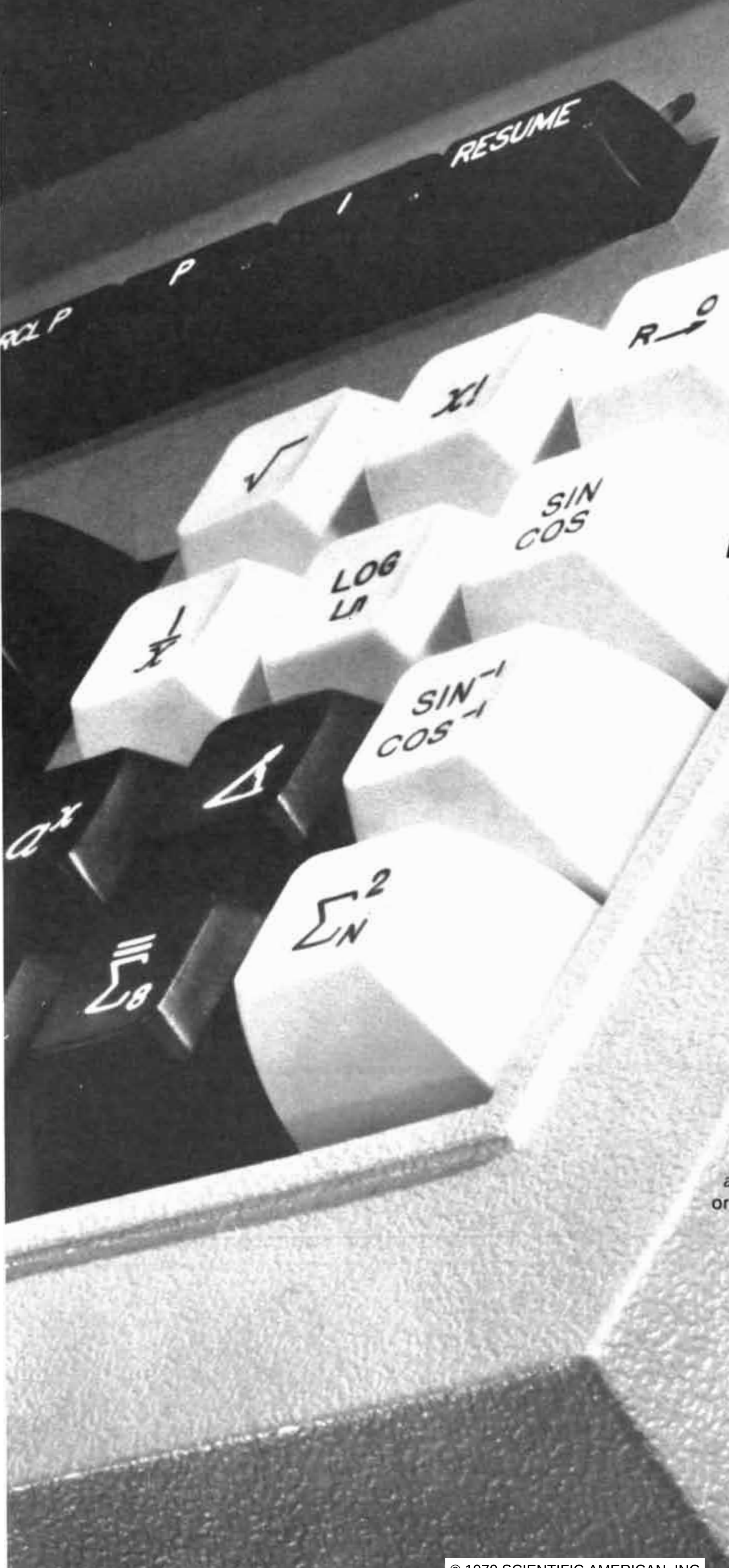
Six years ago Howard M. Temin of the University of Wisconsin presented his doubts about the postulate. If it were true, how could RNA viruses infect healthy cells and then seemingly disappear, leaving no trace of themselves or their RNA? He proposed that the viral RNA must be translated into DNA representing a tiny addition to the cell's own DNA. Temin's hypothesis won few adherents, and supporting evidence proved elusive.

The evidence is now supplied by two papers in *Nature*. One is by Temin and Satoshi Mizutani; the other is by David Baltimore of M.I.T. Both laboratories report that cells infected by Rous sarcoma virus (which produces tumors in chickens) contain an enzyme capable of translating RNA into DNA. Temin and Mizutani also report that the new DNA appears to be a true translation of the viral RNA. Baltimore finds the same kind of enzyme in cells infected by a virus that causes leukemia in mice. In subsequent studies Sol Spiegelman of the University of Illinois has confirmed the discovery by Temin, Mizutani and Baltimore, and he reports that he and his co-workers have found the new enzyme in six more RNA viruses.

Mercury and Mud

Tiny amounts of mercury in the human body can produce kidney damage, muscular tremors, irritability and depression. Larger amounts can be fatal. Until recently, however, the managers of chemical companies and other industrial enterprises that were losing as much as 50 pounds of mercury a day from their plants had no major cause for concern. It was assumed that any of the heavy metal lost during manufacturing cycles would ultimately sink to the bottom of a stream or lake and would lie harmlessly and inertly in the mud. As any chemist knows, the safest place to keep mercury is under water, where it cannot evaporate into the air and enter the body.

In the past few months manufacturers and the public have learned once again that the web of nature is fine-spun and that distorting it can have unexpected effects. It appears that mercury and mercuric chloride escaping from factories producing chlorine, paper, mercury lamps, batteries, electrical appliances and other products do not lie inertly in



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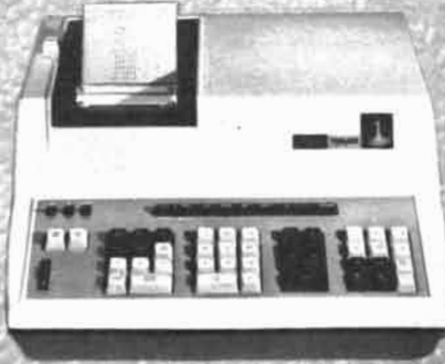

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"...I'm kind of a marriage counselor for the ocean..."

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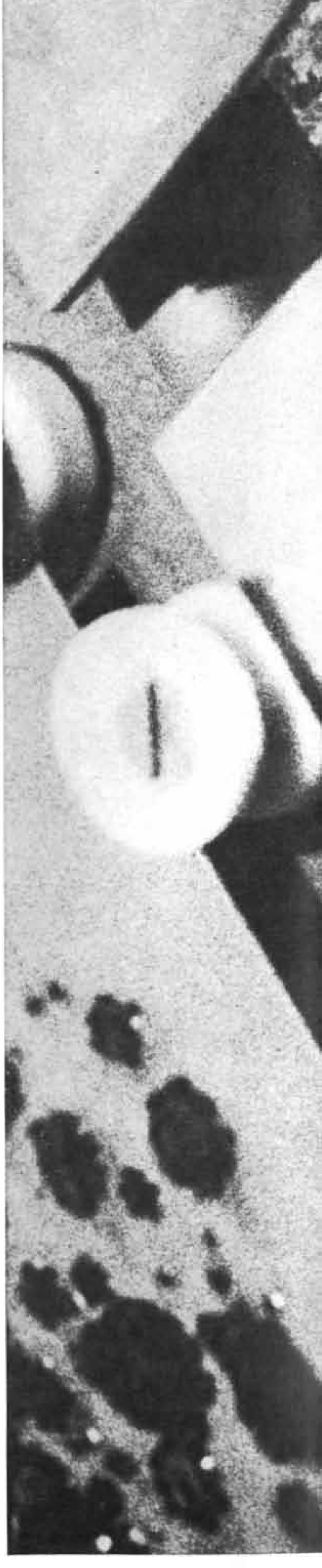
Vic holds a nickel-chrome plated automobile bumper which was tested in the corrosive seaside atmosphere.



Photography by W. Eugene Smith.

the mud. The mercury has been entering the food chain. According to findings by Arne Jernelöv of the University of Stockholm and John M. Wood of the University of Illinois, anaerobic bacteria dwelling in mud take up the inorganic mercury and convert it into organic dimethyl mercury, which they release. Dimethyl mercury is volatile, that is, it diffuses from the mud into the water. Wood believes the anaerobes methylate mercury in order to avoid poisoning. "They clean their environment," he says, "at the expense of ours." Since dimethyl mercury passes easily through membranes, active fishes such as the pike pick up large amounts through their gills. Dimethyl mercury also rises through the food chain from microorganisms to smaller fishes to larger fishes. Once dimethyl mercury has been ingested by a fish, Wood believes, it is converted to monomethyl mercury, the form of organic mercury found when fish are examined for contamination.

As a result of this sequence of events, and perhaps others as well, lakes and streams have been widely polluted with mercury. Since the first reports of contamination in March, mercury has been detected in the waters of at least 17 states. A number of shipments of fish have been found to be contaminated with mercury, and their interstate transportation has been prohibited by the Food and Drug Administration. The Department of Justice has brought suit against several companies, and some concerns have already reduced the loss of mercury from their plants. No cases of mercury poisoning from polluted waters have yet been reported among human beings. The only victims so far, postmortem examinations have shown, have been fish-eating bald eagles.

Unsolution

In 1900 the German mathematician David Hilbert compiled a list of 23 outstanding problems for the consideration of the mathematicians of the 20th century. So far roughly half of these problems have been satisfactorily mastered, in many cases by proving that they are not capable of being solved. Now a young graduate student in mathematics at the University of Leningrad, Yu. V. Matijasevič, is reported to have completed the last link in a chain that "unsolves" another of Hilbert's famous problems: the 10th.

The theorem to be proved in Hilbert's 10th problem states that no algorithm, or set of mathematical operations, can ever be developed that would determine whether or not polynomial equations of a certain form have a solution that can be expressed in whole numbers. The form of the equations is $f(x_1, x_2, \ldots, x_n) = 0$, where f is a polynomial (an expression with two or more terms) that has whole-number coefficients. A set of such equations, $f_1(x_1, x_2, \ldots, x_n) = f_2(x_1, x_2, \ldots, x_n) = \ldots = 0$, has a solution if and only if the single equation $f_1(x_1, x_2, \ldots, x_n)^2 + f_2(x_1, x_2, \ldots, x_n)^2 + \ldots = 0$ has one. Matijasevič's solution, in which the Fibonacci number sequence plays a key role, proves conclusively that no such algorithm is possible. His proof was published in a recent number of *Doklady Academii Nauk S.S.S.R.* (*Proceedings of the Academy of Sciences of the U.S.S.R.*).

Rumbling Moon

Some of the puzzling signals dispatched by the seismometer left on the moon last November by the astronauts of *Apollo 12* have now been sorted out and show a clear-cut pattern. The most distinctive tremors of the more than 160 recorded occur once a month two or three days before the moon is closest to the earth. Within three days after perigee there is another burst of tremors. Since the seismometer was placed on the moon seven series of these highly regular tremors have been recorded, each series nearly identical with the one before. "This implies," said Gary Latham of Columbia University, a member of the lunar seismology group, "that they have a common source, a common location and a common mechanism."

The apparent mechanism is that the pull of the earth's gravity causes the side of the moon to bulge toward the earth, producing a tidal strain that sets off a series of tremors. It has been calculated that the bulge amounts to 20 or 30 inches. A second series of quakes is triggered when the moon starts receding from the earth and the bulge subsides. The earth-moon distance varies from 221,463 miles to 252,710 miles in the 29½ days it takes the moon to make one revolution of the earth.

Pacific Junction

A four-week Pacific cruise this spring by the Navy research vessel *DeSteiguer* has produced further evidence that the earth's crust consists of discrete drifting plates. The expedition, conducted jointly by the Navy and Princeton University, sounded and magnetically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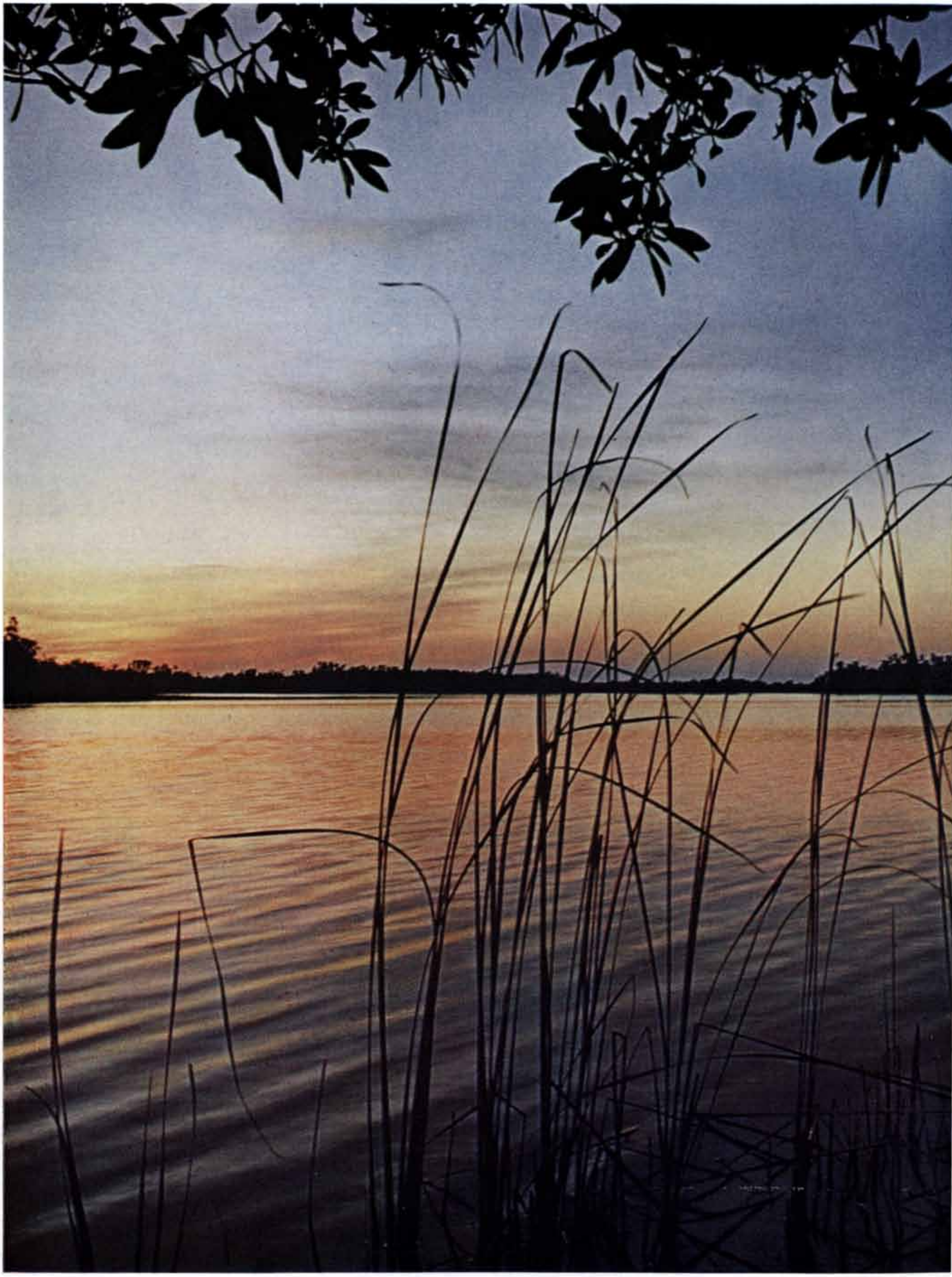

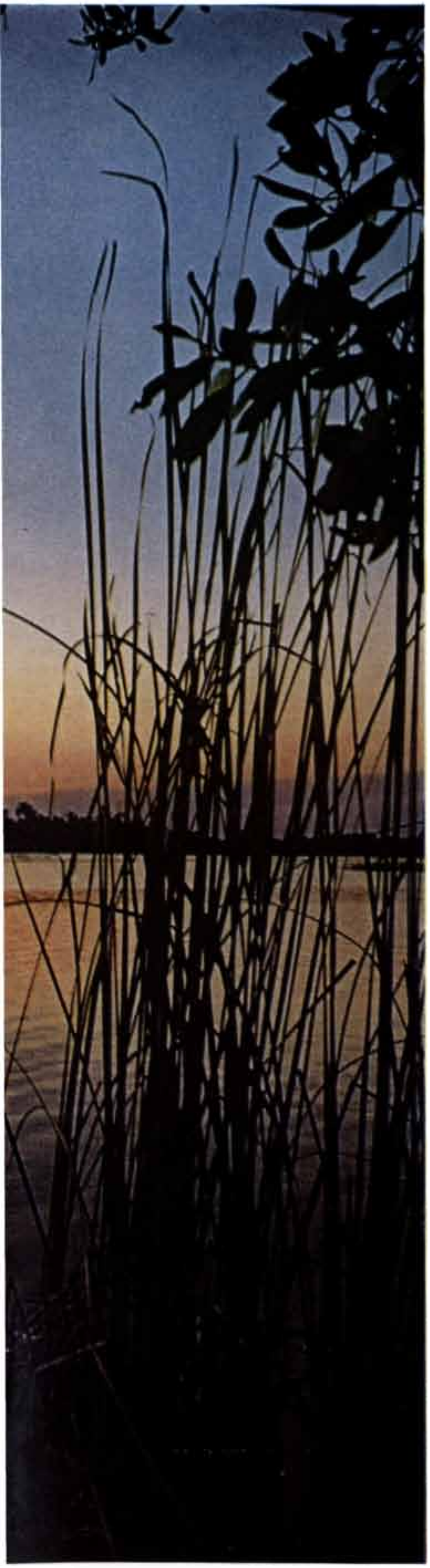

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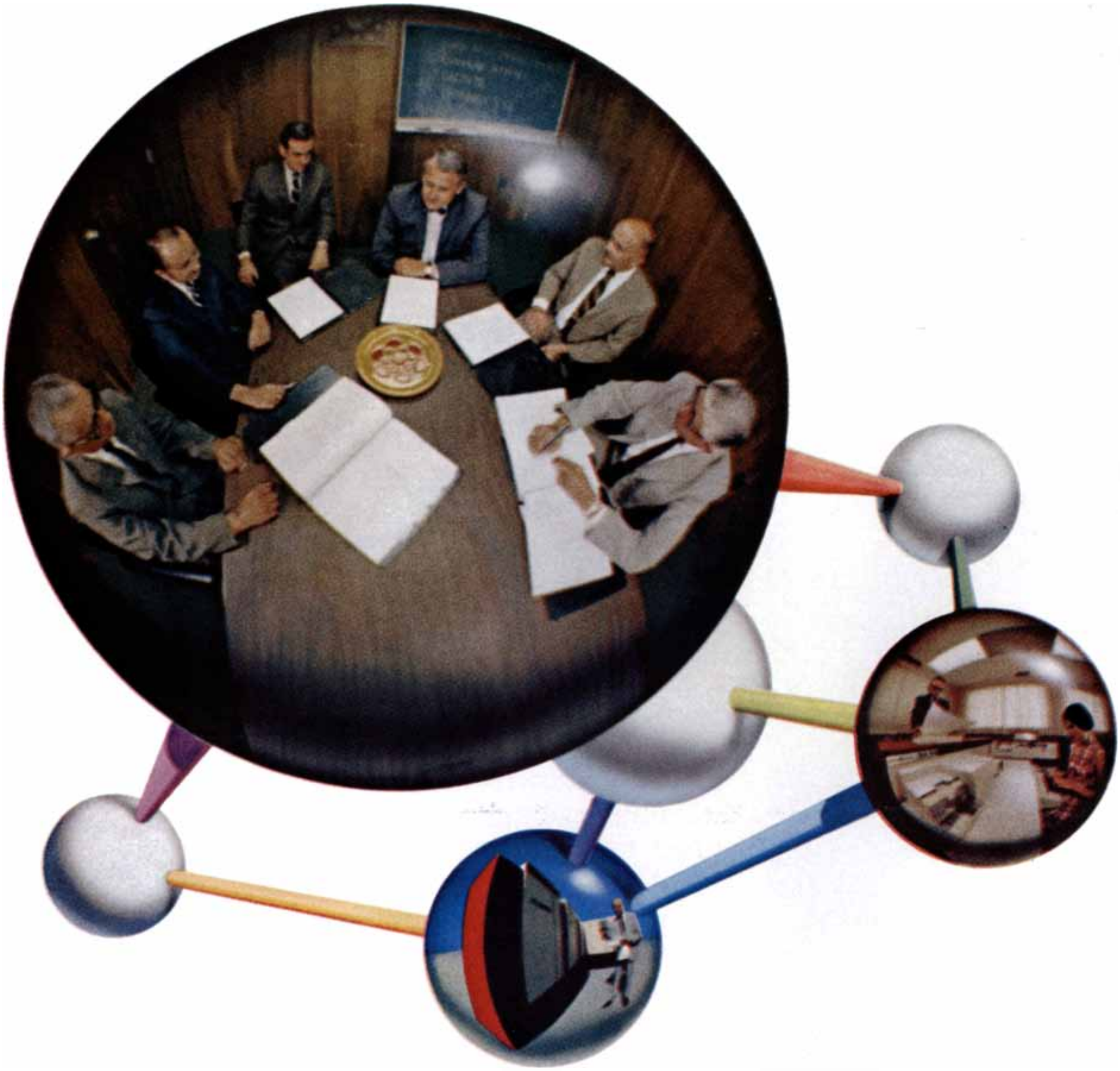

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GENERAL ELECTRIC

General Electric Computers: The United Systems of the 70's

mapped a triangular zone of sea floor; its 300-mile base lies roughly perpendicular to the Equator in the vicinity of the Galápagos Islands and its apex is some 600 miles to the west. The apex marks the junction of three crustal plates. The Cocos plate, north of the Galápagos, is in motion toward Central America to the northeast. The Nazca plate, adjoining the Cocos plate along an east-west line, is in motion toward South America to the southeast. The Pacific plate adjoins the other two along a generally north-south line and is moving to the northwest. The magnetic record frozen into the rock that has welled up to fill the gaps between the plates shows that they have drifted several hundred miles apart in the past 10 million years. The triple junction at the apex of the triangle is marked by a 30-mile-long valley three miles below the surface, bordered by steep walls that reach a height of one and a half miles above the valley floor.

The voyage provides an example of theory successfully predicting fact. A few years ago D. P. McKenzie of the University of Cambridge and W. Jason Morgan of Princeton independently concluded that, if three oceanic plates should drift apart, a wedge-shaped area would appear on the sea floor with its apex at the triple juncture. The McKenzie-Morgan hypothesis was published jointly in 1968; it led one of Morgan's Princeton colleagues, Kenneth S. Deffeyes, to calculate the size and shape of the triple-juncture wedge to be expected in the Galápagos area. Deffeyes then led the *DeSteiguer* expedition and collected the data that proved the correctness of the McKenzie-Morgan hypothesis.

Messenger No. 5

Until recently there were four known types of plant hormone: substances that in tiny quantities mediate such physiological processes as rate of growth, cell division and leaf fall. The four are the auxins (suspected since Darwin's day and finally isolated in 1928), the gibberellins (first isolated by a Japanese investigator in 1926 but unknown outside Japan until after World War II), the cytokinins (discovered in 1954) and the abscisins (discovered in the early 1960's). There is now a fifth type of hormone: the brassins. Isolated recently by investigators at the Department of Agriculture research establishment in Beltsville, Md., the brassins are long-chain glycerides that stimulate the division, elongation and lateral enlargement of plant cells. They take their name from the

genus *Brassica,* a group of plants that includes the oilseed producer rape, whose abundant pollen is the source of the new hormones.

Although the other types of hormone are present in all plants, there is no easy way to extract them in useful quantities. Rape pollen, which could easily be grown in quantity, yields .1 gram of brassin per pound, suggesting the possibility of a natural supply of the substance.

Cat's Whiskers

Can one be sure that the lion sighted on the veld this morning is, or is not, the same lion as the lion encountered yesterday? Two zoologists in Kenya believe one can. Assuming that all its possible permutations are biologically probable, their system might allow the positive identification of some five trillion individual lions, a number that substantially exceeds the lion population of the world. The system depends on the fact that lions possess four or five rows of whisker holes, running parallel to one another on both sides of the muzzle in the area between the nostril and the upper lip. The top row can consist of as many as five holes; the row below, five to nine holes. Each hole in the top row is either directly above one of the lower ones or is offset, so that top-row holes may fall in any of 17 positions with respect to the holes below.

Writing in the *Journal of Zoology,* C. J. Pennycuick and J. Rudnai of University College in Nairobi report that keeping records of whisker patterns has allowed them to positively identify 25 of the 50 lions that comprise the lion population of Nairobi National Park. They photographed both sides of the head of each lion they encountered over an 18-month period and then charted the whisker pattern in terms of the 56 possible positions the lion's 14 to 28 whisker holes happened to occupy. When a lion observed at a subsequent meeting proved to have a whisker pattern recorded earlier, the investigators confirmed the identification by means of independent data, such as scars and ear irregularities. In the course of the study the apparent whisker pattern failed only once to substantiate an identification based on independent data. In that case reexamination of the earlier photographs showed that a whisker hole recorded at the second encounter was indeed present at the first but had not been recorded then because it was almost undetectably small when the lion was younger.

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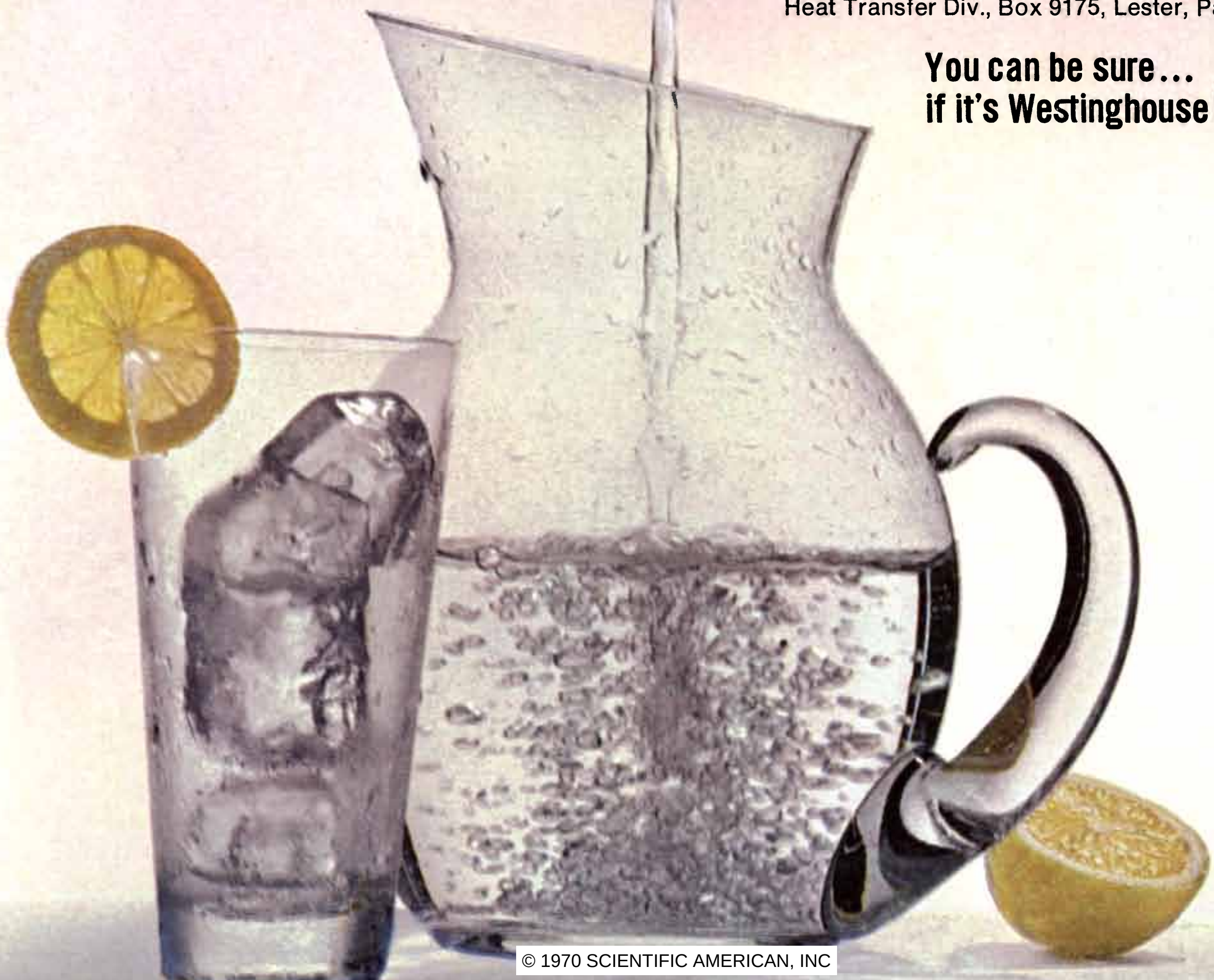

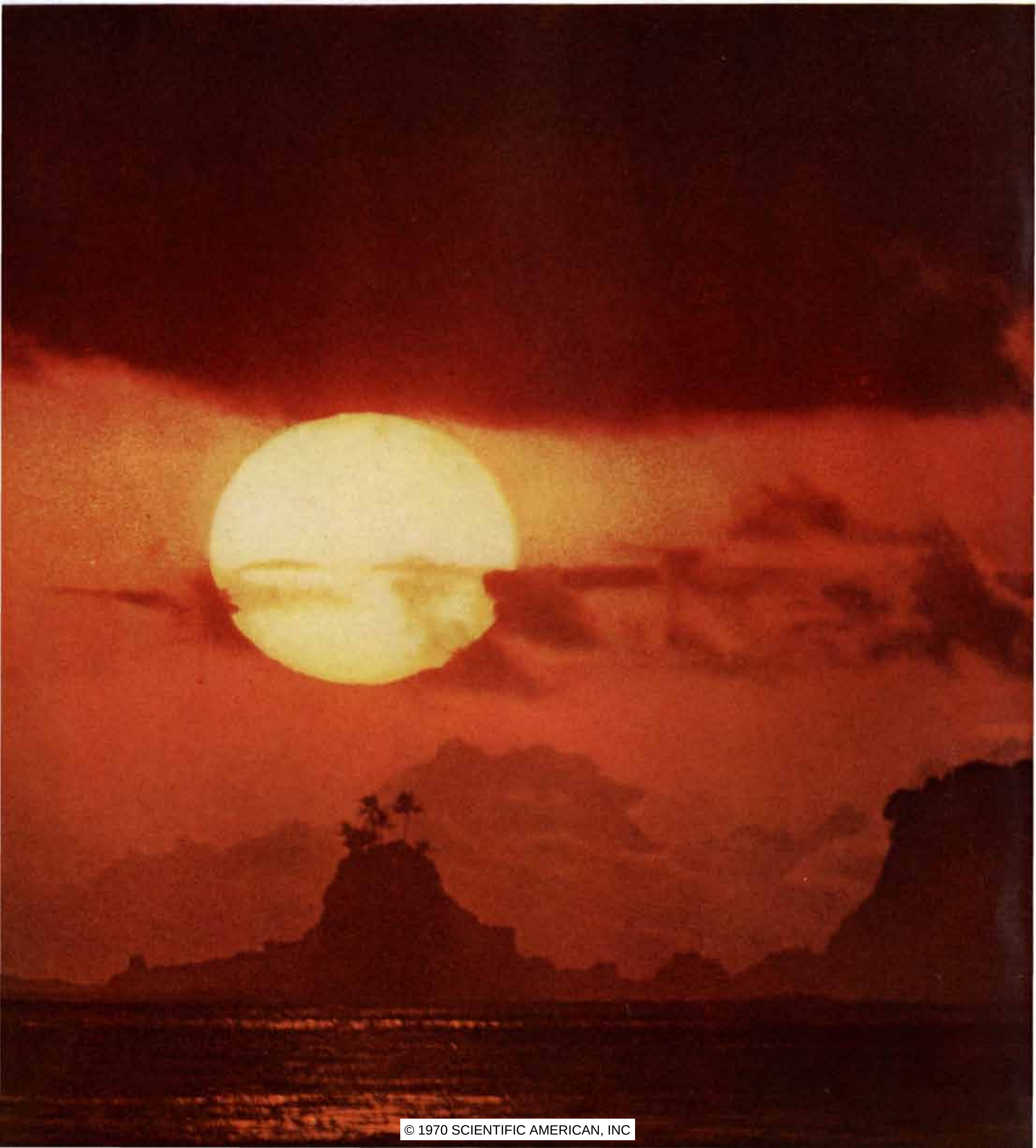

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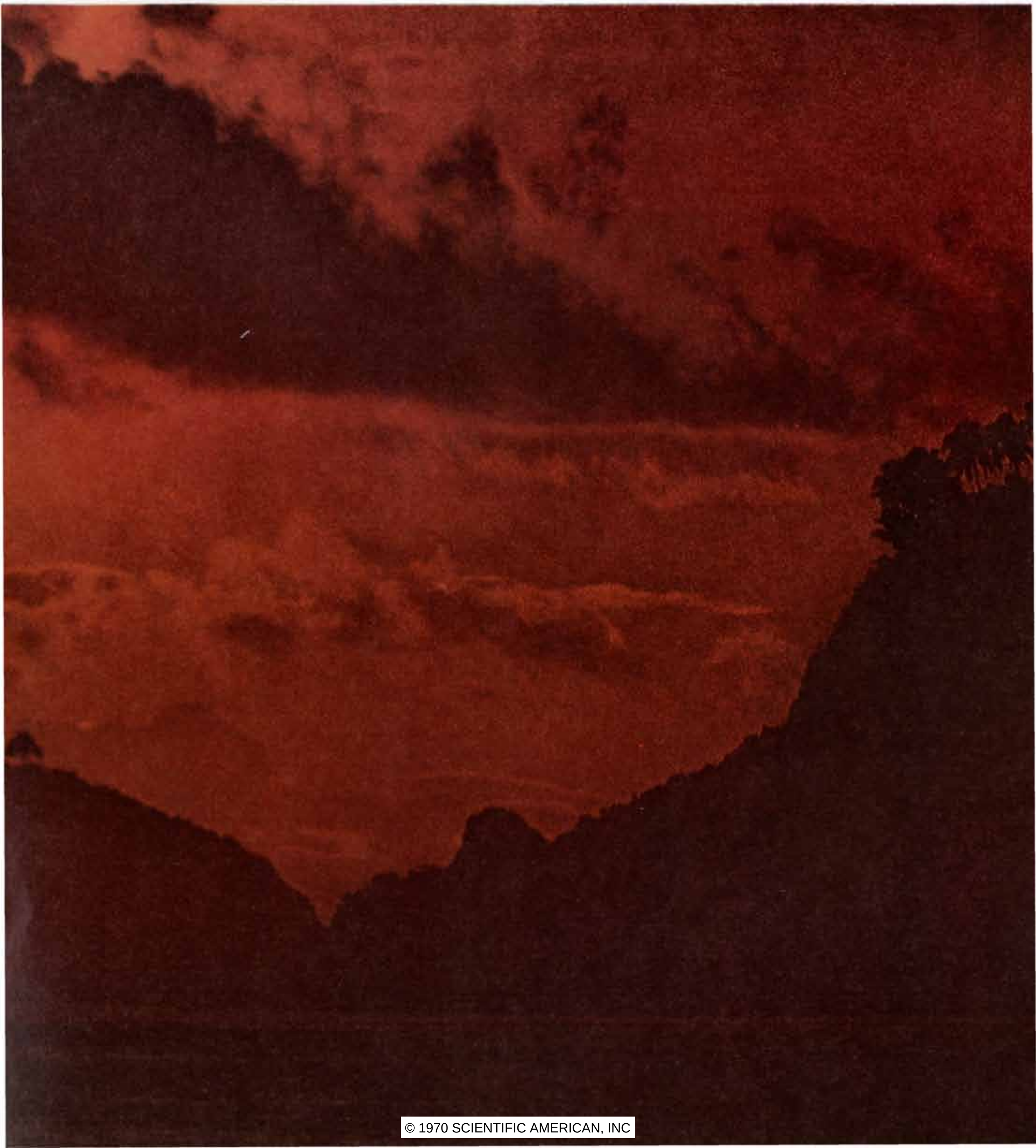


THE WATER CYCLE

Water is the medium of life processes and the source of their hydrogen. It flows through living matter mainly in the stream of transpiration: from the roots of a plant through its leaves

by H. L. Penman

By far the most abundant single substance in the biosphere is the familiar but unusual inorganic compound called water. The earth's oceans, ice caps, glaciers, lakes, rivers, soils and atmosphere contain 1.5 billion cubic kilometers of water in one form or another. In nearly all its physical properties water is either unique or at the extreme end of the range of a property. Its extraordinary physical properties, in turn, endow it with a unique chemistry. From these physical and chemical characteristics flows the biological importance of water. It is the purpose of this article to describe some of water's principal qualities and their significance in the biosphere.

Water remains a liquid within the temperature range most suited to life processes, yet in due season there are occasions when liquid water exists in equilibrium with its solid and gaseous form, for example as ice on the top of a lake with water vapor in the air above it. Freezing starts at the surface of the water and proceeds downward; this follows from one of water's many peculiar attributes. Like everything else, ice included, liquid water contracts when it is cooled, but the shrinkage ceases before solidification, at about four degrees Celsius. From that temperature down to the freezing point the water expands, and because of its decreased density the cooler water floats on top of the warmer. Ice has a density of .92 with respect to the maximum density of water and hence an unconstrained block of ice will float in water with about an eleventh of its volume projecting above the surface. The biological significance of freezing from the surface downward, rather than from the bottom upward, is too well known to need repetition here.

Among its other thermal properties water has the greatest specific heat known among liquids (the ability to store heat energy for a given increase in temperature). The same is true of water's latent heat of vaporization: at 20 degrees C. (68 degrees Fahrenheit), 585 calories are required to evaporate one gram of water. Finally, with the exception of mercury, water has the greatest thermal conductivity of all liquids. Some consequences of water's large latent heat of evaporation, which is a major energizer of the atmosphere, will be considered below. Its great specific heat means that, for a given rate of energy input, the temperature of a given mass of water will rise more slowly than the temperature of any other material. Conversely, as energy is released its temperature will drop more slowly. This slow warming and cooling, together with other important factors, affects yearly, daily and even hourly changes in the temperature of oceans and lakes, which are quite different from the corresponding changes in the temperature of land. Among other things, this can lead to differences in the thermal regimes of soils that are of major importance in ecology. The type of soil, interacting with water, determines the earliness or lateness of plant growth at a given site; the interaction may also affect the local risk of frost.

In basic structure the water molecule has a small dipole moment and is feebly ionized. Water will dissolve almost anything to some extent (fortunately the extent is extremely small for many substances). The dissolved material tends to remain in solution because of another of water's exceptional attributes. The values given by the inverse-square law for the force that attracts separated positive and negative ions are determined by multiplying the square of the distance separating the ions by a constant that varies according to the nature of the separating medium. Known as the dielectric constant, this constant is greater for water than for any other substance. To get the same attractive force in water as in air, for example, the water separation has to be cut down to a ninth of the separation in air.

Because of its extreme dielectric constant liquid water in the biosphere is not chemically pure (unlike water vapor, which is always pure, or ice, which can be and often is pure). Instead liquid water is an ionic solution and one that always contains some hydrogen ions because the water itself can supply them. The concentration of hydrogen ions, expressed as a degree of dilution, gives the physical chemist a numerical index that describes the state of various water samples. The number is the logarithm (to the base 10) of the degree of dilution; the chemist labels it pH. For his tests he is armed with a pH meter, calibrated from zero to 14. Fourteen orders of magnitude is an enormous range for any terrestrial

WATER AT WORK for millenniums in the form of rainfall and stream runoff has produced the dissected land surface seen in the side-looking radar image on the opposite page. The annual work of terrain modeling by rainfall and runoff has been estimated to equal the work of one horse-drawn scraper busy day and night on every 10 acres of land surface. This area, in the vicinity of Sandy Hook, Ky., is drained by tributaries of the Ohio River. Each inch equals 2.3 miles on the ground. The radar mosaic, made by the Autometric division of the Raytheon Company, is reproduced by the courtesy of the Army Topographic Command.

property, yet the water content of the soil may give a reading anywhere from pH 3 (very acid) to pH 10 (very alkaline), which is equivalent to a range of from one to 10 million. These are extremes, however, and most terrestrial plant growth—including much of the world's agriculture—proceeds in soil with a water content that ranges only a few units on each side of pH 6. The range for marine organisms is even more restrictive: coastal waters are about pH 9 and the general oceanic average is just over pH 8. Below pH 7.5 many marine animals die; eggs are particularly vulnerable. Below pH 7 the carbonate in seawater would remain in solution, rendering production of any kind of skeleton impossible.

Another method of describing the state of a given water sample is independent of hydrogen-ion content. Material in solution, whether it is ionized or not, disturbs the liquid structure of the water; in thermodynamic terms the presence of solutes decreases the free energy of the water. Many soil and plant workers find it convenient to use the symbol pF for such changes in free energy, with the steps between units also representing one order of magnitude. As with the pH range, the range of pF values is very great.

The quantity being measured in pF units is basically a potential, with the same dimensions as pressure. If all the water problems in soils, plants and animals were problems of solutions, it would be sufficient to describe the consequent variations in free energy as variations in osmotic potential, expressed in any of the conventional units of pressure. The free energy of water, however, can be decreased in other ways, notably in capillary systems. The energy to lift the water into a capillary tube (or in nature into the porous and cellular systems of soils and plants) comes out of the free energy of the water. Today this is known as "matric" potential, a term that has replaced the earlier "capillary" potential. In soils and plants the matric potential may be more than the osmotic potential. A comparison of numbers will give an idea of the pF scale and its ranges. The pressure is expressed as the height in centimeters of an equivalent column of water; thus one bar equals one atmosphere, which equals a 1,000-centimeter water column. This is equivalent to pF 3.

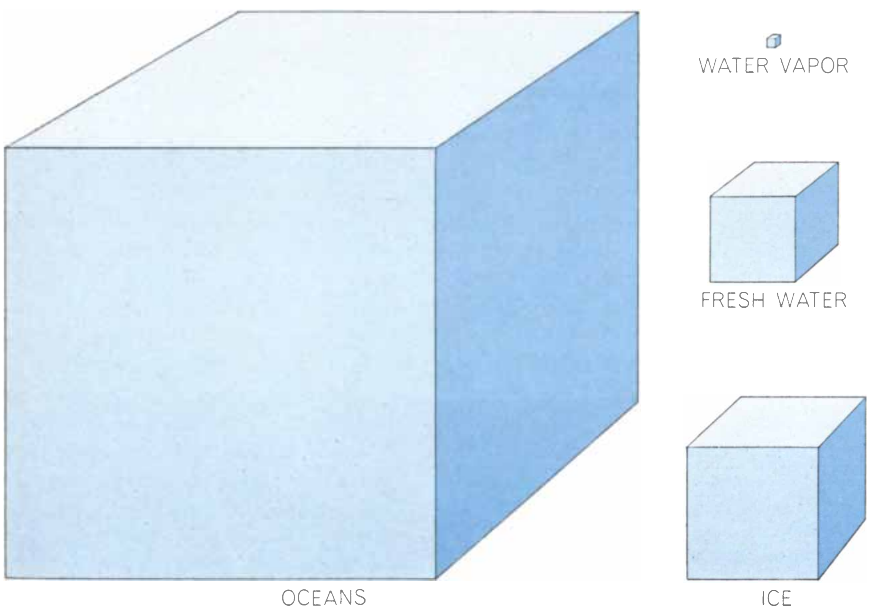
In a waterlogged soil, beginning to drain, the matric potential may be between pF 0 and pF 1; in a fully drained soil the potential may be near pF 1.7. In a soil that is as dry as plant uptake and the transpiration of water from leaves can make it, the matric potential will be about pF 4.2, which is close to 16 atmospheres of suction. The osmotic potential of seawater is near pF 4.5, which makes seawater too "dry" for plant roots; the salt content of plant cells might be anywhere in a range from less than pF 4 up to pF 4.5.

Here once again water is extreme. Associated with the matric potential in a capillary system there is a curved liquid-air interface; the value of the potential is found by doubling the known value of the liquid's surface tension and dividing the product by the radius of curvature. Water has the greatest surface tension of any liquid known, so that at any given matric potential the radius of curvature of a water meniscus will be greater than it could be for another liquid. The greater the radius of curvature, the greater the total water content. In a soil this means that more liquid can be retained as water just because it *is* water. In general, but not always, this is an advantage for plant growth.

The effects of a decrease in the free energy of water contained in porous soils or in the tissues of plants include a lowering of the fluid's freezing point and vapor pressure. If the source of the decrease is a matric potential, there is also negative pressure, or suction, that tends to pull all kinds of retaining walls together. The effect of freezing in soils and rocks is worth a brief aside. As the temperature falls the water in the larger soil pores freezes first and the free-energy gradient is such that water will be withdrawn from the smaller pores. As a result ice lenses form in the coarser pore spaces and the finer pore spaces are exposed to greater shrinkage forces. Because water expands on freezing, the ice lenses have a disruptive effect as they make room for themselves. In rock this is the beginning of one method of soil formation. There tends to be a preferred size for the rock fragments produced by ice disruption. This size is near the optimum for transport by wind and is the dominant size in many of the loess soils that have accumulated in areas near glaciers. In soil the ice disruption is the source of "frost tilth," which is sought by farmers when they leave land roughly plowed in the fall and hope for a sufficiently frosty winter.

There are still some uncertainties with respect to the world's water balance, but agreement was reached on probable values or ranges during an international symposium on the subject held in Britain this summer as one of the activities of the International Hydrological Decade. The figures that follow are taken from the proceedings of the symposium.

The world's water exists as liquid (salt and fresh), as solid (fresh) and as vapor (fresh). There is some uncertainty in the value of the total volume, but it is near 1,500 million cubic kilometers (in U.S. usage 1.5 billion). Estimates of the components are most easily expressed as



WORLD WATER SUPPLY consists mainly of the salt water contained in the oceans (*left*). The world's fresh water comprises only about 3 percent of the total supply; three-quarters of it is locked up in the world's polar ice caps and glaciers and most of the rest is found as ground water or in lakes. The very small amount of water in the atmosphere at any one time (*top right*) is nonetheless of vital importance as a major energizer of weather systems.

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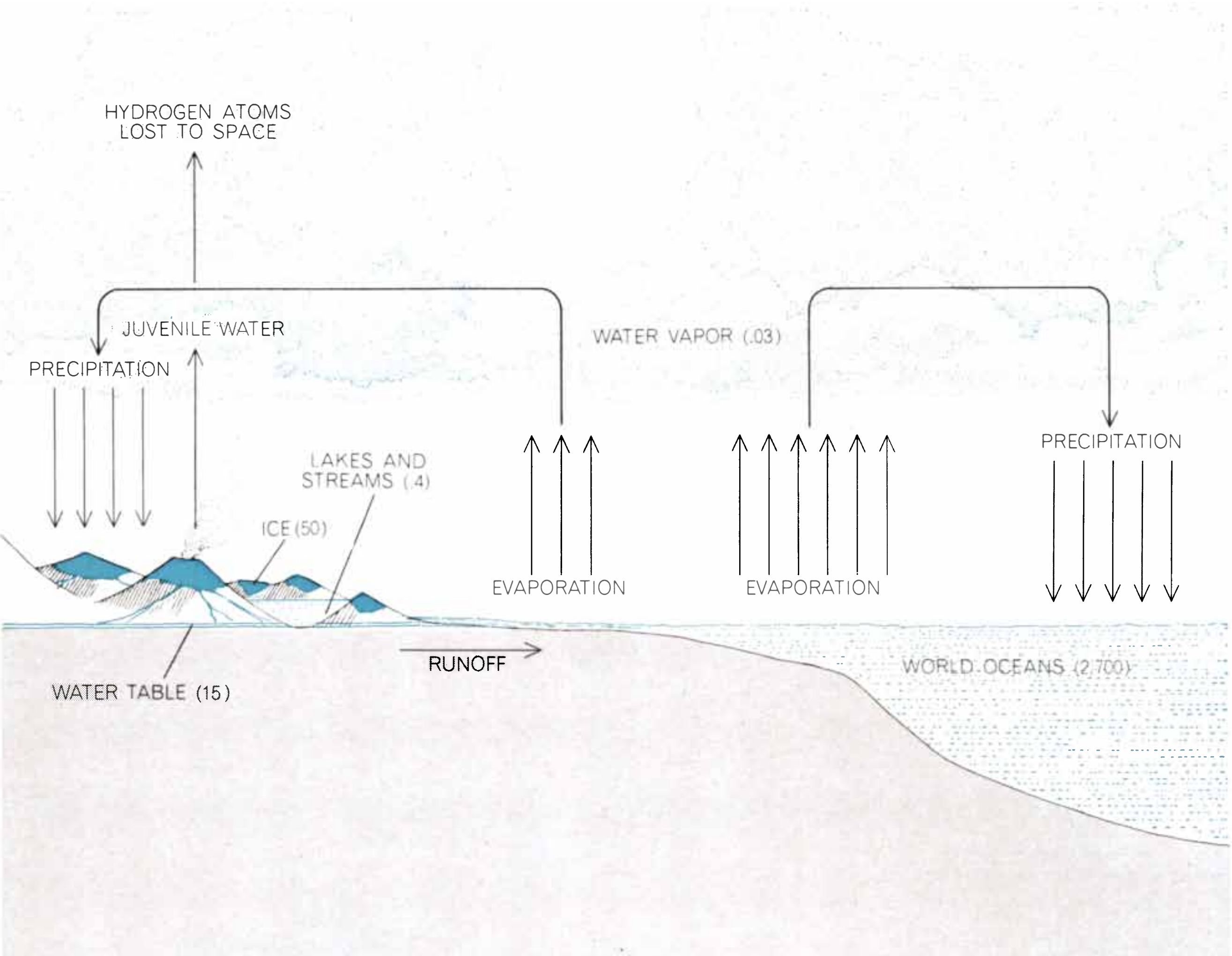
average depths per unit area of the entire surface of the earth, which has a total area of 510 million square kilometers. Oceans and seas—liquid salt water—make up about 97 percent of all water, with an equivalent depth of between 2,700 and 2,800 meters; the greater part is in the Southern Hemisphere. Of the remaining 3 percent, three-quarters is locked up as solid in the polar ice caps and in glaciers. Here measurement is quite difficult, and a spread in estimates is inevitable. The equivalent depth of ice and snow may be near 120 meters, but at the recent symposium a value of 50 meters was not challenged. The other large component of fresh liquid water is subject to similar uncertainty: the estimates for underground water may be near 45 meters, but again a value near 15 meters was not challenged. Estimates for surface water, mainly in the great lakes of the world, ranged from .4 meter to one meter. There is general agreement on the average water-vapor content of the atmosphere, at an equivalent in liquid of .03 meter. Although this is a very small fraction of the total, size is no measure of importance. Without water in the atmosphere there would be no weather; Leonardo da Vinci's dictum, "Water is the driver of nature," is justified on meteorological grounds alone. A little detail at this point will be helpful as an introduction to another aspect of the world circulation of water.

The amount of water vapor is not the same everywhere, either geographically or seasonally. It is greatest at and near the Equator. If the air there were squeezed dry, it would yield about 44 millimeters of rainfall. In middle latitudes, say from 40 to 50 degrees, the summer yield would be near 20 millimeters and the winter yield near 10 millimeters, with large variations that depend on geography and weather patterns. In the polar regions the yield ranges from two millimeters in winter to as much as eight in summer.

Water vapor enters the atmosphere by evaporation (this term includes transpiration by vegetation), and the main oceanic sources are fairly identifiable. It leaves the atmosphere as rain or snow, and because the precipitation may take place close to the source or thousands of miles away, the residence time may vary from a few hours to a few weeks. A general average is nine or 10 days.

The general balance of evaporation and precipitation needs three sets of figures, one set for the entire earth, one for the oceans and one for the land surface.



WATER CYCLE in the biosphere requires that worldwide evaporation and precipitation be equal; hydrogen losses to space are presumably replaced by juvenile water. Ocean evaporation, however, is greater than return precipitation; the reverse is true of the land. Excess land precipitation may end up in ice caps and glaciers that contain 75 percent of all fresh water, may replenish supplies taken from the water table by transpiring plants or may enter lakes and rivers, eventually returning to the sea as runoff. Numbers show minimum estimates of the amount of water present in each reserve, expressed as a depth in meters per unit area of the earth's surface.

Here, within a few percent, there is almost complete agreement on values. For the entire earth, average evaporation and precipitation are equal—as they must be—at very nearly 100 centimeters per year. For the oceans, expressed as equivalent depths over the area of the oceans, the average annual precipitation is between 107 and 114 centimeters, the average annual evaporation is between 116 and 124 centimeters and balance is restored by river flow, with an annual value close to 10 centimeters in all estimates. For the land surface the average annual precipitation is near 71 centimeters, the average annual evaporation is near 47 centimeters and the average annual river discharge is near 24 centimeters. (The ocean figure of 10 centimeters corresponds to the 24-centimeter land figure.)

Because half of the land surface—ice caps, deserts, mountains, tundra—contributes little or nothing to evaporation, a better evaporation average would take into consideration only the land component of the biosphere where the availability of water is combined with the opportunity for evaporation. Here the average evaporation may total 100 centimeters per year. The evaporation in high latitudes would of course be far less than the evaporation nearer the Equator.

Available measurements support this conclusion. In Finland, at 65 degrees north latitude, the average evaporation is 20 centimeters per year; in southeastern England, at 50 degrees north, it is 50; in North Carolina, at 35 degrees north, it ranges from 80 to 120. On the Equator in the Congo basin the average is 120 centimeters per year; at the same latitude in Kenya it is 150. In the papyrus swamps of the Nile in the southern Sudan, 10 degrees north of the Equator, the average is 240 centimeters per year, but this is a special case. Here the river carries its water into the desert environment of the Sudd; evaporation rates are high not only because of the clear skies and intense sunshine overhead but also because the surrounding desert is a source of hot dry air that augments evaporation. This kind of advective augmentation operates in many places other than the Sudan, particularly in semiarid regions where irrigation is practiced, and not quite enough is known about it.

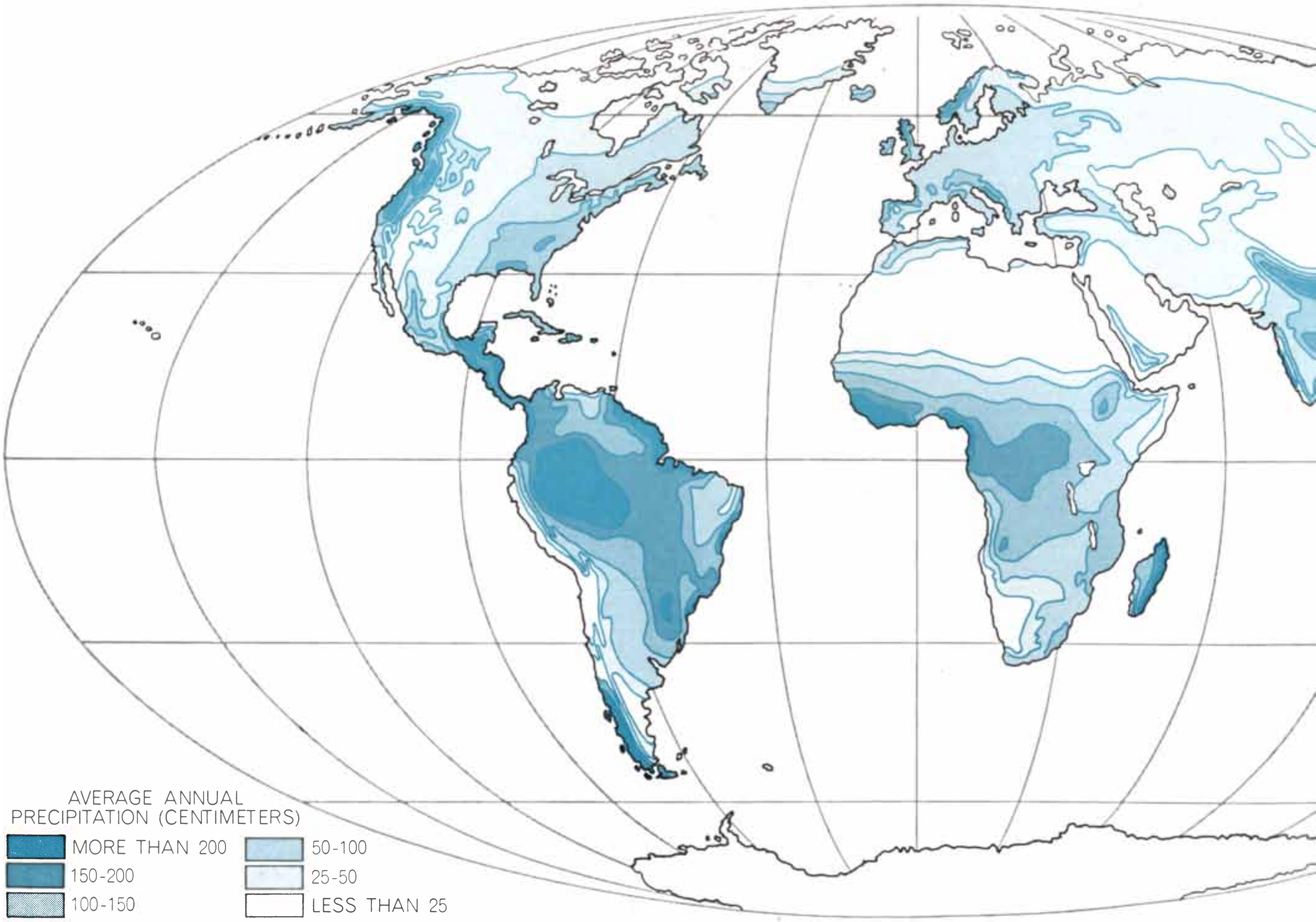
Once in the air, water vapor may circulate locally or become part of the general circulation of the atmosphere. The general circulation is one of the three important ways of moving water across the earth. Some indication of the worldwide volumes involved is given by the fact that the total annual precipitation over the U.S. comes to some 6,000 cubic kilometers, whereas the liquid equivalent of the water vapor that passes over the U.S. in a year owing to the general circulation of the atmosphere is 10 times that amount.

Of the two remaining important ways of moving water across the earth, the major ocean currents comprise one and the discharge of rivers comprises the other. Both have substantial effects on the biosphere. The ocean currents carry energy surpluses or deficits over great distances; one well-known instance accounts for the extreme contrast between the climates on the west and east sides of the Atlantic in the areas between 50 and 55 degrees north latitude. Without the Gulf Stream northwestern Europe would be a much less pleasant place in which to live and work; indeed, if the cold Labrador Current had replaced the Gulf Stream, the history of civilization would have been very different.

The rivers of the world not only are long-distance movers of water but also serve as conduits for dissolved and suspended material. Because of its chemical and physical properties, water is a very efficient erosive agent; erosion, transport and deposition have to be recognized as geological processes associated with water in the biosphere. They are the processes that have produced lands and soils, now densely populated and intensively cropped, where annual floods and silt deposition are regarded as the mainstay of life. Elsewhere, notably in the Americas, silt is an embarrassment in the deltas where it settles, and its production is equally unwelcome in river headwaters.

Two further points about river water deserve mention. First, the salt content of river water differs markedly in composition from that of the oceans. This suggests that the oceanic brine is not merely the accumulation of salts from aeons of land-surface leaching. Second, information about river discharge rates is scanty and not always reliable. As an example, it is only recently that a good estimate of the flow of the Amazon has been obtained. It proved to be twice the best previous estimate and indicates that almost a fifth of the world's river discharge comes from this one stream.

It is not possible to do more than guess at the average amount of water the world's plant and animal populations contain. Considered as the equivalent of rainfall, it may amount to about one millimeter over the entire surface of the earth. This is less by one order of magnitude than the amount of water vapor in the atmosphere, and its distribution is even more varied in space and time. For a fully grown good crop of corn in North America or of sugar beet in northwestern Europe the amount might come to the equivalent of five millimeters of rainfall, and its summer residence time would be two to three days. This is a measure of the rate of water supply needed to maintain optimum conditions for growth. Here, at the point of water uptake by the roots of plants, begins the problem



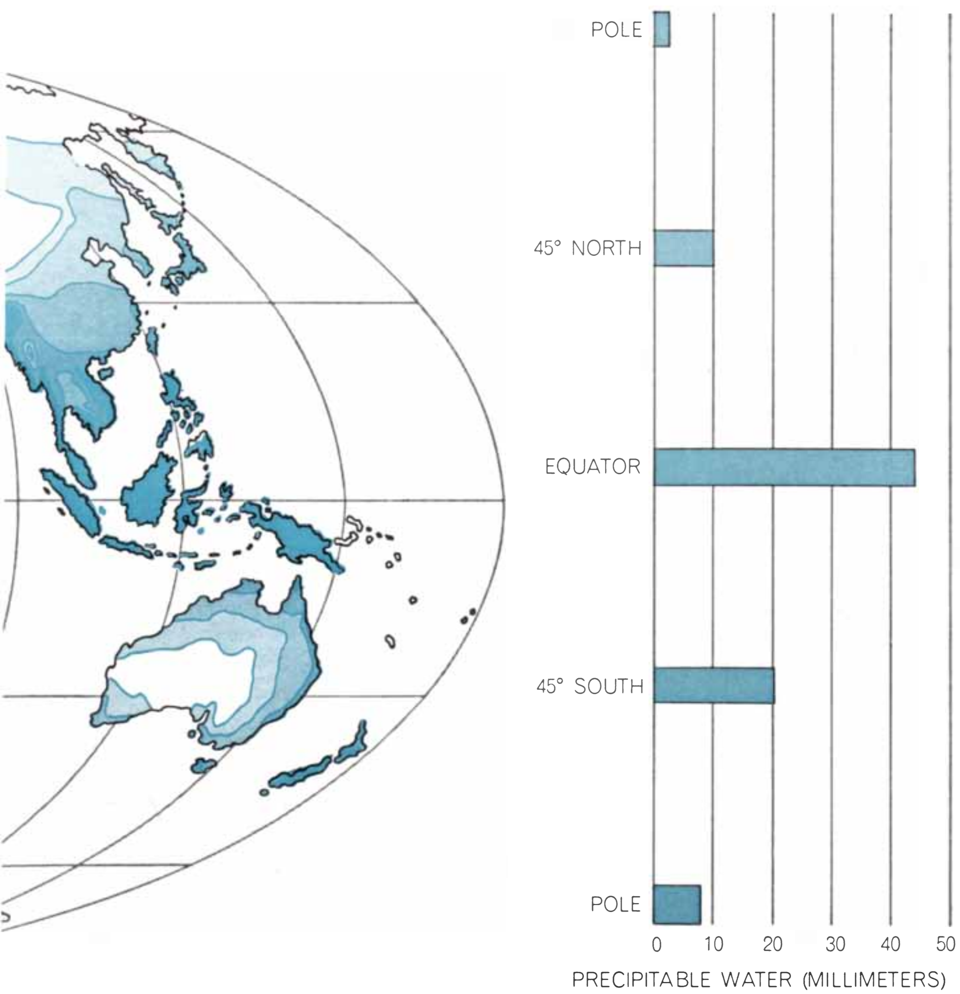
PRECIPITATION reaches the land areas of the world principally in the form of rainfall, which is heaviest at and near the Equator and along some western coasts at higher latitudes (*darker colors*). Variations in precipitation are the result of atmospheric circulawith respect to water in the biosphere that makes all other water problems seem trifling.

With unimportant exceptions, the basis of all life on the earth is photosynthesis by green plants, a process that involves physics (in the fixation of solar energy) and chemistry (in the union of carbon dioxide and water to form carbohydrates and more complex biochemical compounds). Water comes into the story in two ways: in transit (as part of the transpiration stream) and in residence (as its hydrogen is chemically bound into the plant structure). The amount that is bound, however, may be less than a fifth of the amount in transit. To give scale to the argument that follows, here are some values based on a real crop in a real climate. In producing 20 fresh-weight tons of crop, 2,000 tons of water will pass into the plants at their roots. At harvest perhaps 15 tons of the water supply will be in transit, leaving the crop with a dry weight of five tons. To produce the five tons of dry matter three tons of water will have been fixed and transformed. The energy fixed in the dry matter will be 1 percent or less of the total solar energy received by the crop; nearly 40 percent of the energy will have been used to evaporate the transpired water. Here is a clear interaction of the kind envisioned in the article that introduces this issue of *Scientific American*, where G. Evelyn Hutchinson describes the biosphere as "a region in which liquid water can exist [and that] receives an ample supply of energy from an external source."

The average value of 40 percent for the net solar radiation income retained by a green crop cover varies, of course, with season and climate. The first loss is to reflectivity: of the solar radiation reaching the crop about 30 percent is reflected. There is also an income of long-wave radiation from the sky, but this is outweighed by the outgo of long-wave radiation from the earth to the atmosphere. When the deficit is met by deducting it from the remaining balance of short-wave solar income, the net retained income is decreased to 40 percent of the initial input. As already noted, when the water is available, very nearly all this energy is used in evaporating water.

Here once again water stands at the extreme of a range of physical properties. The volume of water evaporated per unit of energy input is less than it would be for any other liquid. The relevant physical constant, the latent heat of vaporization, is somewhat less than 600 calories per gram at ordinary temperatures, but the rounded figure is adequate for the present purpose. If we let R_{I} represent the total radiant income in calories per square centimeter over a period of time, then the net radiation is about $.4R_{\mathrm{I}}$ and the evaporation equivalent is near $R_{\mathrm{I}}/1{,}500$ grams per square centimeter (or centimeters of water depth as the equivalent of rainfall). Consider some real midsummer values to show what this means. In a humid temperate climate the value of R_{I} is close to 450 calories per square centimeter per day. This works out to an evaporation equivalent of three millimeters per day, which is a good estimate for June in southeastern England. For many of the farming areas of the U.S. the R_{I} value is close to 650 calories per square centimeter, bringing the evaporation rate up to about 4.5 millimeters per day. The maximum rates known, which are found in irrigated areas, range from 4.5 to 7.5 millimeters per day. It is possible that the higher rates are influenced by advection from surrounding nonirrigated areas, as is the case in the papyrus swamps of the Nile.

The most important fact to be considered in connection with this wide range of evaporation rates is that there are only very small variations among the evaporation rates of different kinds of plants. Thus the governing factor in variation is almost exclusively a climatic one. This fact and much other evidence suggest that the supposed water "need" of a crop is dictated not by the plants but by the weather. In this connection the concept of "potential transpiration," which came into use simultaneously and independently in at least two parts of the world, is of great value both in research and in the practical aspects of soil water management. It is worthwhile seeing how potential transpiration is linked with elementary plant physiology and with some of the physics of soil water already considered.

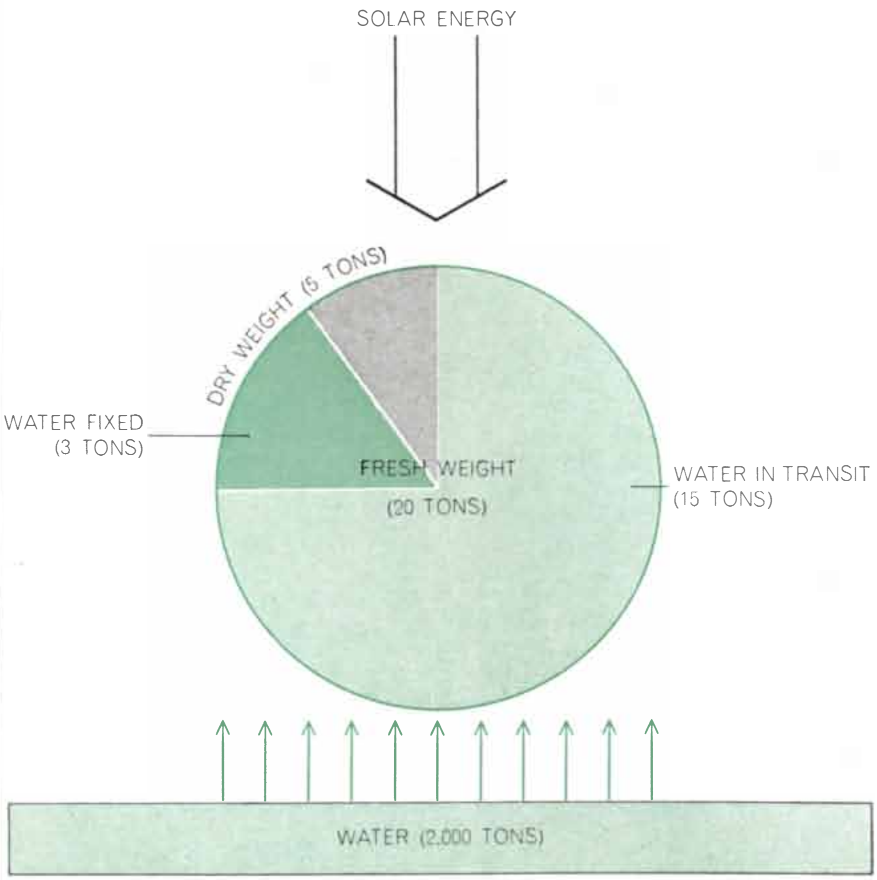


tion patterns and also reflect the amount of precipitable water vapor present. This is greatest at the Equator, least at the poles and more in summer than in winter (*graph at right*).

A growing plant takes in water at the roots and, in the absence of immediate replenishment, the process dries the soil so that more and more energy is required for further extraction. The energy requirement is very small, however, compared with the amount of energy needed to evaporate the same quantity of water from the plant's leaves. There can be no serious error in assuming, as Frank J. Veihmeyer of the University of California at Davis does, that all soil water is equally available for transpiration up to the stage marked by the onset of wilting. The purpose of well-managed irrigation, of course, is to make sure that plants never get to the wilting stage. For maximum growth irrigation may have to consist of frequent small applications of water rather than occasional large ones.

Given an adequate supply of water, the chain of consequences is simple. There are maximum values for each of several factors: water content in the plant, hydrostatic pressure in the plant and leaf turgidity. When neither the intensity of the light nor the concentration of carbon dioxide constitutes a limiting factor, maximum leaf turgidity permits maximum opening of the stomatal apertures in the leaf surface, thus affording the best possible opportunity for movement of carbon dioxide into the leaf. The state of the stomatal opening that allows easy inflow of carbon dioxide, however, also allows equally easy outflow of water vapor. By far the greater part of the water need of plants is actually a "leakage" process that has to be kept going to ensure continued growth. Given a sufficiently wet soil around the plants' roots, the rate of leakage is dictated not by plant physiology but by the physical factors of temperature, humidity and ventilation. The sole constraint is imposed by the law of energy conservation. In its last stages the transpiration stream undergoes a change of state from liquid to vapor, and the rate of change depends on the rate at which energy can reach the system to supply the necessary latent heat of vaporization.

So much for the physics of the process. When the supply of water in the soil approaches exhaustion, plant physiology rather than physics begins to predominate. Plant type, root structure, phase of



ROLE OF WATER in photosynthesis is quantitatively minor compared with its role in transpiration, as this crop-water graph indicates. To produce 20 fresh-weight tons of crop in a season, some 2,000 tons of water will be drawn from the soil. At the harvest, water in transit will account for some 15 tons of the crop's fresh weight. Drying reduces the crop's weight to five tons. Of these, three tons, or .15 percent of the water used in the season, comprise hydrogen atoms from water molecules, photosynthetically bound to carbon atoms.

plant development, soil type, soil depth—these become the important factors. What is available for utilization has more significance than the weather has, particularly in semiarid zones.

Because agriculture is most active in the more humid zones of the biosphere, it is useful to estimate how much reserve soil water is available on the average in these zones. Factors already described prevent any exact answer to this question. Nonetheless, a cautious estimate, advanced with considerable reservation, would be about 10 centimeters of rainfall equivalent. Three examples will suffice to show the need for caution. There are large agricultural areas of North Carolina and neighboring states where an inert subsoil is covered by no more than 20 centimeters of useful topsoil. Here the entire water reserve available to the agricultural cycle cannot exceed a rainfall equivalent of five centimeters. This is one extreme; the deep volcanic soils of East Africa are at the other. In those soils the roots of many plants go down as much as six meters below the surface. The available water in a profile that deep is equivalent to nearly 50 centimeters of rain, and the plant can extract water throughout a long dry season at something very close to the potential transpiration rate. An example from France falls somewhere in between. There the drying of the soil was observed while a crop of sugar beet transpired at the full potential rate throughout a dry summer. At the driest stage the crop had withdrawn from the soil available water equivalent to 27 centimeters of rainfall.

Soil water and ground water are closely related, but whereas soil water is always biologically important, the importance of ground water may range from being trivial to being all that matters. The soil is a kind of buffer between rainfall and ground water. In general any deficit in soil moisture that has built up in a dry period must be completely restored by rain before there is any water surplus available to move down to ground water. This is an important consideration for the water engineer, who may be drawing a water supply from a stream (permanent streams are sustained by ground water) or may be tapping an aquifer directly by means of a well. In the first instance the engineer will presumably have to work within legal constraints on how much river water he can divert. In the second, if he is to choose a safe aquifer pumping rate, the engineer must (or should!) have some awareness of the current soil-moisture deficit

and of the likely rates of rainfall in the months ahead. The river engineer can use the same information for another purpose: the soil-moisture deficit will enable him to estimate the risk of flooding in the event of a heavy storm.

In some countries the control of ground water is a major outlet for engineering skill, and its exploitation is the basis of farming technique. One need only think on the one hand of the Netherlands and on the other of such semiarid regions as Iran, where deep tunnels tap the buried aquifers and carry ground water to valley bottoms. In many semiarid regions the vegetation along transient streams maintains its luxuriance because the ground-water level there is close to the surface and within reach of plant roots. The plants' effective reach depends both on the soil and on the kind of plant, but in general it is seldom more than a few meters. The movement of any water table deeper than that is unaffected by the plant growth or the evaporation processes taking place above it, and its ground water contributes nothing to the biological activity at the surface.

What has been said about water so far has involved terms that are generally accepted, and the concepts themselves are supported by good reasoning, good evidence or both. The remarks that follow, although also based on reasoning and evidence, are more speculative and personal. If the biosphere is taken to be the place where water and energy interact, can the interaction be expressed quantitatively in terms of biological productivity? The answer has to be no. There are too many variables. All the same, by rearranging some of the water quantities and energy quantities that are known, a suggestive relation can be obtained.

Start with the fact that, for a good crop, 1 percent or less of the incoming solar radiation is fixed as dry matter (here and in what follows the 1 percent refers to the total botanical yield, irrespective of economic value). We shall give this percentage the symbol ε, and express it numerically as 100 per 10,000. This degree of efficiency is achieved only by an experiment station or by an extremely competent commercial farmer. Based on the statistics of world cereal production, including straw as well as grain, the average achievement in highly mechanized industrial farming shows an efficiency of only about 35 per 10,000. This decreases to roughly 17 per 10,000 in North America, and in tropical Africa and Asia subsistence farming rarely shows an efficiency better than 8, even when the possibility of two crops per year is allowed for. There is obviously room for improvement everywhere and the question in the present context is: Where does water come in, and how?

Some evidence is now being accumulated suggesting that, when there are no limitations on water supply, the total crop growth is proportional to the total of potential transpiration over the period of growth. The factor of proportionality depends on many things: plant variety, management, kinds and quantities of fertilizer, pest and disease controls and the like. Hence the negative answer to the earlier question. Still, something can be done with ratios. There is reason to believe potential transpiration is a fairly constant fraction of the solar radiation income. Combining this fact with the relation between potential transpiration and total crop growth, it is possible to derive a connection between growth rate and utilization of water, assuming that unlimited water is available (by inference, there would be a similar response to timely irrigation). In what may seem too precise a form, the answer is that the increase in yield (t) equals $.39\varepsilon$. Here ε represents efficiency and t can be read, according to preference, as metric tons per hectare per centimeter of water applied or as tons per acre per inch of water. Considering the fivefold (or perhaps tenfold) world variation in efficiency, some uncertainty in the multiplying factor is unimportant; others may prefer, or find, a different value. Taking the illustration already given, suppose the area involved is one acre and the efficiency is exactly or almost 100 per 10,000. The predicted increase in yield in response to water, *applied when it is needed,* is .39 ton of dry matter per acre per inch of water. In terms of fresh weight the gain is about 1.5 tons per acre per inch. This is the kind of response obtained in experiments with irrigated potatoes in Britain.

There are some countries where the value of ε is small because of lack of water, but there are many, including several of the rice-growing nations, where the small value of ε is more truly a measure of the inefficiency of the farming system itself. To get the most out of water, whether it comes from irrigation or from rainfall, the standard of performance elsewhere in the system must be improved: better varieties, better soil management, better crop husbandry, better plant hygiene and better pest control. Then water may be the driver of nature in agriculture as well as in the atmosphere.

Problem: lubricate a submarine 3 miles under the sea.

The submarine: *Aluminaut*, Reynolds' $3,000,000 craft designed to plumb the ocean as deep as 15,000 feet.

The solution: Texaco.

The overall problem for the technical team was high pressures and low temperatures outside the hull.

Both tend to increase lubricant resistance at great sea depths.

In other words, they tend to thicken things up.

Our technologists had already developed lubricants that would remain fluid at high pressures, and yet not be too thin for surface use.

And after months of testing they proved out one for lubricating the *Aluminaut's* controls.

They also came up with a hydraulic oil for the sub's external dual manipulators (arms) which will perform as well at 15,000 feet down as it has in aircraft 30,000 feet up.

But a submarine without a smooth-closing, tight hatch is about as useful as a parachute made from lace doilies.

So Texaco also came up with a multi-purpose grease for sealing the hatches at great depths.

Quite a job.

But supplying lubricants for undersea experiments (or for any other purpose) is nothing new for Texaco.

Texaco products worked aboard Sir Hubert Wilkins' submarine *Nautilus*—the first to dive under the Arctic ice cap.

Sir Hubert, recalling his historic journey in 1931, commented: "The heart of any submarine is its engine; the life blood is its fuel and lubricants."

He wanted to have an adequate supply of "good red corpuscles" and said that he was given "frequent infusions, delivered with efficient promptness and courtesy unexceeded."

The source was, as we said, Texaco.

THE OXYGEN CYCLE

The oxygen in the atmosphere was originally put there by plants. Hence the early plants made possible the evolution of the higher plants and animals that require free oxygen for their metabolism

by Preston Cloud and Aharon Gibor

The history of our planet, as recorded in its rocks and fossils, is reflected in the composition and the biochemical peculiarities of its present biosphere. With a little imagination one can reconstruct from that evidence the appearance and subsequent evolution of gaseous oxygen in the earth's air and water, and the changing pathways of oxygen in the metabolism of living things.

Differentiated multicellular life (consisting of tissues and organs) evolved only after free oxygen appeared in the atmosphere. The cells of animals that are truly multicellular in this sense, the Metazoa, obtain their energy by breaking down fuel (produced originally by photosynthesis) in the presence of oxygen in the process called respiration. The evolution of advanced forms of animal life would probably not have been possible without the high levels of energy release that are characteristic of oxidative metabolism. At the same time free oxygen is potentially destructive to all forms of carbon-based life (and we know no other kind of life). Most organisms have therefore had to "learn" to conduct their oxidations anaerobically, primarily by removing hydrogen from foodstuff rather than by adding oxygen. Indeed, the anaerobic process called fermentation is still the fundamental way of life, underlying other forms of metabolism.

Oxygen in the free state thus plays a role in the evolution and present functioning of the biosphere that is both pervasive and ambivalent. The origin of life and its subsequent evolution was contingent on the development of systems that shielded it from, or provided chemical defenses against, ordinary molecular oxygen (O_2), ozone (O_3) and atomic oxygen (O). Yet the energy requirements of higher life forms can be met only by oxidative metabolism. The oxidation of the simple sugar glucose, for example, yields 686 kilocalories per mole; the fermentation of glucose yields only 50 kilocalories per mole.

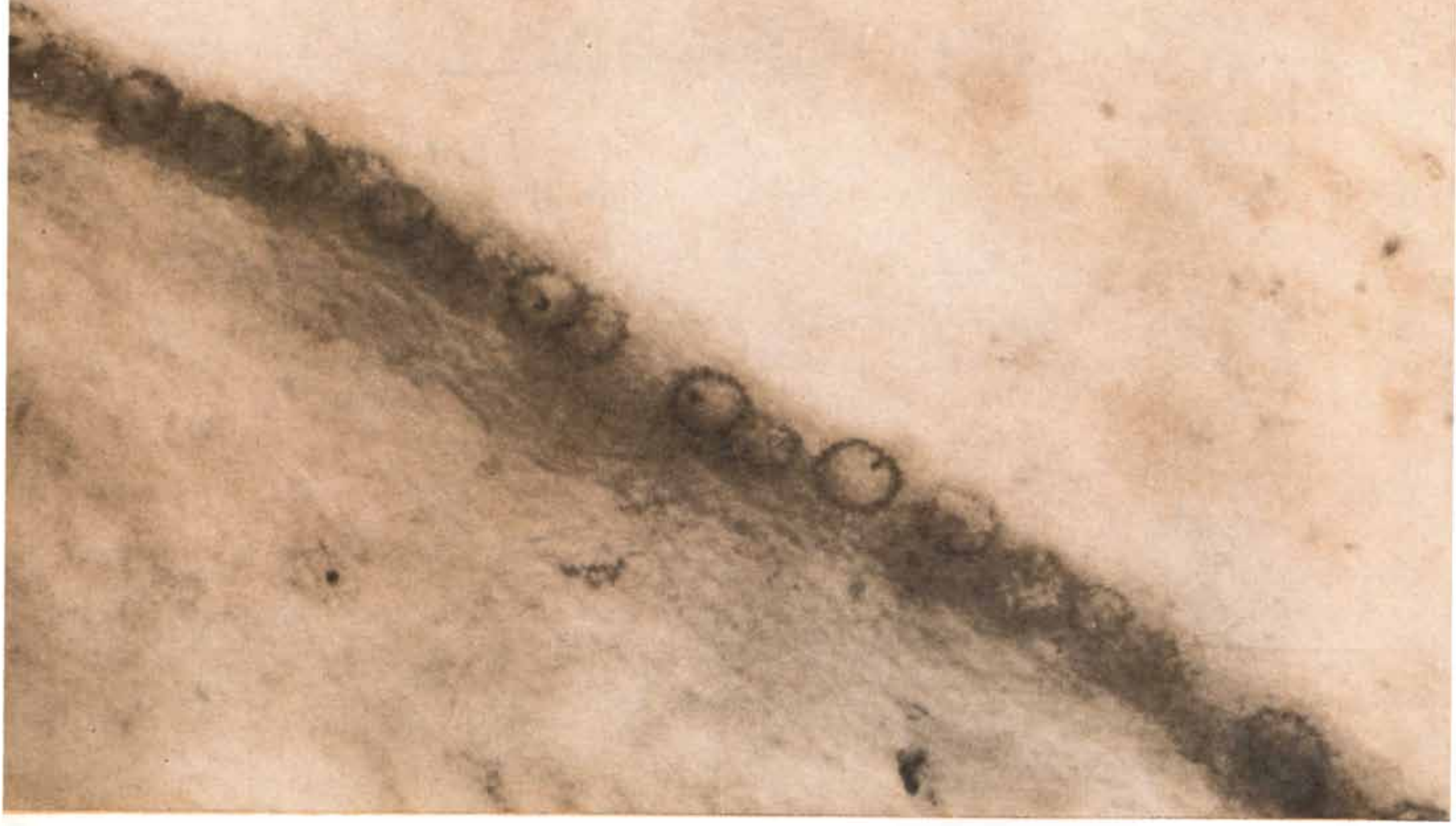
Free oxygen not only supports life; it arises from life. The oxygen now in the atmosphere is probably mainly, if not wholly, of biological origin. Some of it is converted to ozone, causing certain high-energy wavelengths to be filtered out of the radiation that reaches the surface of the earth. Oxygen also combines with a wide range of other elements in the earth's crust. The result of these and other processes is an intimate evolutionary interaction among the biosphere, the atmosphere, the hydrosphere and the lithosphere.

Consider where the oxygen comes from to support the high rates of energy release observed in multicellular organisms and what happens to it and to the carbon dioxide that is respired [*see illustration on page 114*]. The oxygen, of course, comes from the air, of which it constitutes roughly 21 percent. Ultimately, however, it originates with the decomposition of water molecules by light energy in photosynthesis. The 1.5 billion cubic kilometers of water on the earth are split by photosynthesis and reconstituted by respiration once every two million years or so. Photosynthetically generated oxygen temporarily enters the atmospheric bank, whence it is itself recycled once every 2,000 years or so (at current rates). The carbon dioxide that is respired joins the small amount (.03 percent) already in the atmosphere, which is in balance with the carbon dioxide in the oceans and other parts of the hydrosphere. Through other interactions it may be removed from circulation as a part of the carbonate ion (CO_3^-) in calcium carbonate precipitated from solution. Carbon dioxide thus sequestered may eventually be returned to the atmosphere when limestone, formed by the consolidation of calcium carbonate sediments, emerges from under the sea and is dissolved by some future rainfall.

Thus do sea, air, rock and life interact and exchange components. Before taking up these interactions in somewhat greater detail let us examine the function oxygen serves within individual organisms.

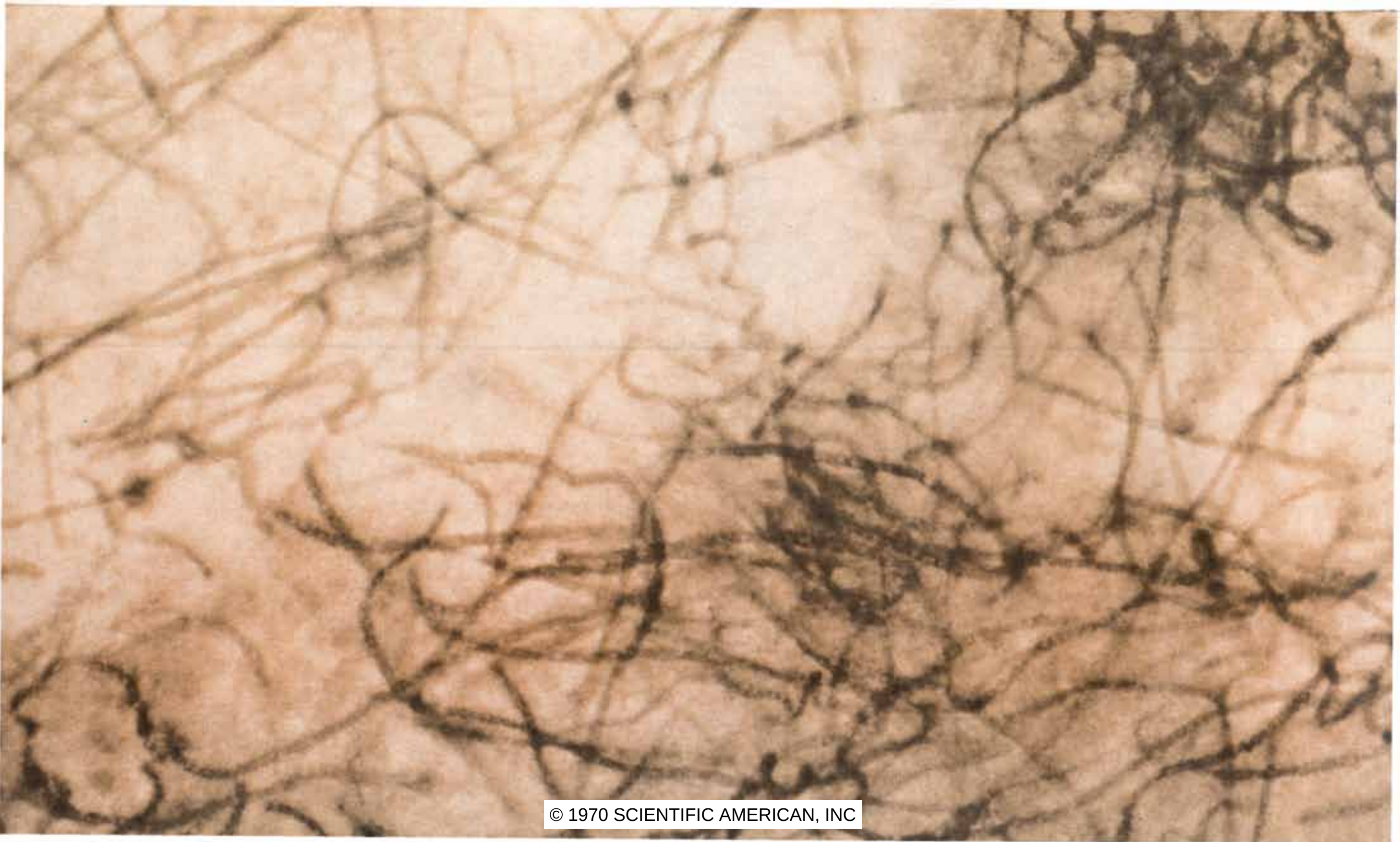
Oxygen plays a fundamental role as a building block of practically all vital molecules, accounting for about a fourth of the atoms in living matter. Practically all organic matter in the present biosphere originates in the process of photosynthesis, whereby plants utilize light energy to react carbon dioxide with water and synthesize organic substances. Since carbohydrates (such as sugar), with the general formula $(CH_2O)_n$, are the common fuels that are stored by plants, the essential reaction of photosynthesis can be written as $CO_2 + H_2O +$ light energy $\rightarrow CH_2O + O_2$. It is not immediately obvious from this formulation which of the reactants serves as the source of oxygen atoms in the carbohydrates and which is the source of free molecular oxygen. In 1941 Samuel Ruben and Mar-

RED BEDS rich in the oxidized (ferric) form of iron mark the advent of oxygen in the atmosphere. The earliest continental red beds are less than two billion years old; the red sandstones and shales of the Nankoweap Formation in the Grand Canyon (*opposite page*) are about 1.3 billion years old. The appearance of oxygen in the atmosphere, the result of photosynthesis, led in time to the evolution of cells that could survive its toxic effects and eventually to cells that could capitalize on the high energy levels of oxidative metabolism.



EUCARYOTIC CELLS, which contain a nucleus and divide by mitosis, were, like oxygen, a necessary precondition for the evolution of higher life forms. The oldest eucaryotes known were found in the Beck Spring Dolomite of eastern California by Cloud and his colleagues. The photomicrograph above shows eucaryotic cells with an average diameter of 14 microns, probably green algae. The regular occurrence and position of the dark spots suggest they may be remnants of nuclei or other organelles. Other cell forms, which do not appear in the picture, show branching and large filament diameters that also indicate the eucaryotic level of evolution.

PROCARYOTIC CELLS, which lack a nucleus and divide by simple fission, were a more primitive form of life than the eucaryotes and persist today in the bacteria and blue-green algae. Procaryotes were found in the Beck Spring Dolomite in association with the primitive eucaryotes such as those in the photograph at the top of the page. A mat of threadlike procaryotic blue-green algae, each thread of which is about 3.5 microns in diameter, is seen in the photomicrograph below. It was made, like the one at top of page, by Gerald R. Licari. Cells of this kind, among others, presumably produced photosynthetic oxygen before eucaryotes appeared.



tin D. Kamen of the University of California at Berkeley used the heavy oxygen isotope oxygen 18 as a tracer to demonstrate that the molecular oxygen is derived from the splitting of the water molecule. This observation also suggested that carbon dioxide is the source of the oxygen atoms of the synthesized organic molecules.

The primary products of photosynthesis undergo a vast number of chemical transformations in plant cells and subsequently in the cells of the animals that feed on plants. During these processes changes of course take place in the atomic composition and energy content of the organic molecules. Such transformations can result in carbon compounds that are either more "reduced" or more "oxidized" than carbohydrates. The oxidation-reduction reactions between these compounds are the essence of biological energy supply and demand. A more reduced compound has more hydrogen atoms and fewer oxygen atoms per carbon atom; a more oxidized compound has fewer hydrogen atoms and more oxygen atoms per carbon atom. The combustion of a reduced compound liberates more energy than the combustion of a more oxidized one. An example of a molecule more reduced than a carbohydrate is the familiar alcohol ethanol (C_2H_6O); a more oxidized molecule is pyruvic acid ($C_3H_4O_3$).

Differences in the relative abundance of hydrogen and oxygen atoms in organic molecules result primarily from one of the following reactions: (1) the removal (dehydrogenation) or addition (hydrogenation) of hydrogen atoms, (2) the addition of water (hydration), followed by dehydrogenation; (3) the direct addition of oxygen (oxygenation). The second and third of these processes introduce into organic matter additional oxygen atoms either from water or from molecular oxygen. On decomposition the oxygen atoms of organic molecules are released as carbon dioxide and water. The biological oxidation of molecules such as carbohydrates can be written as the reverse of photosynthesis: $CH_2O + O_2 \rightarrow CO_2 + H_2O +$ energy. The oxygen atom of the organic molecule appears in the carbon dioxide and the molecular oxygen acts as the acceptor for the hydrogen atoms.

The three major nonliving sources of oxygen atoms are therefore carbon dioxide, water and molecular oxygen, and since these molecules exchange oxygen atoms, they can be considered as a common pool. Common mineral oxides such as nitrate ions and sulfate ions are also oxygen sources for living organisms, which reduce them to ammonia (NH_3) and hydrogen sulfide (H_2S). They are subsequently reoxidized, and so as the oxides circulate through the biosphere their oxygen atoms are exchanged with water.

The dynamic role of molecular oxygen is as an electron sink, or hydrogen acceptor, in biological oxidations. The biological oxidation of organic molecules proceeds primarily by dehydrogenation: enzymes remove hydrogen atoms from the substrate molecule and transfer them to specialized molecules that function as hydrogen carriers [*see top illustration on pages 116 and 117*]. If these carriers become saturated with hydrogen, no further oxidation can take place until some other acceptor becomes available. In the anaerobic process of fermentation organic molecules serve as the hydrogen acceptor. Fermentation therefore results in the oxidation of some organic compounds and the simultaneous reduction of others, as in the fermentation of glucose by yeast: part of the sugar molecule is oxidized to carbon dioxide and other parts are reduced to ethanol.

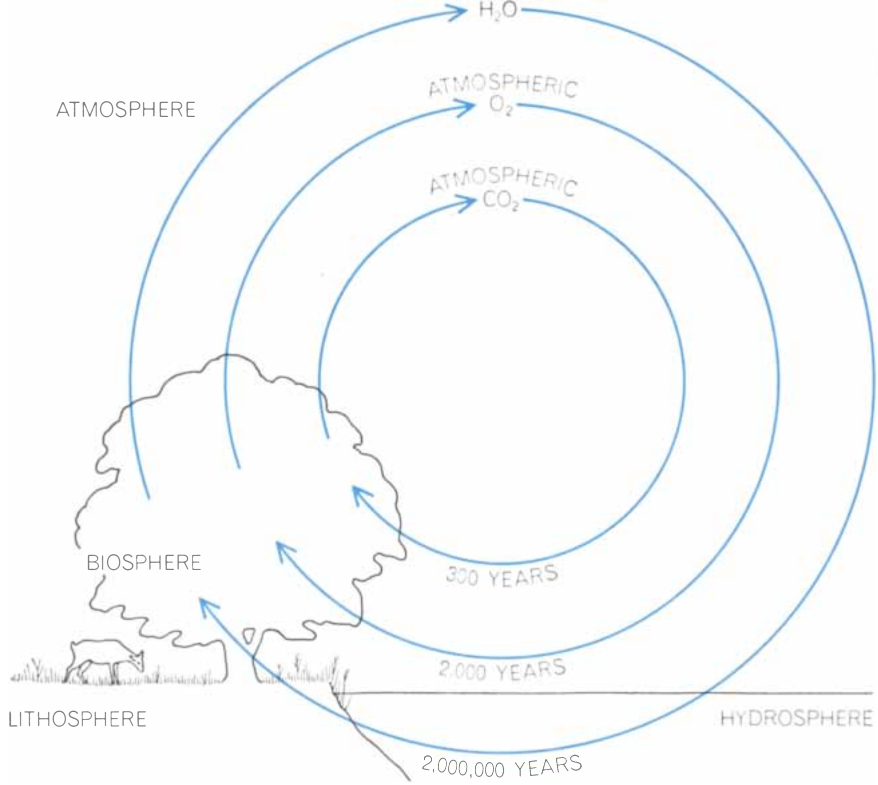
In aerobic respiration oxygen serves as the hydrogen acceptor and water is produced. The transfer of hydrogen atoms (which is to say of electrons and protons) to oxygen is channeled through an array of catalysts and cofactors. Prominent among the cofactors are the iron-containing pigmented molecules called cytochromes, of which there are several kinds that differ in their affinity for electrons. This affinity is expressed as the oxidation-reduction, or "redox," potential of the molecule; the more positive the potential, the greater the affinity of the oxidized molecule for electrons. For example, the redox potential of cytochrome *b* is .12 volt, the potential of cytochrome *c* is .22 volt and the potential of cytochrome *a* is .29 volt. The redox potential for the reduction of oxygen to water is .8 volt. The passage of electrons from one cytochrome to another down a potential gradient, from cytochrome *b* to cytochrome *c* to the cytochrome *a* complex and on to oxygen, results in the alternate reduction and oxidation of these cofactors. Energy liberated in such oxidation-reduction reactions is coupled to the synthesis of high-energy phosphate compounds such as adenosine triphosphate (ATP). The special copper-containing enzyme cytochrome oxidase mediates the ultimate transfer of electrons from the cytochrome *a* complex to oxygen. This activation and binding of oxygen is seen as the fundamental step, and possibly the original primitive step, in the evolution of oxidative metabolism.

In cells of higher organisms the oxidative system of enzymes and electron carriers is located in the special organelles called mitochondria. These organelles can be regarded as efficient low-temperature furnaces where organic molecules are burned with oxygen. Most of the released energy is converted into the high-energy bonds of ATP.

Molecular oxygen reacts spontaneously with organic compounds and other reduced substances. This reactivity explains the toxic effects of oxygen above tolerable concentrations. Louis Pasteur discovered that very sensitive organisms such as obligate anaerobes cannot tolerate oxygen concentrations above about 1 percent of the present atmospheric level. Recently the cells of higher organisms have been found to contain organelles called peroxisomes, whose major function is thought to be the protection of cells from oxygen. The peroxisomes contain enzymes that catalyze the direct reduction of oxygen molecules through the oxidation of metabolites such as amino acids and other organic acids. Hydrogen peroxide (H_2O_2) is one of the products of such oxidation. Another of the peroxisome enzymes, catalase, utilizes the hydrogen peroxide as a hydrogen acceptor in the oxidation of substrates such as ethanol or lactic acid. The rate of reduction of oxygen by the peroxisomes increases proportionately with an increase in oxygen concentration, so that an excessive amount of oxygen in the cell increases the rate of its reduction by peroxisomes.

Christian de Duve of Rockefeller University has suggested that the peroxisomes represent a primitive enzyme system that evolved to cope with oxygen when it first appeared in the atmosphere. The peroxisome enzymes enabled the first oxidatively metabolizing cells to use oxygen as a hydrogen acceptor and so reoxidize the reduced products of fermentation. In some respects this process is similar to the oxidative reactions of the mitochondria. Both make further dehydrogenation possible by liberating oxidized hydrogen carriers. The basic difference between the mitochondrial oxidation reactions and those of peroxisomes is that in peroxisomes the steps of oxidation are not coupled to the synthesis of ATP. The energy released in the peroxisomes is thus lost to the cell; the function of the organelle is primarily to protect against the destructive effects of free molecular oxygen.

Oxygen dissolved in water can diffuse



BIOSPHERE EXCHANGES water vapor, oxygen and carbon dioxide with the atmosphere and hydrosphere in a continuing cycle, shown here in simplified form. All the earth's water is split by plant cells and reconstituted by animal and plant cells about every two million years. Oxygen generated in the process enters the atmosphere and is recycled in about 2,000 years. Carbon dioxide respired by animal and plant cells enters the atmosphere and is fixed again by plant cells after an average atmospheric residence time of about 300 years.

across both the inner and the outer membranes of the cell, and the supply of oxygen by diffusion is adequate for single cells and for organisms consisting of small colonies of cells. Differentiated multicellular organisms, however, require more efficient modes of supplying oxygen to tissues and organs. Since all higher organisms depend primarily on mitochondrial aerobic oxidation to generate the energy that maintains their active mode of life, they have evolved elaborate systems to ensure their tissues an adequate supply of oxygen, the gas that once was lethal (and still is, in excess). Two basic devices serve this purpose: special chemical carriers that increase the oxygen capacity of body fluids, and anatomical structures that provide relatively large surfaces for the rapid exchange of gases. The typical properties of an oxygen carrier are exemplified by those of hemoglobin and of myoglobin, or muscle hemoglobin. Hemoglobin in blood readily absorbs oxygen to near-saturation at oxygen pressures such as those found in the lung. When the blood is exposed to lower oxygen pressures as it moves from the lungs to other tissues, the hemoglobin discharges most of its bound oxygen. Myoglobin, which acts as a reservoir to meet the sharp demand for oxygen in muscle contraction, gives up its oxygen more rapidly. Such reversible bonding of oxygen in response to changes in oxygen pressure is an essential property of biochemical oxygen carriers.

Lungs and gills are examples of anatomical structures in which large wet areas of thin membranous tissue come in contact with oxygen. Body fluids are pumped over one side of these membranes and air, or water containing oxygen, over the other side. This ensures a rapid gas exchange between large volumes of body fluid and the environment.

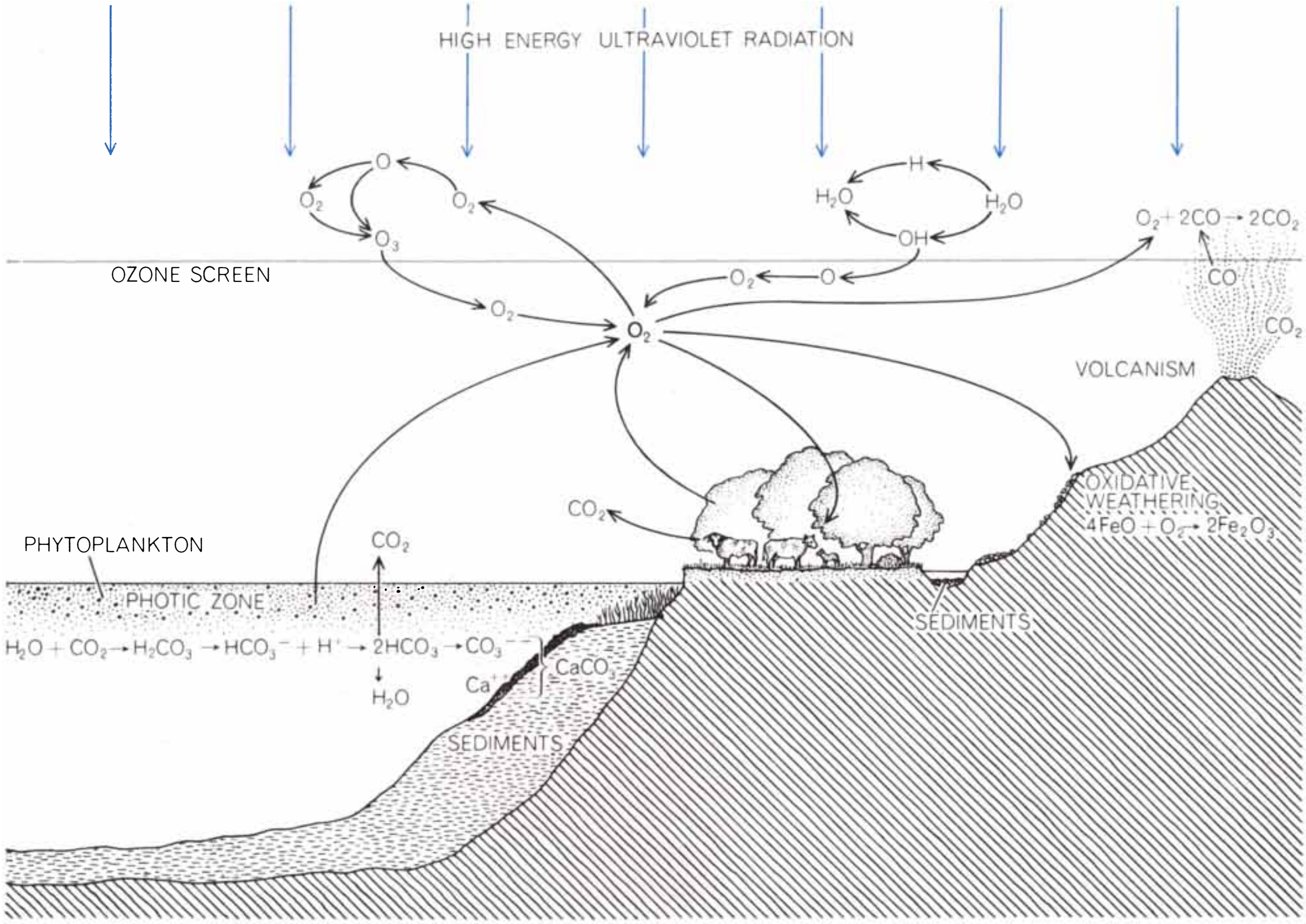
How did the relations between organisms and gaseous oxygen happen to evolve in such a curiously complicated manner? The atmosphere under which life arose on the earth was almost certainly devoid of free oxygen. The low concentration of noble gases such as neon and krypton in the terrestrial atmosphere compared with their cosmic abundance, together with other geochemical evidence, indicates that the terrestrial atmosphere had a secondary origin in volcanic outgassing from the earth's interior. Oxygen is not known among the gases so released, nor is it found as inclusions in igneous rocks. The chemistry of rocks older than about two billion years is also inconsistent with the presence of more than trivial quantities of free atmospheric oxygen before that time. Moreover, it would not have been possible for the essential chemical precursors of life—or life itself—to have originated and persisted in the presence of free oxygen before the evolution of suitable oxygen-mediating enzymes.

On such grounds we conclude that the first living organism must have depended on fermentation for its livelihood. Organic substances that originated in nonvital reactions served as substrates for these primordial fermentations. The first organism, therefore, was not only an anaerobe; it was also a heterotroph, dependent on a preexisting organic food supply and incapable of manufacturing its own food by photosynthesis or other autotrophic processes.

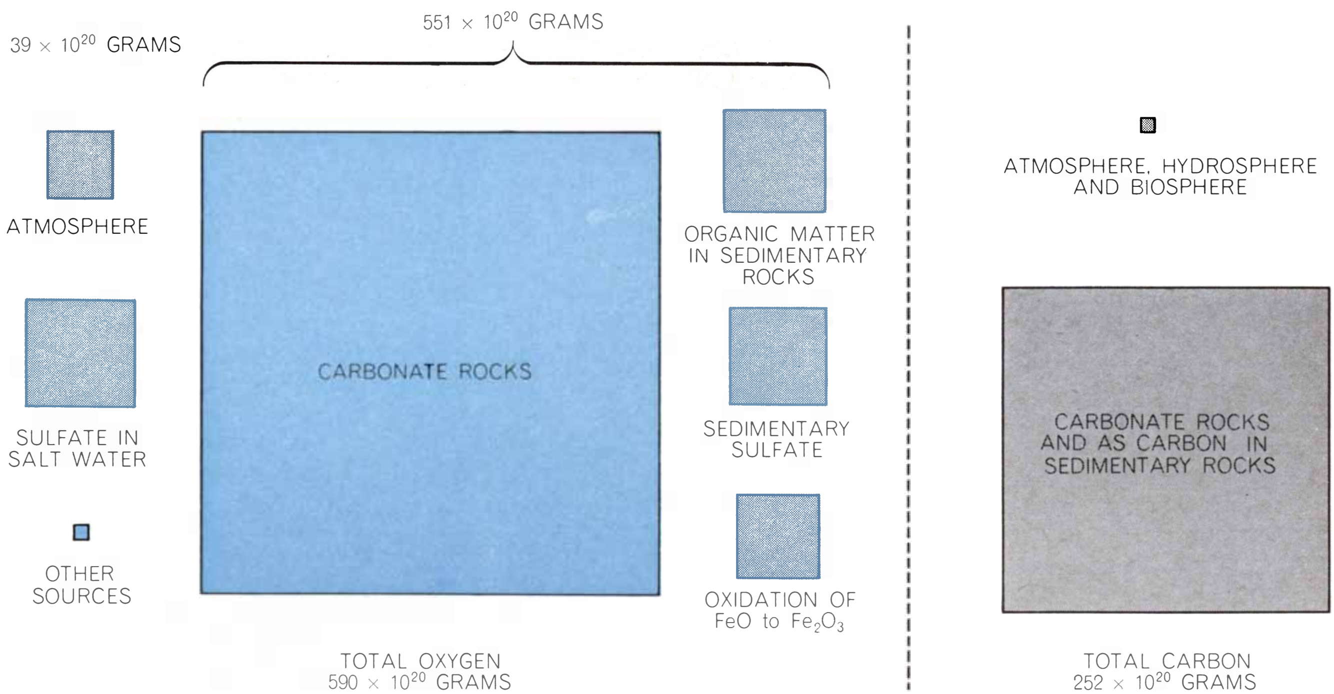
The emergence of an autotroph was an essential step in the onward march of biological evolution. This evolutionary step left its mark in the rocks as well as on all living forms. Some fated eobiont, as we may call these early life forms whose properties we can as yet only imagine, evolved and became an autotroph, an organism capable of manufacturing its own food. Biogeological evidence suggests that this critical event may have occurred more than three billion years ago.

If, as seems inescapable, the first autotrophic eobiont was also anaerobic, it would have encountered difficulty when it first learned to split water and release free oxygen. John M. Olson of the Brookhaven National Laboratory recently suggested biochemical arguments to support the idea that primitive photosynthesis may have obtained electrons from substances other than water. He argues that large-scale splitting of water and release of oxygen may have been delayed until the evolution of appropriate enzymes to detoxify this reactive substance.

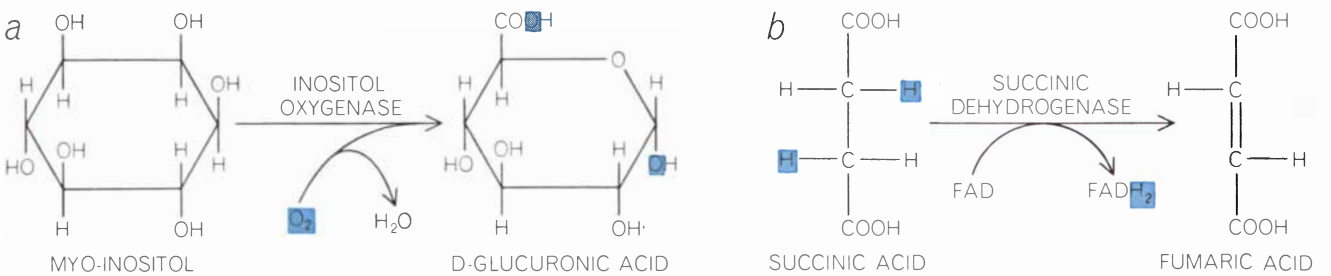
We nevertheless find a long record of oxidized marine sediments of a peculiar type that precedes the first evidence of atmospheric oxygen in rocks about 1.8 billion years old; we do not find them in significant amounts in more recent strata. These oxidized marine sediments, known as banded iron formations, are alternately iron-rich and iron-poor chemical sediments that were laid down in open bodies of water. Much of the iron in them is ferric (the oxidized form, Fe^{+++}) rather than ferrous (the reduced form, Fe^{++}), implying that there was a source of oxygen in the column of water above them. Considering the



OXYGEN CYCLE is complicated because oxygen appears in so many chemical forms and combinations, primarily as molecular oxygen (O_2), in water and in organic and inorganic compounds. Some global pathways of oxygen are shown here in simplified form.



OXYGEN-CARBON BALANCE SHEET suggests that photosynthesis can account not only for all the oxygen in the atmosphere but also for the much larger amount of "fossil" oxygen, mostly in compounds in sediments. The diagram, based on estimates made by William W. Rubey, indicates that the elements are present in about the proportion, 12/32, that would account for their derivation through photosynthesis from carbon dioxide (one atom of carbon, molecular weight 12, to two of oxygen, molecular weight 16).



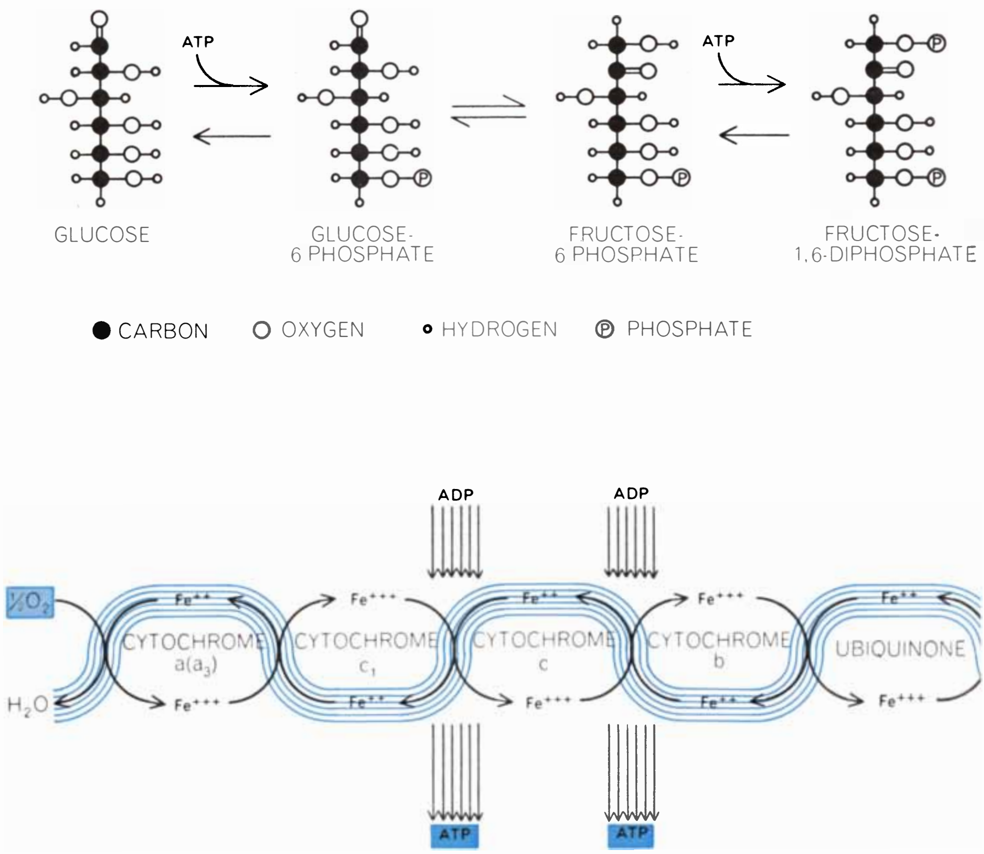
OXIDATION involves a decrease in the number of hydrogen atoms in a molecule or an increase in the number of oxygen atoms. It may be accomplished in several ways. In oxygenation (*a*) oxygen is added directly. In dehydrogenation (*b*) hydrogen is re-

problems that would face a water-splitting photosynthesizer before the evolution of advanced oxygen-mediating enzymes such as oxidases and catalases, one can visualize how the biological oxygen cycle may have interacted with ions in solution in bodies of water during that time. The first oxygen-releasing photoautotrophs may have used ferrous compounds in solution as oxygen acceptors—oxygen for them being merely a toxic waste product. This would have precipitated iron in the ferric form ($4FeO + O_2 \rightarrow 2Fe_2O_3$) or in the ferro-ferric form (Fe_3O_4). A recurrent imbalance of supply and demand might then account for the cyclic nature and differing types of the banded iron formations.

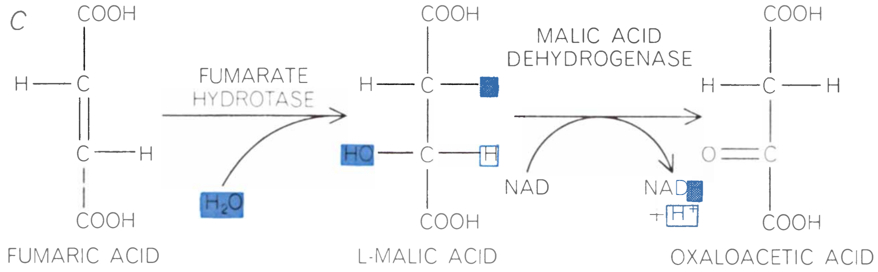
Once advanced oxygen-mediating enzymes arose, oxygen generated by increasing populations of photoautotrophs containing these enzymes would build up in the oceans and begin to escape into the atmosphere. There the ultraviolet component of the sun's radiation would dissociate some of the molecular oxygen into highly reactive atomic oxygen and also give rise to equally reactive ozone. Atmospheric oxygen and its reactive derivatives (even in small quantities) would lead to the oxidation of iron in sediments produced by the weathering of rocks, to the greatly reduced solubility of iron in surface waters (now oxygenated), to the termination of the banded iron formations as an important sedimentary type and to the extensive formation of continental red beds rich in ferric iron [*see illustration on page 110*]. The record of the rocks supports this succession of events: red beds are essentially restricted to rocks younger than about 1.8 billion years, whereas banded iron formation is found only in older rocks.

So far we have assumed that oxygen accumulated in the atmosphere as a consequence of photosynthesis by green plants. How could this happen if the entire process of photosynthesis and respiration is cyclic, representable by the reversible equation $CO_2 + H_2O + \text{energy} \rightleftharpoons CH_2O + O_2$? Except to the extent that carbon or its compounds are somehow sequestered, carbohydrates produced by photosynthesis will be reoxidized back to carbon dioxide and water, and no significant quantity of free oxygen will accumulate. The carbon that is sequestered in the earth as graphite in the oldest rocks and as coal, oil, gas and other carbonaceous compounds in the younger ones, and in the living and dead bodies of plants and animals, is the equivalent of the oxygen in oxidized sediments and in the earth's atmosphere! In attempting to strike a carbon-oxygen balance we must find enough carbon to account not only for the oxygen in the present atmosphere but also for the "fossil" oxygen that went into the conversion of ferrous oxides to ferric oxides, sulfides to sulfates, carbon monoxide to carbon dioxide and so on.

Interestingly, rough estimates made some years ago by William W. Rubey,



OXIDATIVE METABOLISM provides the energy that powers all higher forms of life. It proceeds in two phases: glycolysis (*top*), an anaerobic phase that does not require oxygen, and aerobic respiration (*bottom*), which requires oxygen. In glycolysis (or fermentation, the anaerobic process by which organisms such as yeast derive their energy) a molecule of the six-carbon sugar glucose is broken down into two molecules of the three-carbon compound pyruvic acid with a net gain of two molecules of adenosine triphosphate, the cellular

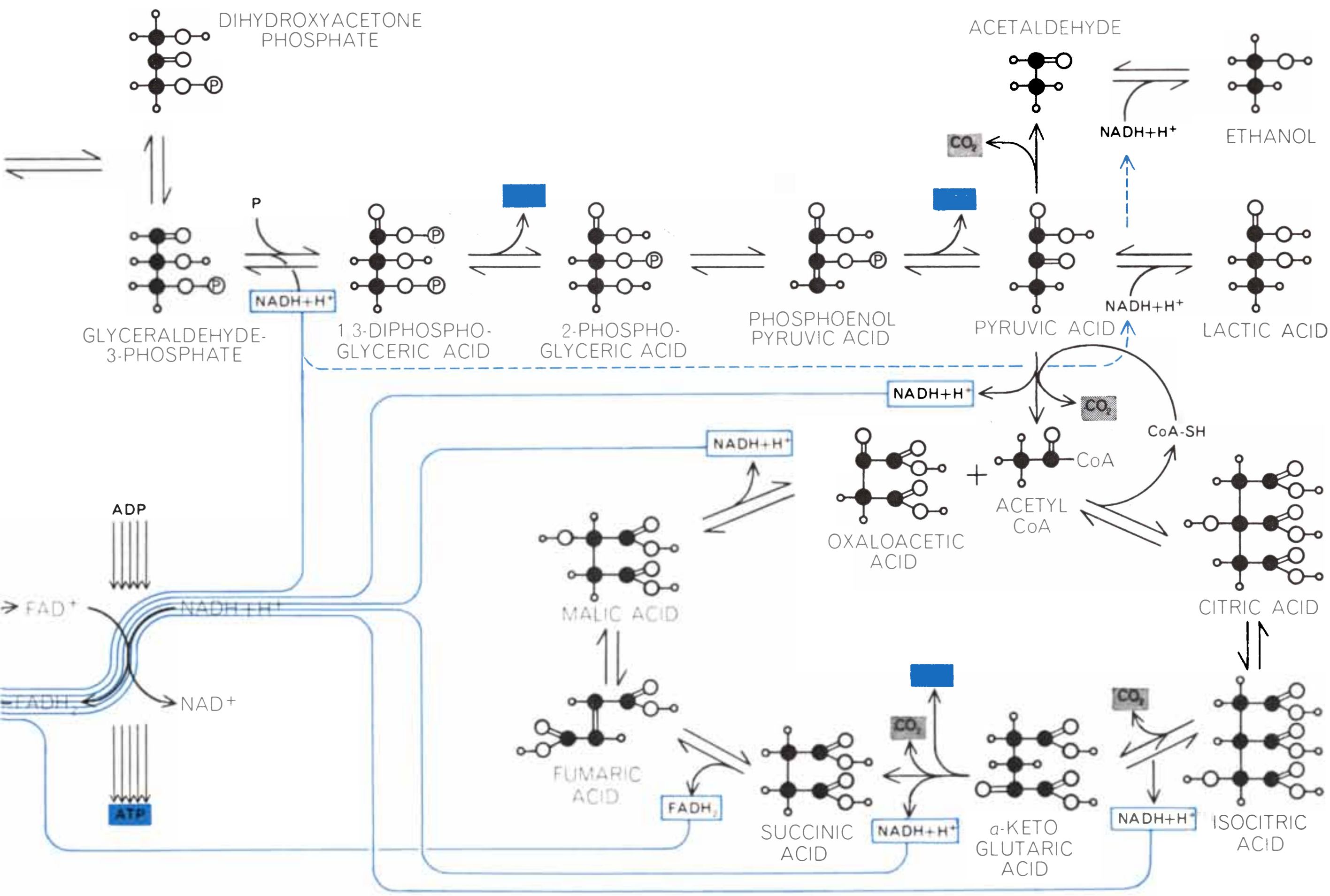


moved. In hydration-dehydrogenation (*c*) water is added and hydrogen is removed. Oxygenation does not occur in respiration, in which oxygen serves only as a hydrogen acceptor.

now of the University of California at Los Angeles, do imply an approximate balance between the chemical combining equivalents of carbon and oxygen in sediments, the atmosphere, the hydrosphere and the biosphere [*see bottom illustration on page 115*]. The relatively small excess of carbon in Rubey's estimates could be accounted for by the oxygen used in converting carbon monoxide to carbon dioxide. Or it might be due to an underestimate of the quantities of sulfate ion or ferric oxide in sediments. (Rubey's estimates could not include large iron formations recently discovered in western Australia and elsewhere.) The carbon dioxide in carbonate rocks does not need to be accounted for, but the oxygen involved in converting it to carbonate ion does. The recycling of sediments through metamorphism, mountain-building and the movement of ocean-floor plates under the continents is a variable of unknown dimensions, but it probably does not affect the approximate balance observed in view of the fact that the overwhelmingly large pools to be balanced are all in the lithosphere and that carbon and oxygen losses would be roughly equivalent. The small amounts of oxygen dissolved in water are not included in this balance.

Nonetheless, water does enter the picture. Another possible source of oxygen in our atmosphere is photolysis, the ultraviolet dissociation of water vapor in the outer atmosphere followed by the escape of the hydrogen from the earth's gravitational field. This has usually been regarded as a trivial source, however. Although R. T. Brinkmann of the California Institute of Technology has recently argued that nonbiological photolysis may be a major source of atmospheric oxygen, the carbon-oxygen balance sheet does not support that belief, which also runs into other difficulties.

When free oxygen began to accumulate in the atmosphere some 1.8 billion years ago, life was still restricted to sites



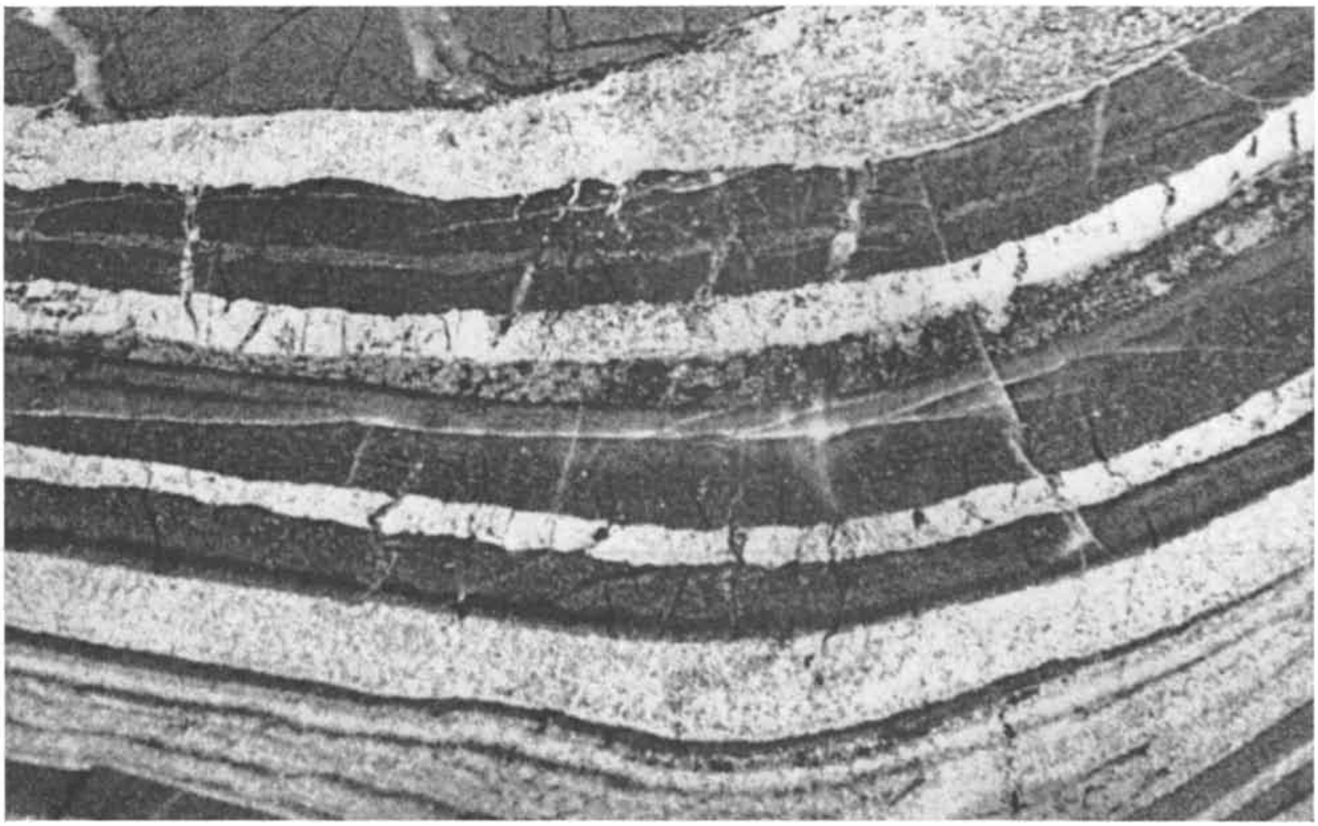
energy carrier. The pyruvic acid is converted into lactic acid in animal cells deprived of oxygen and into some other compound, such as ethanol, in fermentation. In aerobic cells in the presence of oxygen, however, pyruvic acid is completely oxidized to produce carbon dioxide and water. In the process hydrogen ions are removed. The electrons of these hydrogens (and of two removed in glycolysis) are passed along by two electron carriers, nicotinamide adenine dinucleotide (NAD) and flavin adenine dinucleotide (FAD), to a chain of respiratory enzymes, ubiquinone and the cytochromes, which are alternately reduced and oxidized. Energy released in the reactions is coupled to synthesis of ATP, 38 molecules of which are produced for every molecule of glucose consumed.

shielded from destructive ultraviolet radiation by sufficient depths of water or by screens of sediment. In time enough oxygen built up in the atmosphere for ozone, a strong absorber in the ultraviolet, to form a shield against incoming ultraviolet radiation. The late Lloyd V. Berkner and Lauriston C. Marshall of the Graduate Research Center of the Southwest in Dallas calculated that only 1 percent of the present atmospheric level of oxygen would give rise to a sufficient level of ozone to screen out the most deleterious wavelengths of the ultraviolet radiation. This also happens to be the level of oxygen at which Pasteur found that certain microorganisms switch over from a fermentative type of metabolism to an oxidative one. Berkner and Marshall therefore jumped to the conclusion (reasonably enough on the evidence they considered) that this was the stage at which oxidative metabolism arose. They related this stage to the first appearance of metazoan life somewhat more than 600 million years ago.

The geological record has long made it plain, however, that free molecular oxygen existed in the atmosphere well before that relatively late date in geologic time. Moreover, recent evidence is consistent with the origin of oxidative metabolism at least twice as long ago. Eucaryotic cells—cells with organized nuclei and other organelles—have been identified in rocks in eastern California that are believed to be about 1.3 billion years old [*see top illustration on page 112*]. Since all living eucaryotes depend on oxidative metabolism, it seems likely that these ancestral forms did too. The oxygen level may nonetheless have still been quite low at this stage. Simple diffusion would suffice to move enough oxygen across cell boundaries and within the cell, even at very low concentrations, to supply the early oxidative metabolizers. A higher order of organization and of atmospheric oxygen was required, however, for advanced oxidative metabolism. Perhaps that is why, although the eucaryotic cell existed at least 1.2 billion years ago, we have no unequivocal fossils of metazoan organisms from rocks older than perhaps 640 million years.

In other words, perhaps Berkner and Marshall were mistaken only in trying to make the appearance of the Metazoa coincide with the onset of oxidative metabolism. Once the level of atmospheric oxygen was high enough to generate an effective ozone screen, photosynthetic organisms would have been able to spread throughout the surface waters of the sea, greatly accelerating the rate of oxygen production. The plausible episodes in geological history to correlate with this development are the secondary oxidation of the banded iron formations and the appearance of sedimentary calcium sulfate (gypsum and anhydrite) on a large scale. These events occurred just as or just before the Metazoa first appeared in early Paleozoic time. The attainment of a suitable level of atmospheric oxygen may thus be correlated with the emergence of metazoan root stocks from premetazoan ancestors beginning about 640 million years ago. The fact that oxygen could accumulate no faster than carbon (or hydrogen) was removed argues against the likelihood of a rapid early buildup of oxygen.

That subsequent biospheric and atmospheric evolution were closely interlinked can now be taken for granted. What is not known are the details. Did oxygen levels in the atmosphere increase steadily throughout geologic time, marking regular stages of biological evolution such as the emergence of land plants, of



BANDED IRON FORMATION provides the first geological evidence of free oxygen in the hydrosphere. The layers in this polished cross section result from an alternation of iron-rich and iron-poor depositions. This sample from the Soudan Iron Formation in Minnesota is more than 2.7 billion years old. The layers, originally horizontal, were deformed while soft and later metamorphosed.

Packaging alternatives in a consumption oriented economy.

A report from The Coca-Cola Company.

In the good old days, a bottle of Coca-Cola came back for refilling 40 or 50 times. Small kids used to comb the countrysides and back-alleys looking for 2¢ deposit empties. The Coca-Cola Company and the soft drink industry were both built on the packaging of returnable beverage bottles. This container was obviously one of the most efficient recycling mechanisms ever developed.

Introduced in 1916, this became the standard bottle for Coca-Cola.

But many pressures have brought about changes in the returnable bottle system. Many consumers don't want to be involved in handling, inventoring, and transporting returnable bottles. Actually, returnable bottle trippage has decreased over the years because more consumers are not returning them, thus increasing the costs associated with being in a returnable system. The development of efficient systems for handling one-way bottles and cans has narrowed the price differential between convenience packages and returnables, which makes the returnables less of a consumer value than it used to be. More importantly, the consumer is more affluent today and willing to spend a little extra for convenience in any form i.e. foods, packaging, etc., etc.

As a result, today about 50% of our industry's products are sold in returnable bottles and 50% in convenience containers, either cans or one-way bottles. This is considerably different with Coca-Cola. Our ratio is approximately 70% returnables & 30% in convenience containers.

However, one-way penetration varies substantially from market to market. The availability of more convenience packaging also makes it more "convenient" for the consumer to enjoy Coke and throw the container away. Sometimes in the proper place. Sometimes not.

As a result, the soft drink industry has come under a substantial amount of pressure because our trade-mark containers are among the more visible components of a very visible stream of litter. Results from a recent litter study conducted by the Highway Research Board, indicates that soft drink containers account for less than 6% of total litter. For many months The Coca-Cola Company has been involved in a mix of activities with the objectives of mitigating solid waste and litter problems:

1. We have gone back through all of the packaging materials' recycling mechanisms to evaluate the flow where we can participate and have defined the circumstances that have to exist to facilitate participation. This analysis is now an input into our marketing and business plan.

The no-deposit no-return bottle for Coca-Cola, first appeared in 1961.

2. We are always promoting the returnable bottle because it remains one of the best recycling mechanisms. There are also attractive economies associated with this container—both for the consumer and bottler. A completely new advertising campaign is now available to our bottlers for the purpose of promoting its economical and ecological values.

3. At the present time, we are test-marketing a plastic bottle for carbonated beverages. The particular plastic involved can be incinerated without generating any corrosion because of combustion. We are also exploring business systems for reclaiming material values existing in used containers.

4. We are making a complete system study of all packaging strategies from extraction to deposing or recycling to determine the impacts on land, water, and air, energy resources, and environment, etc.

In addition to these actions, many bottling plants are presently recycling paper board, glass cullet, and other operational bi-products and some cities have installed steel can recovery systems after incineration.

The Coca-Cola Company is aware of the need to develop more efficient packaging systems that will help solve some of the problems of solid waste and litter. As you see we're working very hard at it.

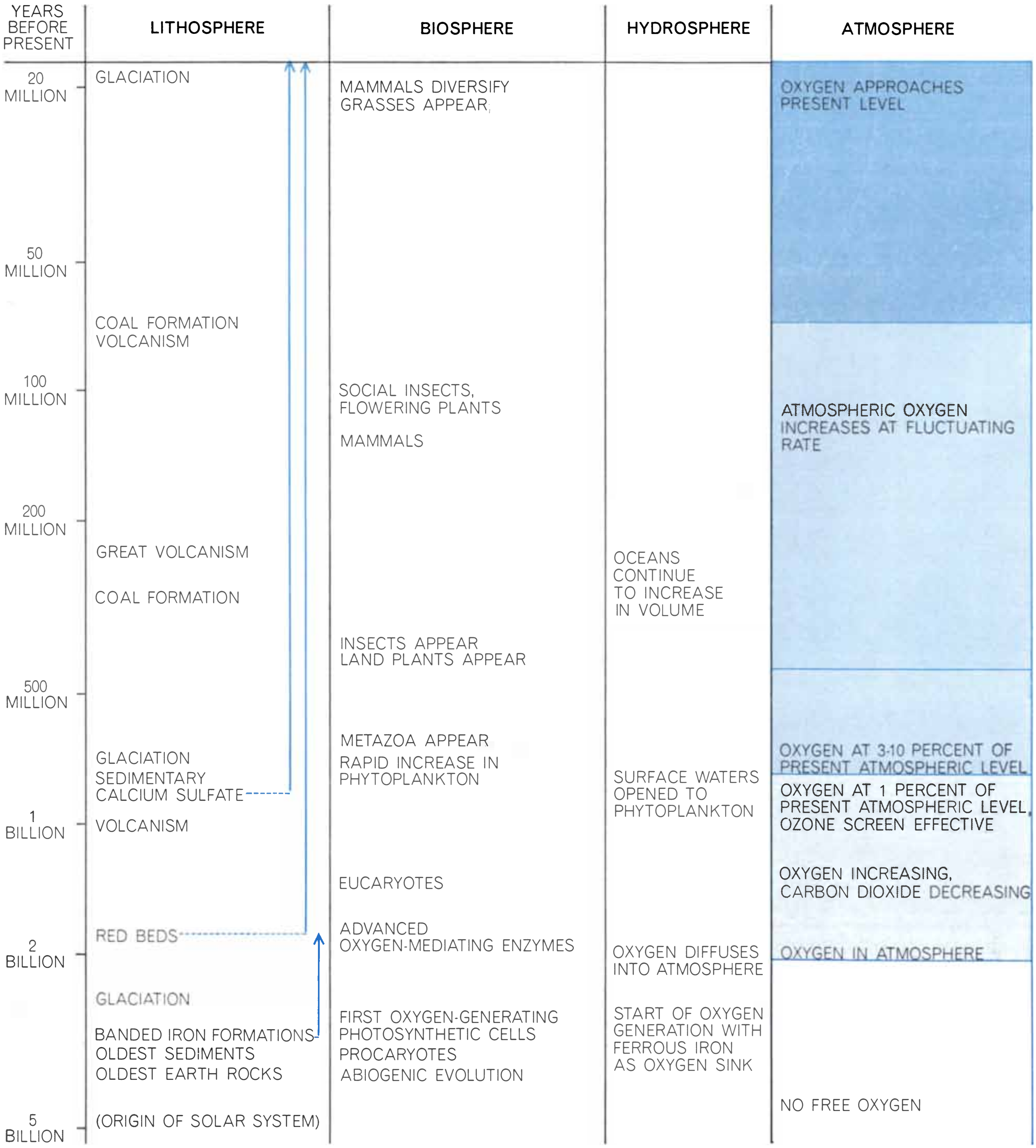
In 1959, Coca-Cola was made available in cans.

The Coca-Cola Company

Enjoy Coca-Cola

insects, of the various vertebrate groups and of flowering plants, as Berkner and Marshall suggested? Or were there wide swings in the oxygen level? Did oxygen decrease during great volcanic episodes, as a result of the oxidation of newly emitted carbon monoxide to carbon dioxide, or during times of sedimentary sulfate precipitation? Did oxygen increase when carbon was being sequestered during times of coal and petroleum formation? May there have been fluctuations in both directions as a result of plant and animal evolution, of phytoplankton eruptions and extinctions and of the extent and type of terrestrial plant cover? Such processes and events are now being seriously studied, but the answers are as yet far from clear.

What one can say with confidence is that success in understanding the oxy-

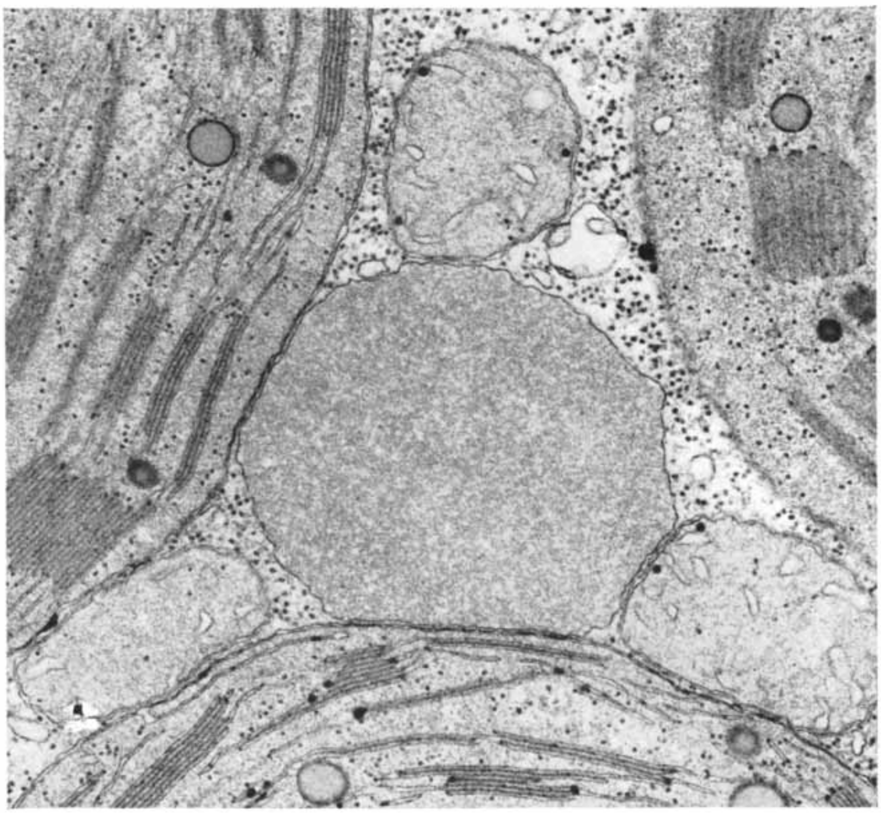


CHRONOLOGY that interrelates the evolutions of atmosphere and biosphere is gradually being established from evidence in the geological record and in fossils. According to calculations by Lloyd V. Berkner and Lauriston C. Marshall, when oxygen in the atmosphere reached 1 percent of the present atmospheric level, it provided enough ozone to filter out the most damaging high-energy ultraviolet radiation so that phytoplankton could survive everywhere in the upper, sunlit layers of the seas. The result may have been a geometric increase in the amount of photosynthesis in the oceans that, if accompanied by equivalent sequestration of carbon, might have resulted in a rapid buildup of atmospheric oxygen, leading in time to the evolution of differentiated multicelled animals.

gen cycle of the biosphere in truly broad terms will depend on how good we are at weaving together the related strands of biospheric, atmospheric, hydrospheric and lithospheric evolution throughout geologic time. Whatever we may conjecture about any one of these processes must be consistent with what is known about the others. Whereas any one line of evidence may be weak in itself, a number of lines of evidence, taken together and found to be consistent, reinforce one another exponentially. This synergistic effect enhances our confidence in the proposed time scale linking the evolution of oxygen in the atmosphere and the management of the gaseous oxygen budget within the biosphere [*see illustration on page 120*].

The most recent factor affecting the oxygen cycle of the biosphere and the oxygen budget of the earth is man himself. In addition to inhaling oxygen and exhaling carbon dioxide as a well-behaved animal does, man decreases the oxygen level and increases the carbon dioxide level by burning fossil fuels and paving formerly green land. He is also engaged in a vast but unplanned experiment to see what effects oil spills and an array of pesticides will have on the world's phytoplankton. The increase in the albedo, or reflectivity, of the earth as a result of covering its waters with a molecule-thick film of oil could also affect plant growth by lowering the temperature and in other unforeseen ways. Reductions in the length of growing seasons and in green areas would limit terrestrial plant growth in the middle latitudes. (This might normally be counterbalanced by increased rainfall in the lower latitudes, but a film of oil would also reduce evaporation and therefore rainfall.) Counteracting such effects, man moves the earth's fresh water around to increase plant growth and photosynthesis in arid and semiarid regions. Some of this activity, however, involves the mining of ground water, thereby favoring processes that cause water to be returned to the sea at a faster rate than evaporation brings it to the land.

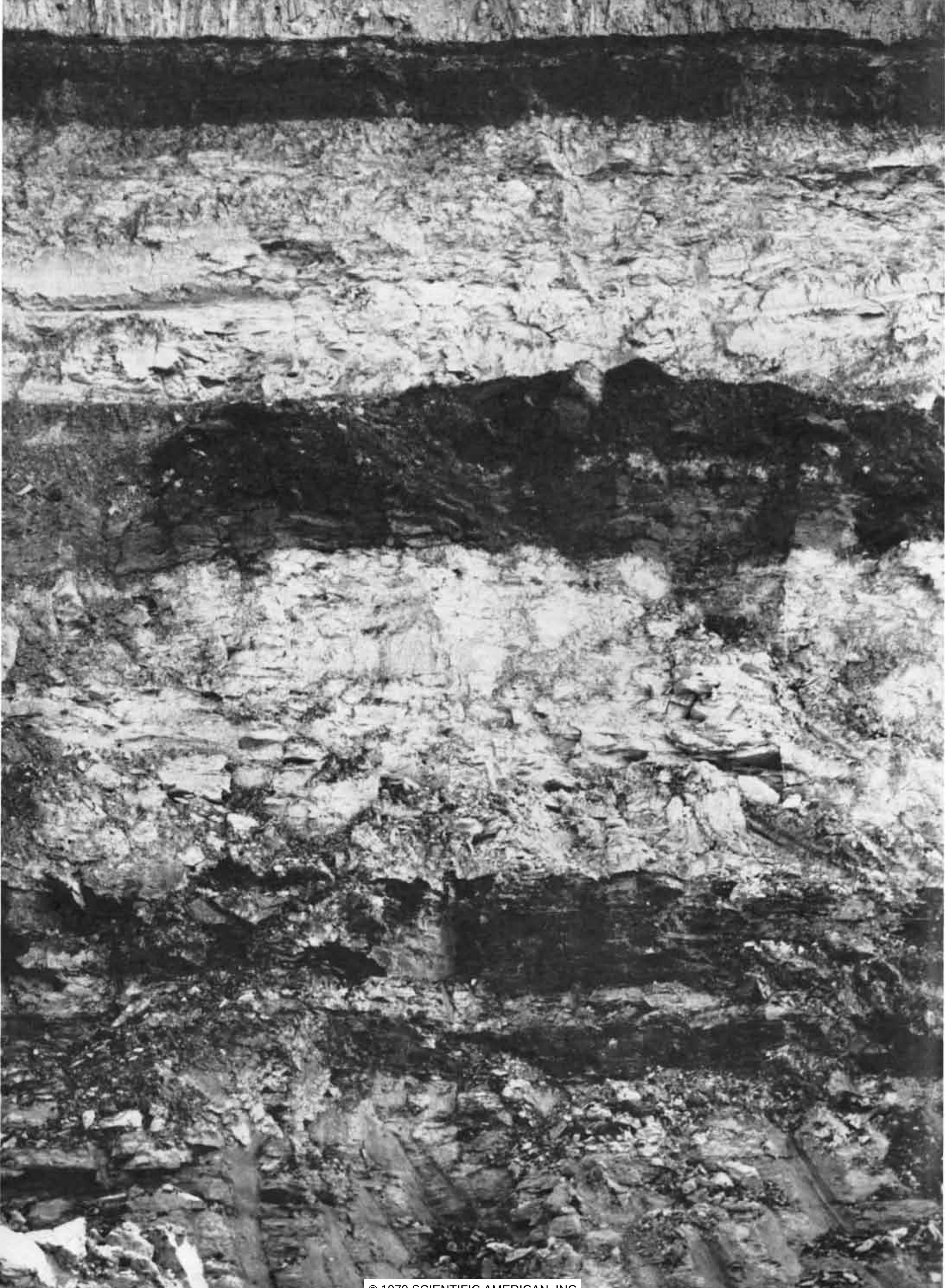
He who is willing to say what the final effects of such processes will be is wiser or braver than we are. Perhaps the effects will be self-limiting and self-correcting, although experience should



THREE ORGANELLES that are involved in oxygen metabolism in the living cell are enlarged 40,000 diameters in an electron micrograph of a tobacco leaf cell made by Sue Ellen Frederick in the laboratory of Eldon H. Newcomb at the University of Wisconsin. A peroxisome (*center*) is surrounded by three mitochondria and three chloroplasts. Oxygen is produced in the grana (*layered objects*) in the chloroplasts and is utilized in aerobic respiration in the mitochondria. Peroxisomes contain enzymes involved in oxygen metabolism.

warn us not to gamble on that. Oxygen in the atmosphere might be reduced several percent below the present level without adverse effects. A modest increase in the carbon dioxide level might enhance plant growth and lead to a corresponding increase in the amount of oxygen. Will a further increase in carbon dioxide also have (or renew) a "greenhouse effect," leading to an increase in temperature (and thus to a rising sea level)? Or will such effects be counterbalanced or swamped by the cooling effects of particulate matter in the air or by increased albedo due to oil films? It is anyone's guess. (Perhaps we should be more alarmed about a possible decrease of atmospheric carbon dioxide, on which all forms of life ultimately depend, but the sea contains such vast amounts that it can presumably keep carbon dioxide in the atmosphere balanced at about the present level for a long time to come.) The net effect of the burning of fossil fuels may in the long run be nothing more than a slight increase (or decrease?) in the amount of limestone deposited. In any event the recoverable fossil fuels whose combustion releases carbon dioxide are headed for depletion in a few more centuries, and then man will have other problems to contend with.

What we want to stress is the indivisibility and complexity of the environment. For example, the earth's atmosphere is so thoroughly mixed and so rapidly recycled through the biosphere that the next breath you inhale will contain atoms exhaled by Jesus at Gethsemane and by Adolf Hitler at Munich. It will also contain atoms of radioactive strontium 90 and iodine 131 from atomic explosions and gases from the chimneys and exhaust pipes of the world. Present environmental problems stand as a grim monument to the cumulatively adverse effects of actions that in themselves were reasonable enough but that were taken without sufficient thought to their consequences. If we want to ensure that the biosphere continues to exist over the long term and to have an oxygen cycle, each new action must be matched with an effort to foresee its consequences throughout the ecosystem and to determine how they can be managed favorably or avoided. Understanding also is needed, and we are woefully short on that commodity. This means that we must continue to probe all aspects of the indivisible global ecosystem and its past, present and potential interactions. That is called basic research, and basic research at this critical point in history is gravely endangered by new crosscurrents of anti-intellectualism.



THE CARBON CYCLE

The main cycle is from carbon dioxide to living matter and back to carbon dioxide. Some of the carbon, however, is removed by a slow epicycle that stores huge inventories in sedimentary rocks

by Bert Bolin

The biosphere contains a complex mixture of carbon compounds in a continuous state of creation, transformation and decomposition. This dynamic state is maintained through the ability of phytoplankton in the sea and plants on land to capture the energy of sunlight and utilize it to transform carbon dioxide (and water) into organic molecules of precise architecture and rich diversity. Chemists and molecular biologists have unraveled many of the intricate processes needed to create the microworld of the living cell. Equally fundamental and no less interesting is the effort to grasp the overall balance and flow of material in the worldwide community of plants and animals that has developed in the few billion years since life began. This is ecology in the broadest sense of the word: the complex interplay between, on the one hand, communities of plants and animals and, on the other, both kinds of community and their nonliving environment.

We now know that the biosphere has not developed in a static inorganic environment. Rather the living world has profoundly altered the primitive lifeless earth, gradually changing the composition of the atmosphere, the sea and the top layers of the solid crust, both on land and under the ocean. Thus a study of the carbon cycle in the biosphere is fundamentally a study of the overall global interactions of living organisms and their physical and chemical environment. To bring order into this world of complex interactions biologists must combine their knowledge with the information available to students of geology, oceanography and meteorology.

The engine for the organic processes that reconstructed the primitive earth is photosynthesis. Regardless of whether it takes place on land or in the sea, it can be summarized by a single reaction: $CO_2 + 2H_2A + \text{light} \rightarrow CH_2O + H_2O + 2A + \text{energy}$. The formaldehyde molecule CH_2O symbolizes the simplest organic compound; the term "energy" indicates that the reaction stores energy in chemical form. H_2A is commonly water (H_2O), in which case 2A symbolizes the release of free oxygen (O_2). There are, however, bacteria that can use compounds in which A stands for sulfur, for some organic radical or for nothing at all.

Organisms that are able to use carbon dioxide as their sole source of carbon are known as autotrophs. Those that use light energy for reducing carbon dioxide are called phototrophic, and those that use the energy stored in inorganic chemical bonds (for example the bonds of nitrates and sulfates) are called chemolithotrophic. Most organisms, however, require preformed organic molecules for growth; hence they are known as heterotrophs. The nonsulfur bacteria are an unusual group that is both photosynthetic and heterotrophic. Chemoheterotrophic organisms, for example animals, obtain their energy from organic compounds without need for light. An organism may be either aerobic or anaerobic regardless of its source of carbon or energy. Thus some anaerobic chemoheterotrophs can survive in the deep ocean and deep lakes in the total absence of light or free oxygen.

There is more to plant life than the creation of organic compounds by photosynthesis. Plant growth involves a series of chemical processes and transformations that require energy. This energy is obtained by reactions that use the oxygen in the surrounding water and air to unlock the energy that has been stored by photosynthesis. The process, which releases carbon dioxide, is termed respiration. It is a continuous process and is therefore dominant at night, when photosynthesis is shut down.

If one measures the carbon dioxide at various levels above the ground in a forest, one can observe pronounced changes in concentration over a 24-hour period [*see top illustration on page 127*]. The average concentration of carbon dioxide in the atmosphere is about 320 parts per million. When the sun rises, photosynthesis begins and leads to a rapid decrease in the carbon dioxide concentration as leaves (and the needles of conifers) convert carbon dioxide into organic compounds. Toward noon, as the temperature increases and the humidity decreases, the rate of respiration rises and the net consumption of carbon dioxide slowly declines. Minimum values of carbon dioxide 10 to 15 parts per million below the daily average are reached around noon at treetop level. At sunset photosynthesis ceases while respiration continues, with the result that the carbon dioxide concentration close to the

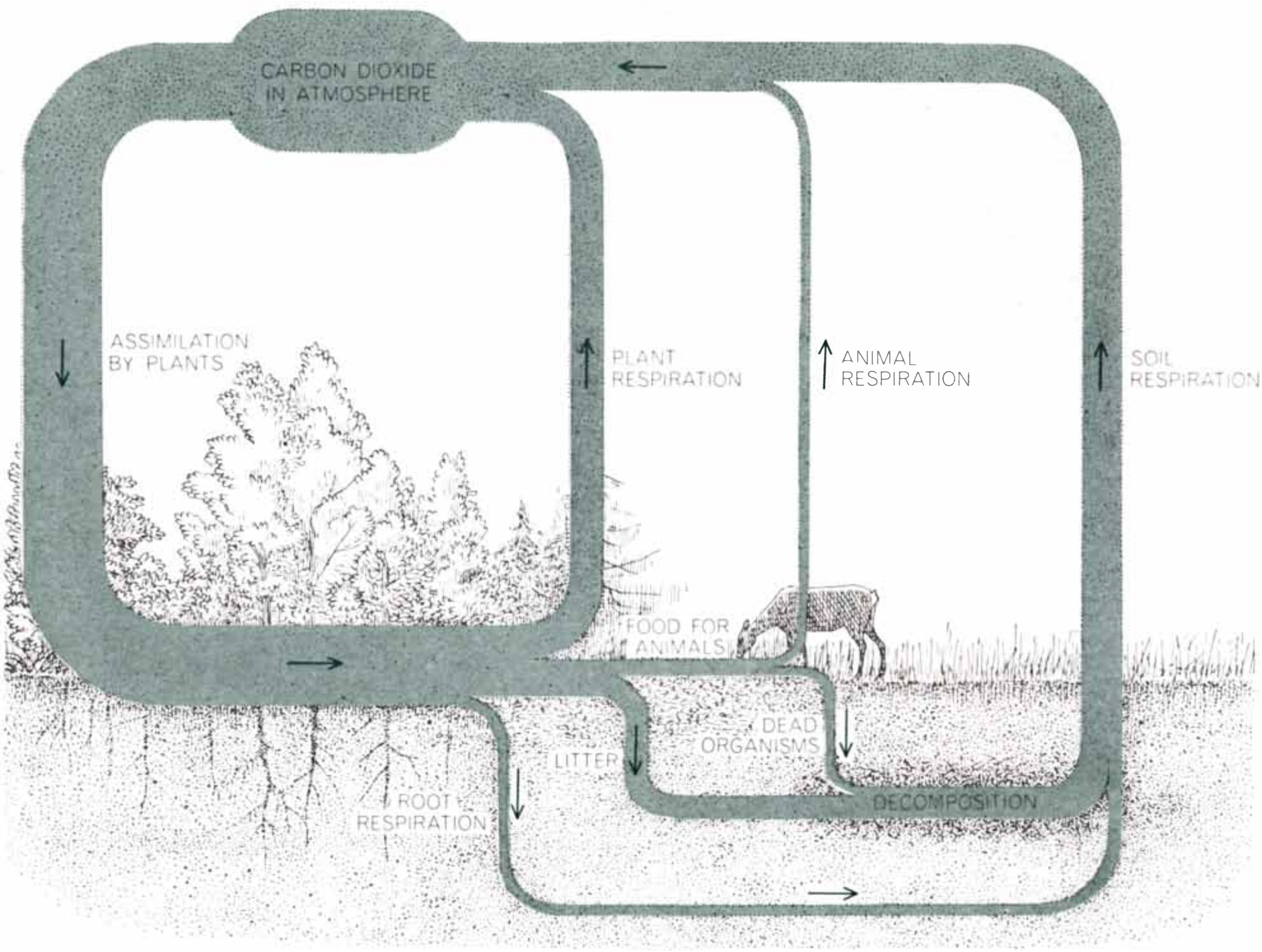
CARBON LOCKED IN COAL and oil exceeds by a factor of about 50 the amount of carbon in all living organisms. The estimated world reserves of coal alone are on the order of 7,500 billion tons. The photograph on the opposite page shows a sequence of lignite coal seams being strip-mined in Stanton, N.D., by the Western Division of the Consolidation Coal Company. The seam, about two feet thick, is of low quality and is discarded. The second seam from the top, about three feet thick, is marketable, as is the third seam, 10 feet farther down. This seam is really two seams separated by about 10 inches of gray clay. The upper is some 3½ feet thick; the lower is about two feet thick. Twenty-four feet below the bottom of this seam is still another seam (*not shown*) eight feet thick, which is also mined.

ground may exceed 400 parts per million. This high value reflects partly the release of carbon dioxide from the decomposition of organic matter in the soil and partly the tendency of air to stagnate near the ground at night, when there is no solar heating to produce convection currents.

The net productivity, or net rate of fixation, of carbon dioxide varies greatly from one type of vegetation to another. Rapidly growing tropical rain forests annually fix between one kilogram and two kilograms of carbon (in the form of carbon dioxide) per square meter of land surface, which is roughly equal to the amount of carbon dioxide in a column of air extending from the same area of the earth's surface to the top of the atmosphere. The arctic tundra and the nearly barren regions of the desert may fix as little as 1 percent of that amount. The forests and cultivated fields of the middle latitudes assimilate between .2 and .4 kilogram per square meter. For the earth as a whole the areas of high productivity are small. A fair estimate is that the land areas of the earth fix into organic compounds 20 to 30 billion net metric tons of carbon per year. There is considerable uncertainty in this figure; published estimates range from 10 to 100 billion tons.

The amount of carbon in the form of carbon dioxide consumed annually by phytoplankton in the oceans is perhaps 40 billion tons, or roughly the same as the gross assimilation of carbon dioxide by land vegetation. Both the carbon dioxide consumed and the oxygen released are largely in the form of gas dissolved near the ocean surface. Therefore most of the carbon cycle in the sea is self-contained: the released oxygen is consumed by sea animals, and their ultimate decomposition releases carbon dioxide back into solution. As we shall see, however, there is a dynamic exchange of carbon dioxide (and oxygen) between the atmosphere and the sea, brought about by the action of the wind and waves. At any given moment the amount of carbon dioxide dissolved in the surface layers of the sea is in close equilibrium with the concentration of carbon dioxide in the atmosphere as a whole.

The carbon fixed by photosynthesis on land is sooner or later returned to the atmosphere by the decomposition of dead organic matter. Leaves and litter fall to the ground and are oxidized by a series of complicated processes in the soil. We can get an approximate idea of the rate at which organic matter in the soil is

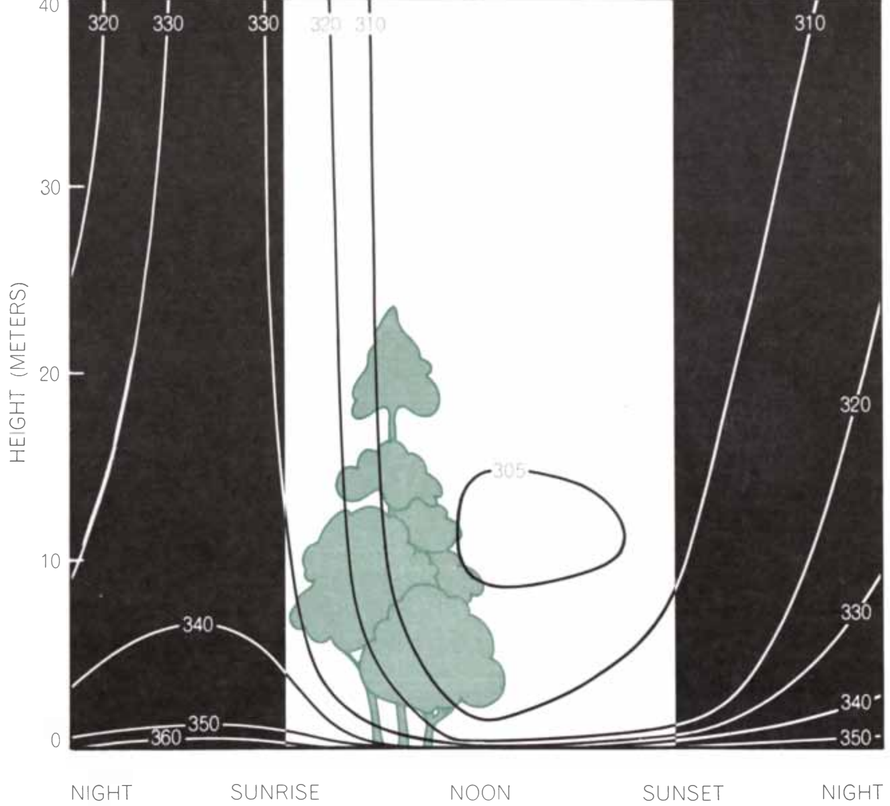


CARBON CYCLE begins with the fixation of atmospheric carbon dioxide by the process of photosynthesis, conducted by plants and certain microorganisms. In this process carbon dioxide and water react to form carbohydrates, with the simultaneous release of free oxygen, which enters the atmosphere. Some of the carbohydrate is directly consumed to supply the plant with energy; the carbon dioxide so generated is released either through the plant's leaves or through its roots. Part of the carbon fixed by plants is consumed by animals, which also respire and release carbon dioxide. Plants and animals die and are ultimately decomposed by microorganisms in the soil; the carbon in their tissues is oxidized to carbon dioxide and returns to the atmosphere. The widths of the pathways are roughly proportional to the quantities involved. A similar carbon cycle takes place within the sea. There is still no general agreement as to which of the two cycles is larger. The author's estimates of the quantities involved appear in the flow chart on page 130.

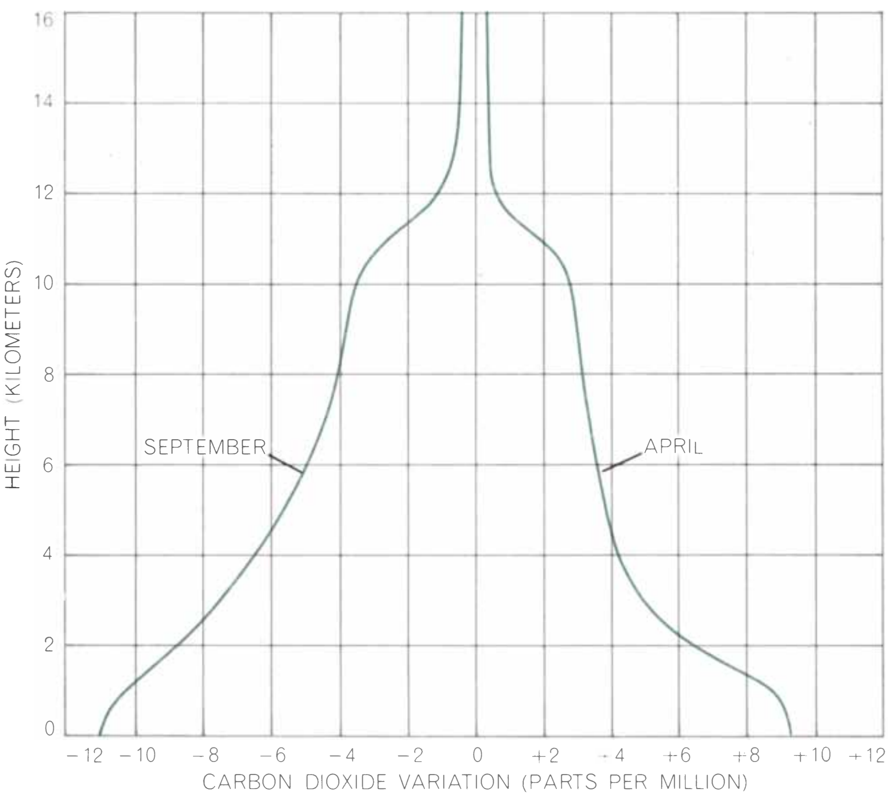
being transformed by measuring its content of the radioactive isotope carbon 14. At the time carbon is fixed by photosynthesis its ratio of carbon 14 to the nonradioactive isotope carbon 12 is the same as the ratio in the atmosphere (except for a constant fractionation factor), but thereafter the carbon 14 decays and becomes less abundant with respect to the carbon 12. Measurements of this ratio yield rates for the oxidation of organic matter in the soil ranging from decades in tropical soils to several hundred years in boreal forests.

In addition to the daily variations of carbon dioxide in the air there is a marked annual variation, at least in the Northern Hemisphere. As spring comes to northern regions the consumption of carbon dioxide by plants greatly exceeds the return from the soil. The increased withdrawal of carbon dioxide can be measured all the way up to the lower stratosphere. A marked decrease in the atmospheric content of carbon dioxide occurs during the spring. From April to September the atmosphere north of 30 degrees north latitude loses nearly 3 percent of its carbon dioxide content, which is equivalent to about four billion tons of carbon [*see bottom illustration at right*]. Since the decay processes in the soil go on simultaneously, the net withdrawal of four billion tons implies an annual gross fixation of carbon in these latitudes of at least five or six billion tons. This amounts to about a fourth of the annual terrestrial productivity referred to above (20 to 30 billion tons), which was based on a survey of carbon fixation. In this global survey the estimated contribution from the Northern Hemisphere, where plant growth shows a marked seasonal variation, constituted about 25 percent of the total tonnage. Thus two independent estimates of worldwide carbon fixation on land show a quite satisfactory agreement.

The forests of the world not only are the main carbon dioxide consumers on land; they also represent the main reservoir of biologically fixed carbon (except for fossil fuels, which have been largely removed from the carbon cycle save for the amount reintroduced by man's burning of it). The forests contain between 400 and 500 billion tons of carbon, or roughly two-thirds of the amount present as carbon dioxide in the atmosphere (700 billion tons). The figure for forests can be estimated only approximately. The average age of a tree can be assumed to be about 30 years, which implies that about 15 billion tons of carbon



VERTICAL DISTRIBUTION OF CARBON DIOXIDE in the air around a forest varies with time of day. At night, when photosynthesis is shut off, respiration from the soil can raise the carbon dioxide at ground level to as much as 400 parts per million (ppm). By noon, owing to photosynthetic uptake, the concentration at treetop level can drop to 305 ppm.



SEASONAL VARIATIONS in the carbon dioxide content of the atmosphere reach a maximum in September and April for the region north of 30 degrees north latitude. The departure from a mean value of about 320 ppm varies with altitude as shown by these two curves.

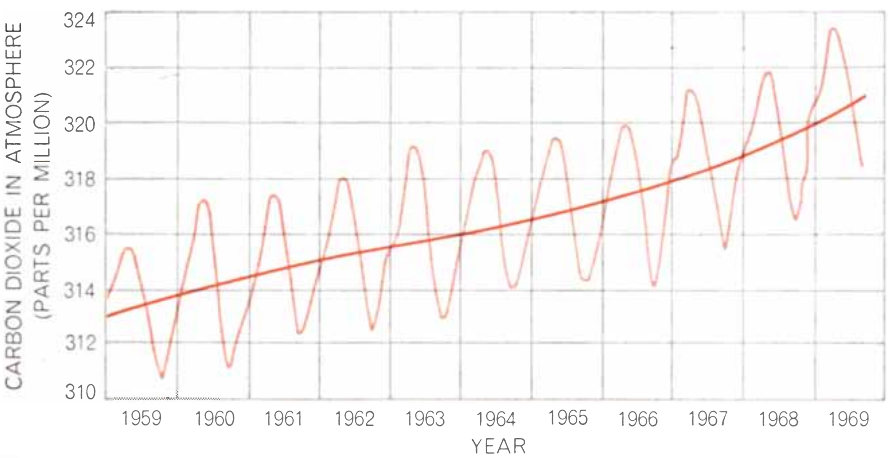
transformed into wood, which seems reasonable in comparison with a total annual assimilation of 20 to 30 billion tons.

The pattern of carbon circulation in the sea is quite different from the pattern on land. The productivity of the soil is mostly limited by the availability of fresh water and phosphorus, and only to a degree by the availability of other nutrients in the soil. In the oceans the overriding limitation is the availability of inorganic substances. The phytoplankton require not only plentiful supplies of phosphorus and nitrogen but also trace amounts of various metals, notably iron.

The competition for food in the sea is so keen that organisms have gradually developed the ability to absorb essential minerals even when these nutrients are available only in very low concentration. As a result high concentrations of nutrients are rarely found in surface waters, where solar radiation makes it possible for photosynthetic organisms to exist. If an ocean area is uncommonly productive, one can be sure that nutrients are supplied from deeper layers. (In limited areas they are supplied by the wastes of human activities.) The most productive waters in the world are therefore near the Antarctic continent, where the deep waters of the surrounding oceans well up and mix with the surface layers. There are similar upwellings along the coast of Chile, in the vicinity of Japan and in the Gulf Stream. In such regions fish are abundant and the maximum annual fixation of carbon approaches .3 kilogram per square meter. In the "desert" areas of the oceans, such the fixation rate may be less than a tenth of that value. In the Tropics warm surface layers are usually effective in blocking the vertical water exchange needed to carry nutrients up from below.

Phytoplankton, the primary fixers of carbon dioxide in the sea, are eaten by the zooplankton and other tiny animals. These organisms in turn provide food for the larger animals. The major part of the oceanic biomass, however, consists of microorganisms. Since the lifetime of such organisms is measured in weeks, or at most in months, their total mass can never accumulate appreciably. When microorganisms die, they quickly disintegrate as they sink to deeper layers. Soon most of what was once living tissue has become dissolved organic matter.

A small fraction of the organic particulate matter escapes oxidation and settles into the ocean depths. There it profoundly influences the abundance of chemical substances because (except in special regions) the deep layers exchange water with the surface layers very slowly. The enrichment of the deep layers goes hand in hand with a depletion of oxygen. There also appears to be an increase in carbon dioxide (in the form of carbonate and bicarbonate ions) in the ocean depths. The overall distribution of carbon dioxide, oxygen and various minor constituents in the sea reflects a balance between the marine life and its chemical milieu in the surface layers and the slow transport of substances by the general circulation of the ocean. The net effect is to prevent the ocean from becoming saturated with oxygen and to enrich the deeper strata with carbonate and bicarbonate ions.



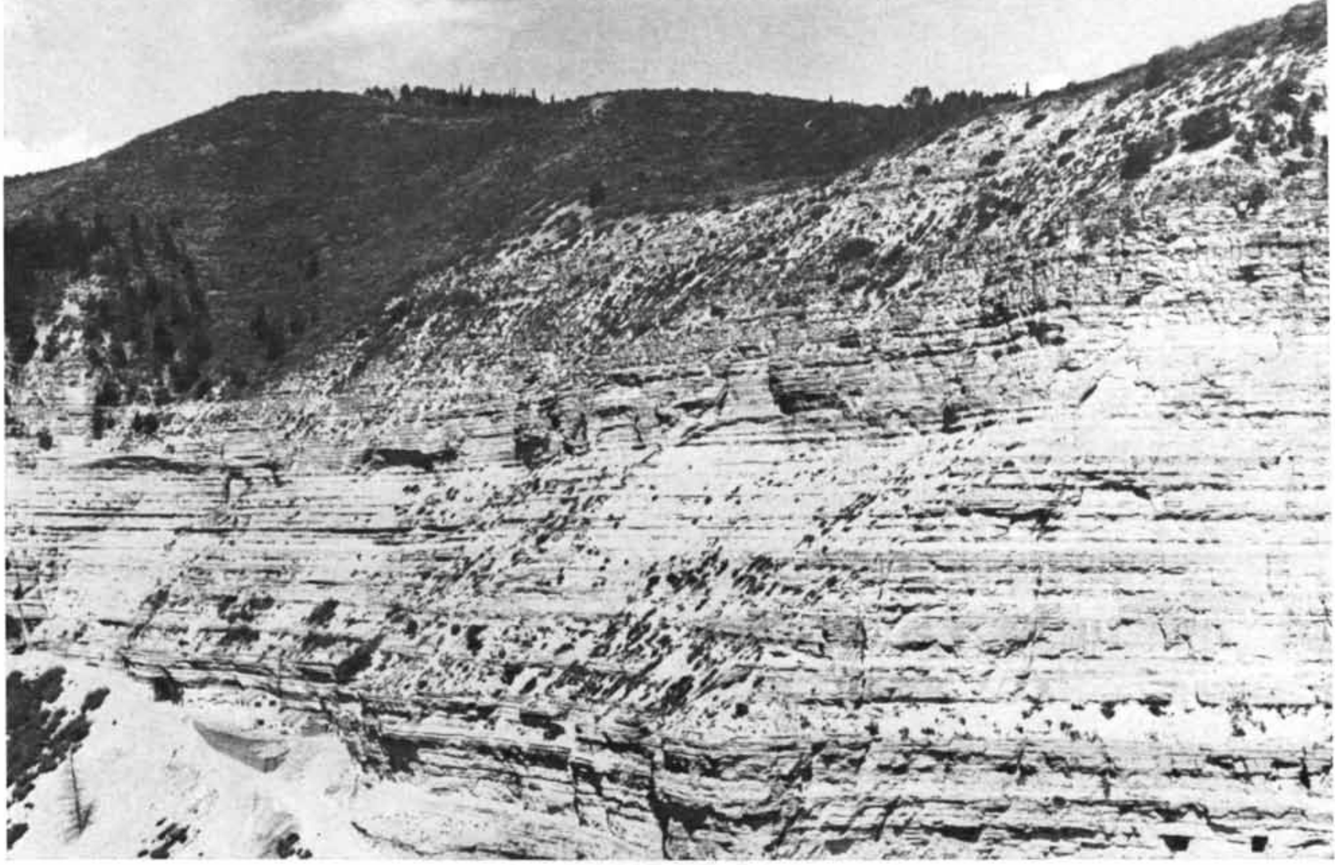
LONG-TERM VARIATIONS in the carbon dioxide content of the atmosphere have been followed at the Mauna Loa Observatory in Hawaii by the Scripps Institution of Oceanography. The sawtooth curve indicates the month-to-month change in concentration since January, 1959. The oscillations reflect seasonal variations in the rate of photosynthesis, as depicted in the bottom illustration on the preceding page. The smooth curve shows the trend.

the oceans today could well be quite different if the mechanisms for the exchange of water between the surface layers and the deep ones were either more intense or less so. The present state is determined primarily by the sinking of cold water in the polar regions, particularly the Antarctic. In these regions the water is also slightly saltier, and therefore still denser, because some of it has been frozen out in floating ice. If the climate of the earth were different, the distribution of carbon dioxide, oxygen and minerals might also be quite different. If the difference were large enough, oxygen might completely vanish from the ocean depths, leaving them to be populated only by chemibarotrophic bacteria. (This is now the case in the depths of the Black Sea.)

The time required to establish a new equilibrium in the ocean is determined by the slowest link in the chain of processes that has been described. This link is the oceanic circulation; it seems to take at least 1,000 years for the water in the deepest basins to be completely replaced. One can imagine other conditions of circulation in which the oceans would interact differently with sediments and rocks, producing a balance of substances that one can only guess at.

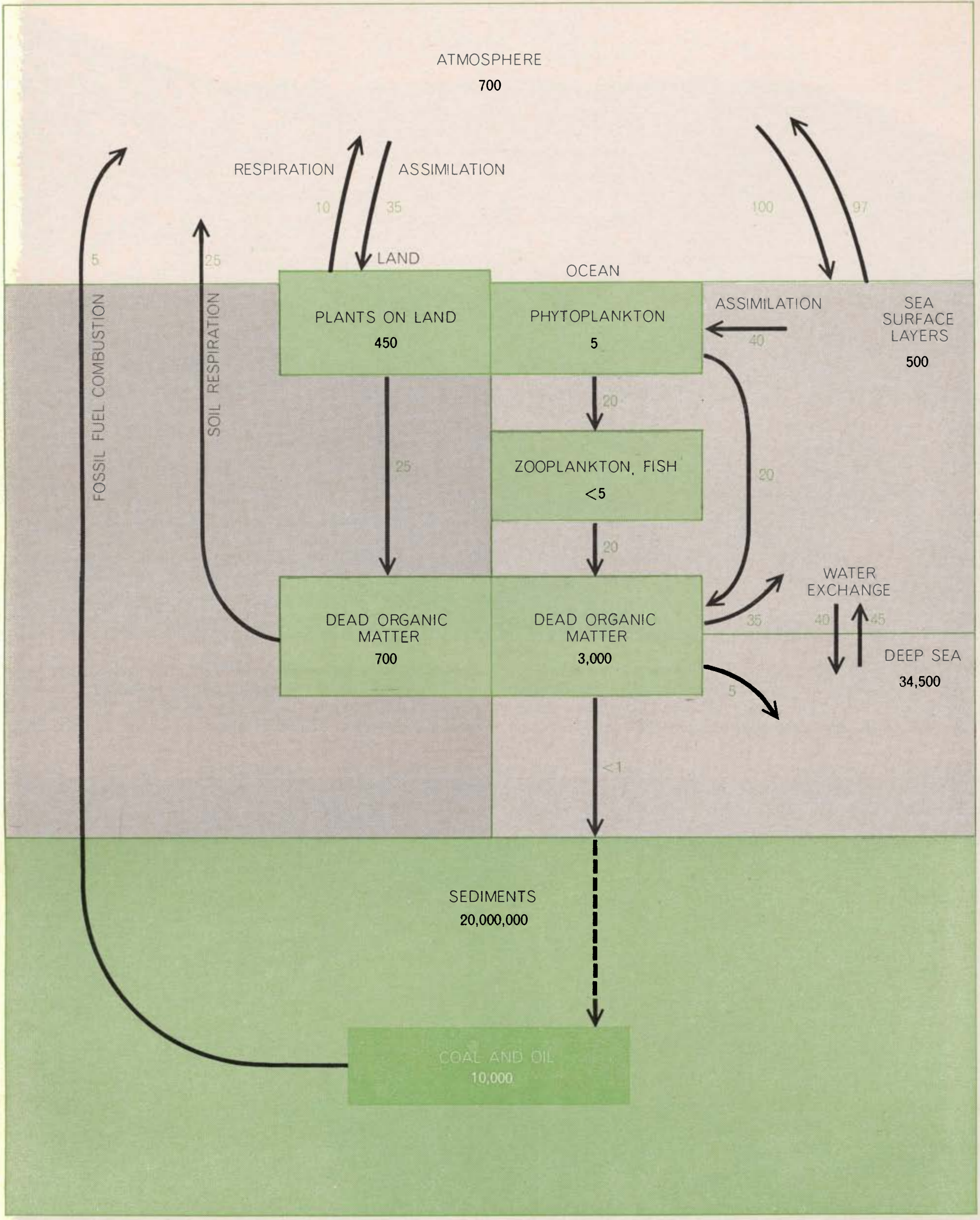
So far we have been concerned only with the basic biological and ecological processes that provide the mechanisms for circulating carbon through living organisms. Plants on land, with lifetimes measured in years, and phytoplankton in the sea, with lifetimes measured in weeks, are merely the innermost wheels in a biogeochemical machine that embraces the entire earth and that retains important characteristics over much longer time periods. In order to understand such interactions we shall need some rough estimates of the size of the various carbon reservoirs involved and the nature of their contents [*see illustration on page 130*]. In the context of the present argument the large uncertainties in such estimates are of little significance.

Only a few tenths of a percent of the immense mass of carbon at or near the surface of the earth (on the order of 20×10^{15} tons) is in rapid circulation in the biosphere, which includes the atmosphere, the hydrosphere, the upper portions of the earth's crust and the biomass itself. The overwhelming bulk of near-surface carbon consists of inorganic deposits (chiefly carbonates) and organic fossil deposits (chiefly oil shale, coal and petroleum) that required hundreds of



OIL SHALE is one of the principal sedimentary forms in which carbon has been deposited over geologic time. This photograph, taken at Anvil Points, Colo., shows a section of the Green River Formation, which extends through Colorado, Utah and Wyoming. The formation is estimated to contain the equivalent of more than a trillion barrels of oil in seams containing more than 10 barrels of oil per ton of rock. Of this some 80 billion barrels is considered recoverable. The shale seams are up to 130 feet thick.

WHITE CLIFFS OF DOVER consist of almost pure calcium carbonate, representing the skeletons of phytoplankton that settled to the bottom of the sea over a period of millions of years more than 70 million years ago. The worldwide deposits of limestone, oil shale and other carbon-containing sediments are by far the largest repository of carbon: an estimated 20 quadrillion (10^{15}) tons.



CARBON CIRCULATION IN BIOSPHERE involves two quite distinct cycles, one on land and one in the sea, that are dynamically connected at the interface between the ocean and the atmosphere. The carhon cycle in the sea is essentially self-contained in that phytoplankton assimilate the carbon dioxide dissolved in seawater and release oxygen back into solution. Zooplankton and fish consume the carbon fixed by the phytoplankton, using the dissolved oxygen for respiration. Eventually the decomposition of organic matter replaces the carbon dioxide assimilated by the phytoplankton. All quantities are in billions of metric tons. It will be seen that the combustion of fossil fuels at the rate of about five billion tons per year is sufficient to increase the carbon dioxide in the atmosphere by about .7 percent, equivalent to adding some two parts per million to the existing 320 ppm. Since the observed annual increase is only about .7 ppm, it appears that two-thirds of the carbon dioxide released from fossil fuels is quickly removed from the atmosphere, going either into the oceans or adding to the total mass of terrestrial plants. The estimated tonnages are the author's.

magnitude. Over time intervals as brief as those of which we have been speaking—up to 1,000 years for the deep-ocean circulation—the accretion of such deposits is negligible. We may therefore consider the life processes on land and in the sea as the inner wheels that spin at comparatively high velocity in the carbon-circulating machine. They are coupled by a very low gear to more majestic processes that account for the overall circulation of carbon in its various geologic and oceanic forms.

We now know that the two great systems, the atmosphere and the ocean, are closely coupled to each other through the transfer of carbon dioxide across the surface of the oceans. The rate of exchange has recently been estimated by measuring the rate at which the radioactive isotope carbon 14 produced by the testing of nuclear weapons has disappeared from the atmosphere. The neutrons released in such tests form carbon 14 by reacting with the nitrogen 14 of the atmosphere. In this reaction a nitrogen atom ($_7N^{14}$) captures a neutron and subsequently releases a proton, yielding $_6C^{14}$. (The subscript before the letter represents the number of protons in the nucleus; the superscript after the letter indicates the sum of protons and neutrons.)

The last major atmospheric tests were conducted in 1963. Sampling at various altitudes and latitudes shows that the constituents of the atmosphere became rather well mixed over a period of a few years. The decline of carbon 14, however, was found to be rapid; it can be explained only by assuming an exchange of atmospheric carbon dioxide, enriched in carbon 14, with the reservoir of much less radioactive carbon dioxide in the sea. The measurements indicate that the characteristic time for the residence of carbon dioxide in the atmosphere before the gas is dissolved in the sea is between five and 10 years. In other words, every year something like 100 billion tons of atmospheric carbon dioxide dissolves in the sea and is replaced by a nearly equivalent amount of oceanic carbon dioxide.

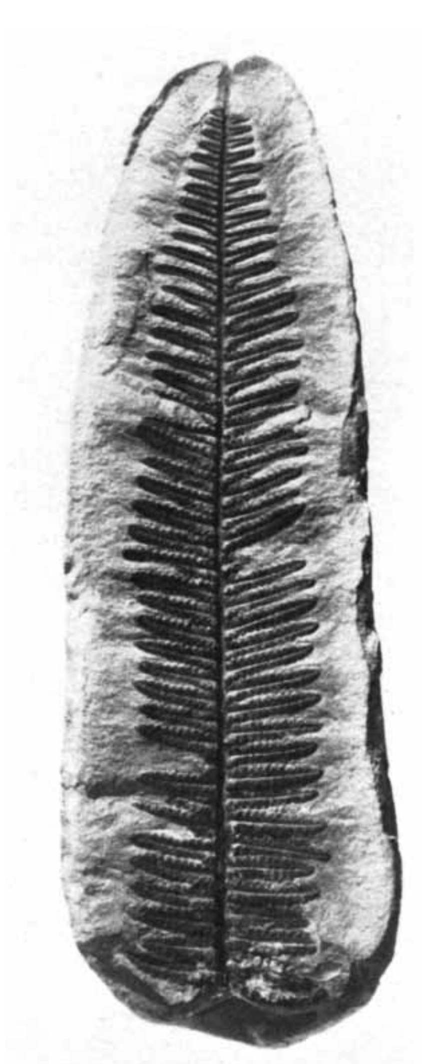
Since around 1850 man has inadvertently been conducting a global geochemical experiment by burning large amounts of fossil fuel and thereby returning to the atmosphere carbon that was fixed by photosynthesis millions of years ago. Currently between five and six billion tons of fossil carbon per year are being released into the atmosphere. This would be enough to increase the 2.3 parts per million per year if the carbon dioxide were uniformly distributed and not removed. Within the past century the carbon dioxide content of the atmosphere has risen from some 290 parts per million to 320, with more than a fifth of the rise occurring in just the past decade [*see illustration on page 128*]. The total increase accounts for only slightly more than a third of the carbon dioxide (some 200 billion tons in all) released from fossil fuels. Although most of the remaining two-thirds has presumably gone into the oceans, a significant fraction may well have increased the total amount of vegetation on land. Laboratory studies show that plants grow faster when the surrounding air is enriched in carbon dioxide. Thus it is possible that man is fertilizing fields and forests by burning coal, oil and natural gas. The biomass on land may have increased by as much as 15 billion tons in the past century. There is, however, little concrete evidence for such an increase.

Man has of course been changing his environment in other ways. Over the past century large areas covered with forest have been cleared and turned to agriculture. In such areas the character of soil respiration has undoubtedly changed, producing effects that might have been detectable in the atmospheric content of carbon dioxide if it had not been for the simultaneous increase in the burning of fossil fuels. In any case the dynamic equilibrium among the major carbon dioxide reservoirs in the biomass, the atmosphere, the hydrosphere and the soil has been disturbed, and it can be said that they are in a period of transition. Since even the most rapid processes of adjustment among the reservoirs take decades, new equilibriums are far from being established. Gradually the deep oceans become involved; their turnover time of about 1,000 years and their rate of exchange with bottom sediments control the ultimate partitioning of carbon.

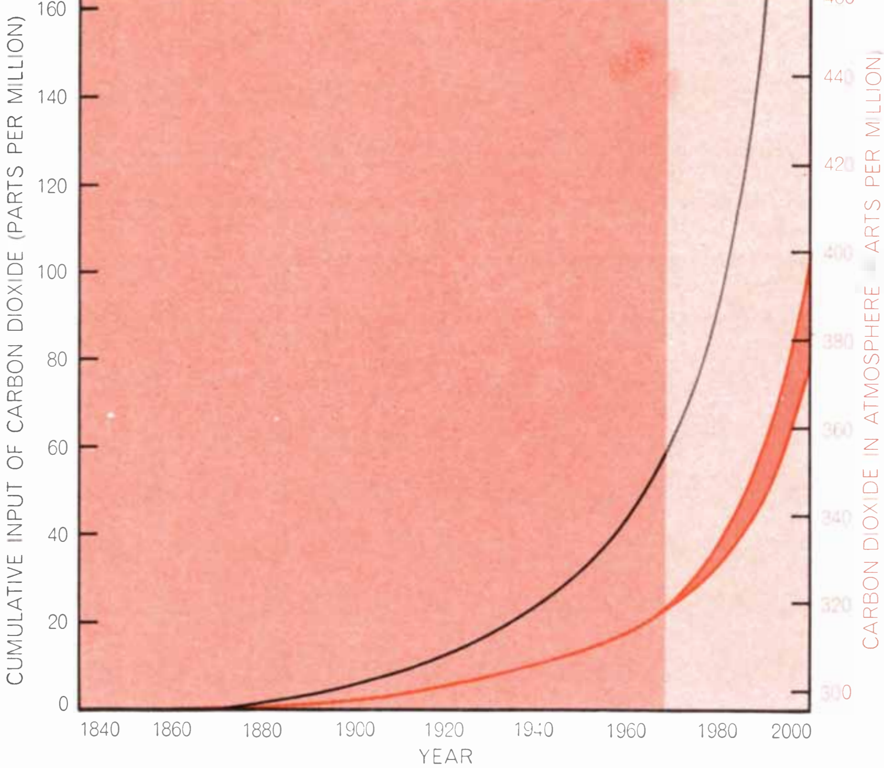
Meanwhile human activities continue to change explosively. The acceleration in the consumption of fossil fuels implies that the amount of carbon dioxide in the atmosphere will keep climbing from its present value of 320 parts per million to between 375 and 400 parts per million by the year 2000, in spite of anticipated large removals of carbon dioxide by land vegetation and the ocean reservoir [*see illustrations on next page*]. A fundamental question is: What will happen over the next 100 or 1,000 years? Clearly the exponential changes cannot continue.

which we are viewing the carbon cycle by several orders of magnitude, to hundreds of thousands or millions of years, we can anticipate large-scale exchanges between organic carbon on land and carbonates of biological origin in the sea. We do know that there have been massive exchanges in the remote past. Any discussion of these past events and their implications for the future, however, must necessarily be qualitative and uncertain.

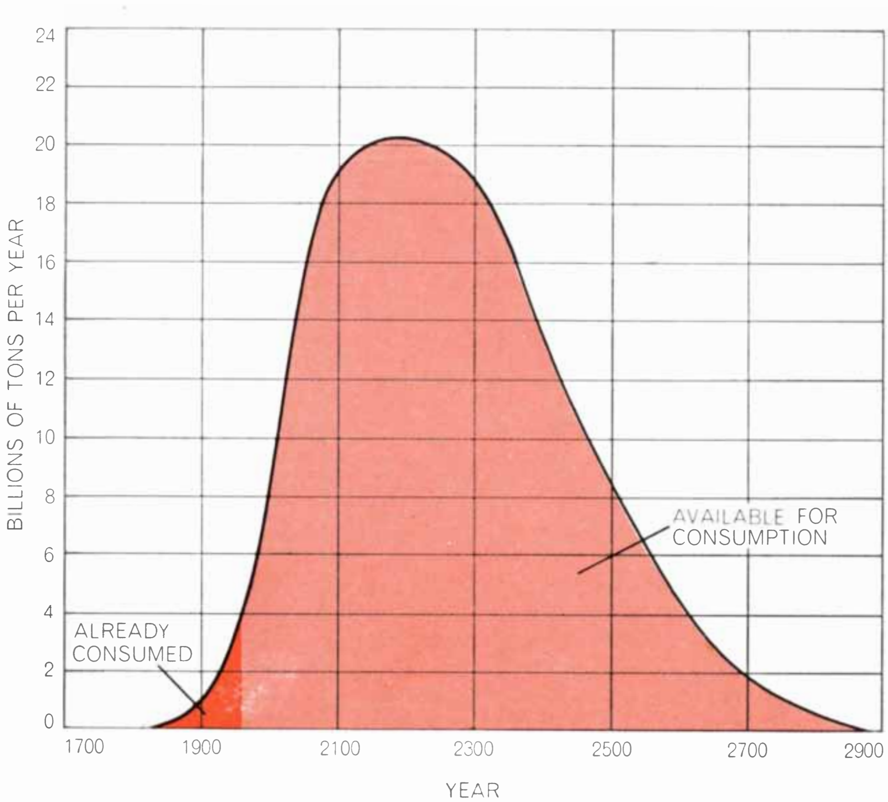
Although the plants on land have probably played an important role in the deposition of organic compounds in the soil, the oceans have undoubtedly acted as the main regulator. The amount of carbon dioxide in the atmosphere is essentially determined by the partial pressure of carbon dioxide dissolved in the



GIANT FERN of the genus *Pecopteris*, which fixed atmospheric carbon dioxide 300 million years ago, left the imprint of this frond in a thin layer of shale just above a coal seam in Illinois. The specimen is in the collection of the Smithsonian Institution.



INCREASE IN ATMOSPHERIC CARBON DIOXIDE since 1860 is shown by the lower curve, with a projection to the year 2000. The upper curve shows the cumulative input of carbon dioxide. The difference between the two curves represents the amount of carbon dioxide removed by the ocean or by additions to the total biomass of vegetation on land.



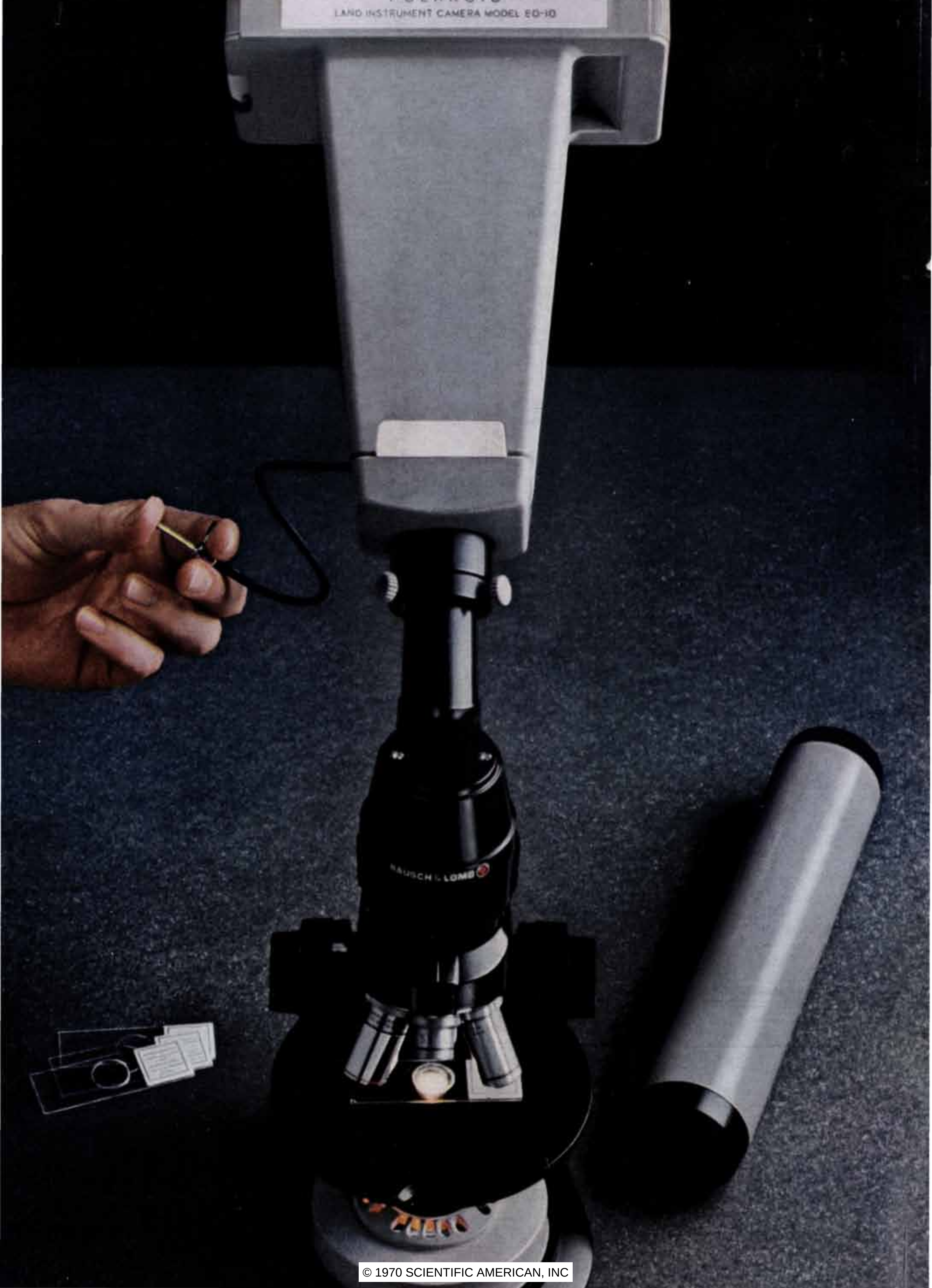
POSSIBLE CONSUMPTION PATTERN OF FOSSIL FUELS was projected by Harrison Brown in the mid-1950's. Here the fuel consumed is updated to 1960. If a third of the carbon dioxide produced by burning it all were to remain in the atmosphere, the carbon dioxide level would rise from 320 ppm today to about 1,500 ppm over the next several centuries.

sea. Over a period of, say, 100,000 years the leaching of calcium carbonates from land areas tends to increase the amount of carbon dioxide in the sea, but at the same time a converse mechanism—the precipitation and deposition of oceanic carbonates—tends to reduce the amount of carbon dioxide in solution. Thus the two mechanisms tend to cancel each other.

Over still longer periods of time—millions or tens of millions of years—the concentrations of carbonate and bicarbonate ions in the sea are probably buffered still further by reactions involving potassium, silicon and aluminum, which are slowly weathered from rocks and carried into the sea. The net effect is to stabilize the carbon dioxide content of the oceans and hence the carbon dioxide content of the atmosphere. Therefore it appears that the carbon dioxide environment, on which the biosphere fundamentally depends, may have been fairly constant right up to the time, barely a moment ago geologically speaking, when man's consumption of fossil fuels began to change the carbon dioxide content of the atmosphere.

The illustration on page 130 represents an attempt to synthesize into a single picture the circulation of carbon in nature, particularly in the biosphere. In addition to the values for inventories and transfers already mentioned, the flow chart contains other quantities for which the evidence is still meager. They have been included not only to balance the books but also to suggest where further investigation might be profitable. This may be the principal value of such an exercise. Such a flow chart also provides a semiquantitative model that enables one to begin to discuss how the global carbon system reacts to disturbances. A good model should of course include inventories and pathways for all the elements that play a significant role in biological processes.

The greatest disturbances of which we are aware are those now being introduced by man himself. Since his tampering with the biological and geochemical balances may ultimately prove injurious—even fatal—to himself, he must understand them much better than he does today. The story of the circulation of carbon in nature teaches us that we cannot control the global balances. Therefore we had better leave them close to the natural state that existed until the beginning of the Industrial Revolution. Out of a simple realization of this necessity may come a new industrial revolution.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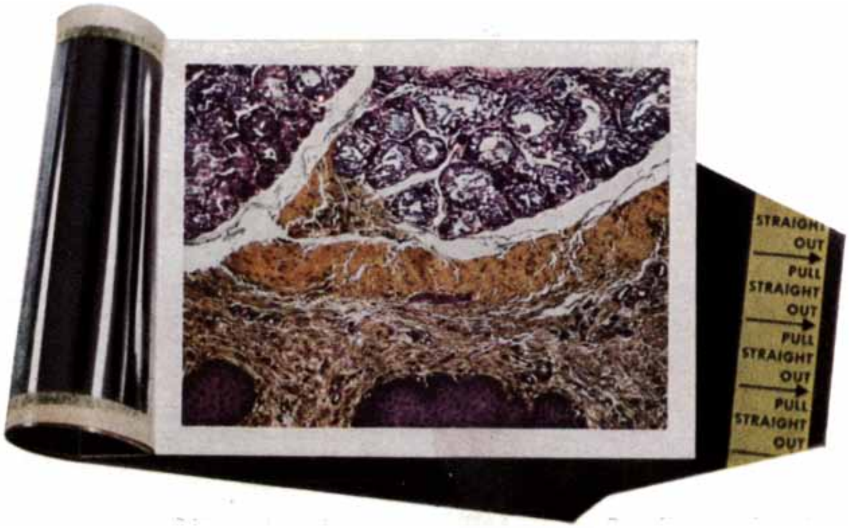
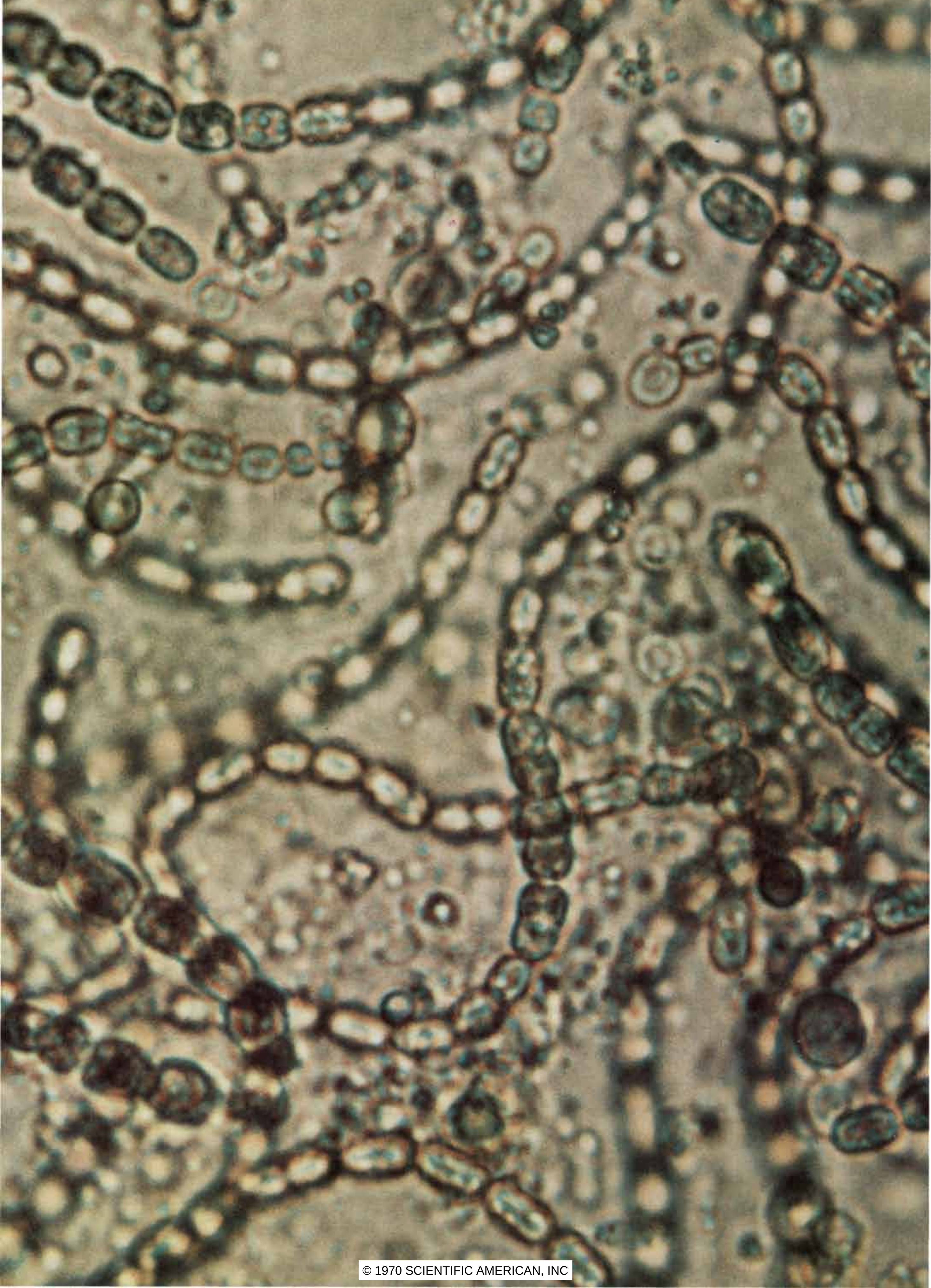




THE NITROGEN CYCLE

Nitrogen is 79 percent of the atmosphere, but it cannot be used directly by the large majority of living things. It must first be "fixed" by specialized organisms or by industrial processes

by C. C. Delwiche

Although men and other land animals live in an ocean of air that is 79 percent nitrogen, their supply of food is limited more by the availability of fixed nitrogen than by that of any other plant nutrient. By "fixed" is meant nitrogen incorporated in a chemical compound that can be utilized by plants and animals. As it exists in the atmosphere nitrogen is an inert gas except to the comparatively few organisms that have the ability to convert the element to a combined form. A smaller but still significant amount of atmospheric nitrogen is fixed by ionizing phenomena such as cosmic radiation, meteor trails and lightning, which momentarily provide the high energy needed for nitrogen to react with oxygen or the hydrogen of water. Nitrogen is also fixed by marine organisms, but the largest single natural source of fixed nitrogen is probably terrestrial microorganisms and associations between such microorganisms and plants.

Of all man's recent interventions in the cycles of nature the industrial fixation of nitrogen far exceeds all the others in magnitude. Since 1950 the amount of nitrogen annually fixed for the production of fertilizer has increased approximately fivefold, until it now equals the amount that was fixed by all terrestrial ecosystems before the advent of modern agriculture. In 1968 the world's annual output of industrially fixed nitrogen amounted to about 30 million tons of nitrogen; by the year 2000 the industrial fixation of nitrogen may well exceed 100 million tons.

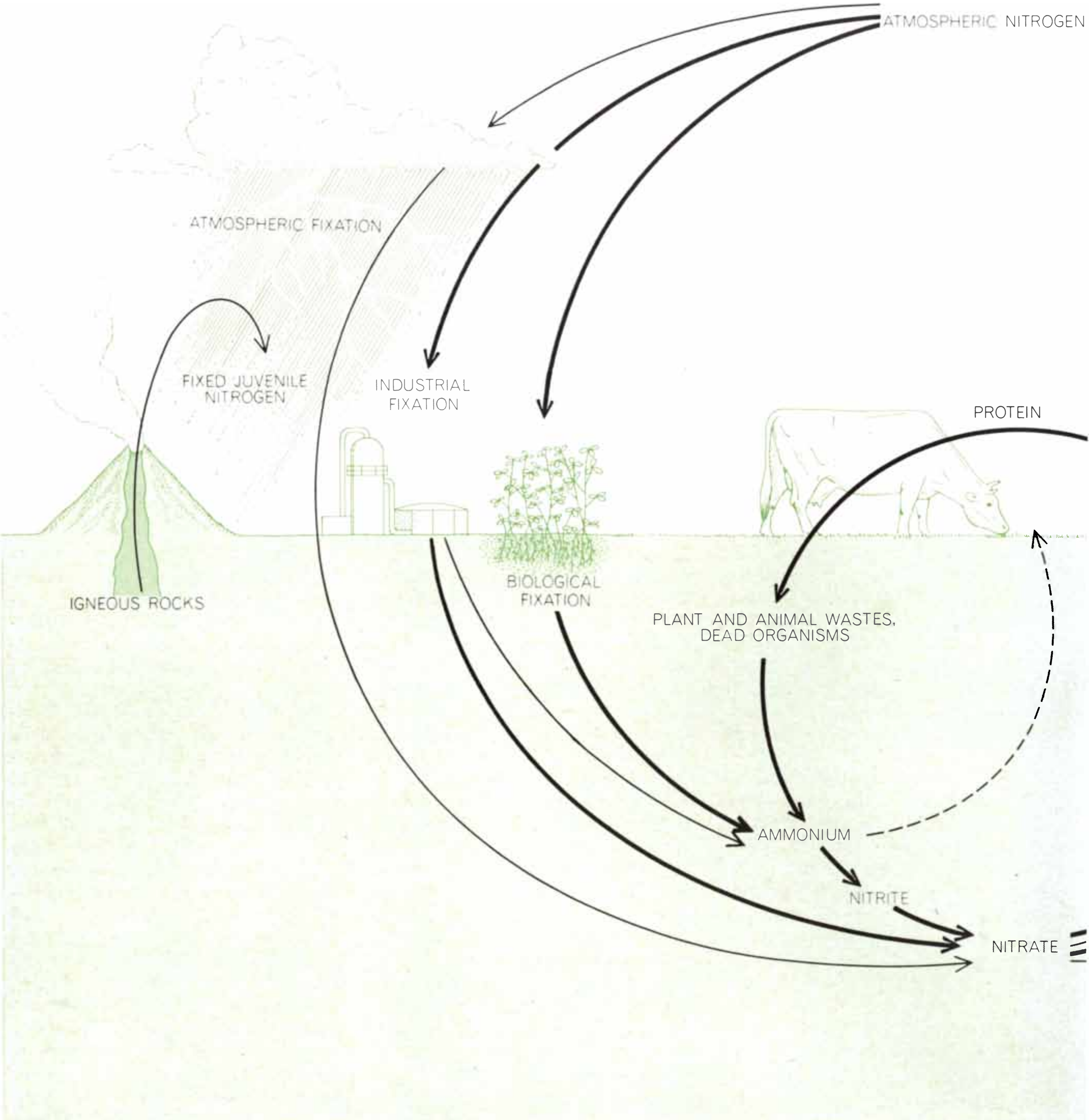
Before the large-scale manufacture of synthetic fertilizers and the wide cultivation of the nitrogen-fixing legumes one could say with some confidence that the amount of nitrogen removed from the atmosphere by natural fixation processes was closely balanced by the amount returned to the atmosphere by organisms that convert organic nitrates to gaseous nitrogen. Now one cannot be sure that the denitrifying processes are keeping pace with the fixation processes. Nor can one predict all the consequences if nitrogen fixation were to exceed denitrification over an extended period. We do know that excessive runoff of nitrogen compounds in streams and rivers can result in "blooms" of algae and intensified biological activity that deplete the available oxygen and destroy fish and other oxygen-dependent organisms. The rapid eutrophication of Lake Erie is perhaps the most familiar example.

To appreciate the intricate web of nitrogen flow in the biosphere let us trace the course of nitrogen atoms from the atmosphere into the cells of microorganisms, and then into the soil as fixed nitrogen, where it is available to higher plants and ultimately to animals. Plants and animals die and return the fixed nitrogen to the soil, at which point the nitrogen may simply be recycled through a new generation of plants and animals or it may be broken down into elemental nitrogen and returned to the atmosphere [*see illustration on next two pages*].

BLUE-GREEN ALGAE, magnified 4,200 diameters on the opposite page, are among the few free-living organisms capable of combining nitrogen with hydrogen. Until this primary fixation process is accomplished, the nitrogen in the air (or dissolved in water) cannot be assimilated by the overwhelming majority of plants or by any animal. A few bacteria are also free-living nitrogen fixers. The remaining nitrogen-fixing microorganisms live symbiotically with higher plants. This micrograph, which shows blue-green algae of the genus *Nostoc*, was made by Herman S. Forest of the State University of New York at Geneseo.

Because much of the terminology used to describe steps in the nitrogen cycle evolved in previous centuries it has an archaic quality. Antoine Laurent Lavoisier, who clarified the composition of air, gave nitrogen the name azote, meaning without life. The term is still found in the family name of an important nitrogen-fixing bacterium: the Azotobacteraceae. One might think that fixation would merely be termed nitrification, to indicate the addition of nitrogen to some other substance, but nitrification is reserved for a specialized series of reactions in which a few species of microorganisms oxidize the ammonium ion (NH_4^+) to nitrite (NO_2^-) or nitrite to nitrate (NO_3^-). When nitrites or nitrates are reduced to gaseous compounds such as molecular nitrogen (N_2) or nitrous oxide (N_2O), the process is termed denitrification. "Ammonification" describes the process by which the nitrogen of organic compounds (chiefly amino acids) is converted to ammonium ion. The process operates when microorganisms decompose the remains of dead plants and animals. Finally, a word should be said about the terms oxidation and reduction, which have come to mean more than just the addition of oxygen or its removal. Oxidation is any process that removes electrons from a substance. Reduction is the reverse process: the addition of electrons. Since electrons can neither be created nor destroyed in a chemical reaction, the oxidation of one substance always implies the reduction of another.

One may wonder how it is that some organisms find it profitable to oxidize nitrogen compounds whereas other organisms—even organisms in the same environment—owe their survival to their ability to reduce nitrogen compounds. Apart from photosynthetic organisms, which obtain their energy from radiation, all living forms depend for their energy on chemical transformations. These transformations normally involve the oxidation of one compound and the reduction of another, although in some cases the compound being oxidized and the compound being reduced are different molecules of the same substance, and in other cases the reactants are fragments of a single molecular species. Nitrogen can be cycled because the reduced inorganic compounds of nitrogen can be oxidized by atmospheric oxygen with a yield of useful energy. Under anaerobic conditions the oxidized compounds of nitrogen can act as oxidizing agents for the burning of organic compounds (and a few inorganic com-



NITROGEN CYCLE, like the water, oxygen and carbon cycles, involves all regions of the biosphere. Although the supply of nitrogen in the atmosphere is virtually inexhaustible, it must be combined with hydrogen or oxygen before it can be assimilated by higher plants, which in turn are consumed by animals. Man has intervened in the historical nitrogen cycle by the large-scale cultivation of nitrogen-fixing legumes and by the industrial fixation of nitrogen. The amount of nitrogen fixed annually by these two expedients now exceeds by perhaps 10 percent the amount of nitrogen fixed by terrestrial ecosystems before the advent of agriculture.

pounds), again with a yield of useful energy.

Nitrogen is able to play its complicated role in life processes because it has an unusual number of oxidation levels, or valences [*see illustration on page 141*]. An oxidation level indicates the number of electrons that an atom in a particular compound has "accepted" or "donated." In plants and animals most nitrogen exists either in the form of the ammonium ion or of amino ($-NH_2$) compounds. In either case it is highly reduced; it has acquired three electrons by its association with three other atoms and thus is said to have a valence of minus 3. At the other extreme, when nitrogen is in the highly oxidized form of the nitrate ion (the principal form it takes in the soil), it shares five of its electrons with oxygen atoms and so has a valence of plus 5. To convert nitrogen as it is found in the ammonium ion or amino acids to nitrogen as it exists in soil nitrates involves a total valence change of eight, or the removal of eight electrons. Conversely, to convert nitrate nitrogen into amino nitrogen requires the addition of eight electrons.

By and large the soil reactions that reduce nitrogen, or add electrons to it, release considerably more energy than the reactions that oxidize nitrogen, or remove electrons from it. The illustration on page 142 lists some of the principal reactions involved in the nitrogen cycle, together with the energy released (or required) by each. As a generalization one can say that for almost every reaction in nature where the conversion of one compound to another yields an energy of at least 15 kilocalories per mole (the equivalent in grams of a compound's molecular weight), some organism or group of organisms has arisen that can exploit this energy to survive.

The fixation of nitrogen requires an investment of energy. Before nitrogen can be fixed it must be "activated," which means that molecular nitrogen must be split into two atoms of free nitrogen. This step requires at least 160 kilocalories for each mole of nitrogen (equivalent to 28 grams). The actual fixation step, in which two atoms of nitrogen combine with three molecules of hydrogen to form two molecules of ammonia (NH_3), releases about 13 kilocalories. Thus the two steps together require a net input of at least 147 kilocalories. Whether nitrogen-fixing organisms actually invest this much energy, however, is not known. Reactions catalyzed by enzymes involve the penetration of activation barriers and not a simple change in energy between a set of initial reactants and their end products.

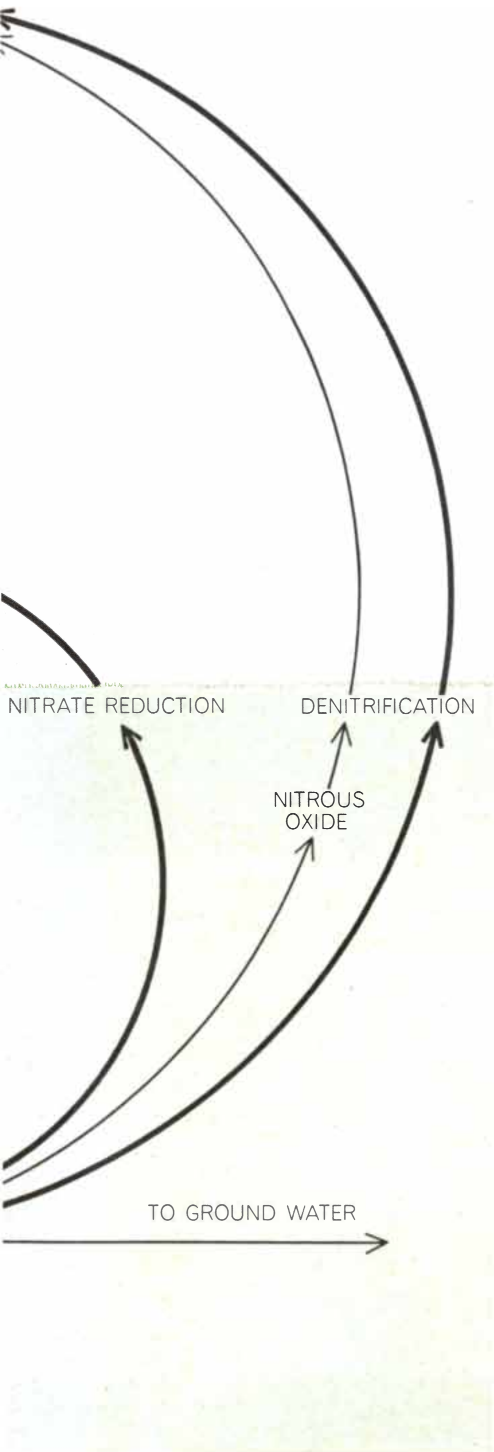
Once ammonia or the ammonium ion has appeared in the soil, it can be absorbed by the roots of plants and the nitrogen can be incorporated into amino acids and then into proteins. If the plant is subsequently eaten by an animal, the nitrogen may be incorporated into a new protein. In either case the protein ultimately returns to the soil, where it is decomposed (usually with bacterial help) into its component amino acids. Assuming that conditions are aerobic, meaning that an adequate supply of oxygen is present, the soil will contain many microorganisms capable of oxidizing amino acids to carbon dioxide, water and ammonia. If the amino acid happens to be glycine, the reaction will yield 176 kilocalories per mole.

A few microorganisms represented by the genus *Nitrosomonas* employ nitrification of the ammonium ion as their sole source of energy. In the presence of oxygen, ammonia is converted to nitrite ion (NO_2^-) plus water, with an energy yield of about 65 kilocalories per mole, which is quite adequate for a comfortable existence. *Nitrosomonas* belongs to the group of microorganisms termed autotrophs, which get along without an organic source of energy. Photoautotrophs obtain their energy from light; chemoautotrophs (such as *Nitrosomonas*) obtain energy from inorganic compounds.

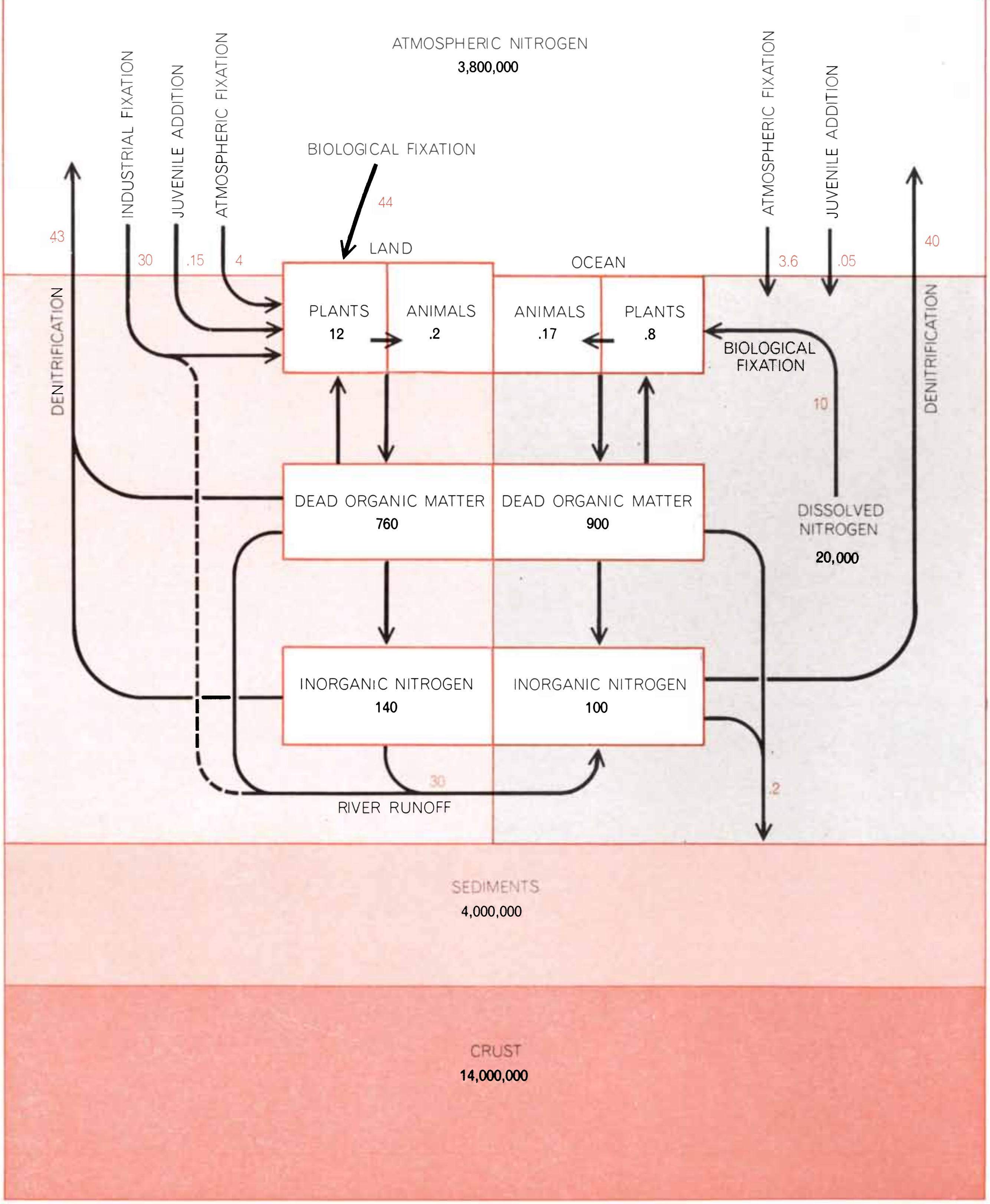
There is another specialized group of microorganisms, represented by *Nitrobacter*, that are capable of extracting additional energy from the nitrite generated by *Nitrosomonas*. The result is the oxidation of a nitrite ion to a nitrate ion with the release of about 17 kilocalories per mole, which is just enough to support the existence of *Nitrobacter*.

In the soil there are numerous kinds of denitrifying bacteria (for example *Pseudomonas denitrificans*) that, if obliged to exist in the absence of oxygen, are able to use the nitrate or nitrite ion as electron acceptors for the oxidation of organic compounds. In these reactions the energy yield is nearly as large as it would be if pure oxygen were the oxidizing agent. When glucose reacts with oxygen, the energy yield is 686 kilocalories per mole of glucose. In microorganisms living under anaerobic conditions the reaction of glucose with nitrate ion yields about 545 kilocalories per mole of glucose if the nitrogen is reduced to nitrous oxide, and 570 kilocalories if the nitrogen is reduced all the way to its elemental gaseous state.

The comparative value of ammonium and nitrate ions as a source of nitrogen for plants has been the subject of a number of investigations. One might think that the question would be readily resolved in favor of the ammonium ion: its valence is minus 3, the same as the valence of nitrogen in amino acids, whereas the valence of the nitrate ion is plus 5.



A cycle similar to the one illustrated also operates in the ocean, but its characteristics and transfer rates are less well understood. A global nitrogen flow chart, using the author's estimates, appears on the next page.



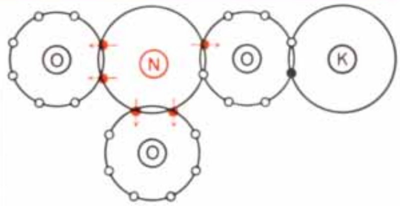
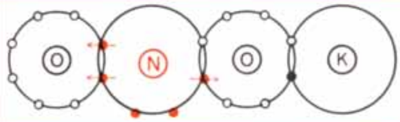
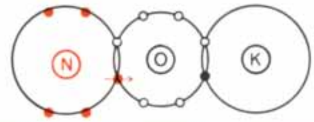
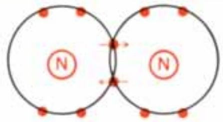
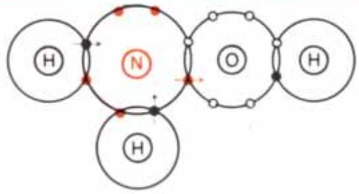
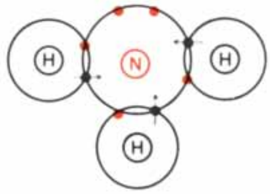
DISTRIBUTION OF NITROGEN in the biosphere and annual transfer rates can be estimated only within broad limits. The two quantities known with high confidence are the amount of nitrogen in the atmosphere and the rate of industrial fixation. The apparent precision in the other figures shown here reflects chiefly an effort to preserve indicated or probable ratios among different inventories. Thus the figures for atmospheric fixation and biological fixation in the oceans could well be off by a factor of 10. The figures for inventories are given in billions of metric tons; the figures for transfer rates (*color*) are given in millions of metric tons. Because of the extensive use of industrially fixed nitrogen the amount of nitrogen available to land plants may significantly exceed the nitrogen returned to the atmosphere by denitrifying bacteria in the soil. A portion of this excess fixed nitrogen is ultimately washed into the sea but it is not included in the figure shown for river runoff. Similarly, the value for oceanic denitrification is no more than a rough estimate that is based on the assumption that the nitrogen cycle was in overall balance before man's intervention.

On this basis plants must expend energy to reduce nitrogen from a valence of plus 5 to one of minus 3. The fact is, however, that there are complicating factors; the preferred form of nitrogen depends on other variables. Because the ammonium ion has a positive charge it tends to be trapped on clay particles near the point where it is formed (or where it is introduced artificially) until it has been oxidized. The nitrate ion, being negatively charged, moves freely through the soil and thus is more readily carried downward into the root zone. Although the demand for fertilizer in solid form (such as ammonium nitrate and urea) remains high, anhydrous ammonia and liquid ammoniacal fertilizers are now widely applied. The quantity of nitrogen per unit weight of ammonia is much greater than it is per unit of nitrate; moreover, liquids are easier to handle than solids.

Until the end of the 19th century little was known about the soil organisms that fix nitrogen. In fact, at that time there was some concern among scientists that the denitrifying bacteria, which had just been discovered, would eventually deplete the reserve of fixed nitrogen in the soil and cripple farm productivity. In an address before the Royal Society of London, Sir William Crookes painted a bleak picture for world food production unless artificial means of fixing nitrogen were soon developed. This was a period when Chilean nitrate reserves were the main source of fixed nitrogen for both fertilizer and explosives. As it turned out, the demand for explosives provided the chief incentive for the invention of the catalytic fixation process by Fritz Haber and Karl Bosch of Germany in 1914. In this process atmospheric nitrogen and hydrogen are passed over a catalyst (usually nickel) at a temperature of about 500 degrees Celsius and a pressure of several hundred atmospheres. In a French version of the process, developed by Georges Claude, nitrogen was obtained by the fractional liquefaction of air. In current versions of the Haber process the source of hydrogen is often the methane in natural gas [*see illustration on page 143*].

As the biological fixation of nitrogen and the entire nitrogen cycle became better understood, the role of the denitrifying bacteria fell into place. Without such bacteria to return nitrogen to the atmosphere most of the atmospheric nitrogen would now be in the oceans or locked up in sediments. Actually, of course, there is not enough oxygen in the atmosphere today to convert all the free nitrogen into nitrates. One can imagine, however, that if a one-way process were to develop in the absence of denitrifying bacteria, the addition of nitrates to the ocean would make seawater slightly more acidic and start the release of carbon dioxide from carbonate rocks. Eventually the carbon dioxide would be taken up by plants, and if the carbon were then deposited as coal or other hydrocarbons, the remaining oxygen would be available in the atmosphere to be combined with nitrogen. Because of the large number of variables involved it is difficult to predict how the world would look without the denitrification reaction, but it would certainly not be the world we know.

The full story of the biological fixation of nitrogen has not yet been written. One would like to know how the activating enzyme (nitrogenase) used by nitrogen-fixing bacteria can accomplish at ordinary temperatures and pressures what

VALENCE	COMPOUND	FORMULA	VALENCE ELECTRONS
+5	NITRATE ION	NO_3^-	
+3	NITRITE ION	NO_2^-	
+1	NITROXYL	[HNO]	
0	NITROGEN GAS	N_2	
−1	HYDROXYLAMINE	$HONH_2$	
−3	AMMONIA	NH_3	

NITROGEN'S VARIETY OF OXIDATION LEVELS, or valence states, explains its ability to combine with hydrogen, oxygen and other atoms to form a great variety of biological compounds. Six of its valence states are listed with schematic diagrams (*right*) showing the disposition of electrons in the atom's outer (valence) shell. The ions are shown combined with potassium (K). In the oxidized (+) states nitrogen's outer electrons complete the outer shells of other atoms. In the reduced (−) states the two electrons needed to complete the outer shell of nitrogen are supplied by other atoms. Actually the outer electrons of two bound atoms spend some time in the shells of both atoms, contributing to the electrostatic attraction between them. Electrons of nitrogen (N) are in color; those of other atoms are black dots or open circles. The nitroxyl radical, HNO, is placed in brackets because it is not stable. It can exist in its dimeric form, hyponitrous acid (HONNOH).

takes hundreds of degrees and thousands of pounds of pressure in a synthetic-ammonia reactor. The total amount of nitrogenase in the world is probably no more than a few kilograms.

The nitrogen-fixing microorganisms are divided into two broad classes: those that are "free-living" and those that live in symbiotic association with higher plants. This distinction, however, is not as sharp as it was once thought to be, because the interaction of plants and microorganisms has varying degrees of intimacy. The symbionts depend directly on the plants for their energy supply and probably for special nutrients as well. The free-living nitrogen fixers are indirectly dependent on plants for their energy or, as in the case of the blue-green algae and photosynthetic bacteria, obtain energy directly from sunlight.

Although the nitrogen-fixation reaction is associated with only a few dozen species of higher plants, these species are widely distributed in the plant kingdom. Among the more primitive plants whose symbionts can fix nitrogen are the cycads and the ginkgos, which can be traced back to the Carboniferous period of some 300 million years ago [see bottom illustration on page 145]. It is probable that the primitive atmosphere of the earth contained ammonia, in which case the necessity for nitrogen fixation did not arise for hundreds of millions of years.

Various kinds of bacteria, particularly the Azotobacteraceae, are evidently the chief suppliers of fixed nitrogen in grasslands and other ecosystems where plants with nitrogen-fixing symbionts are absent. Good quantitative information on the rate of nitrogen fixation in such ecosystems is hard to obtain. Most investigations indicate a nitrogen-fixation rate of only two or three kilograms per hectare per year, with a maximum of perhaps five or six kilograms. Blue-green algae seem to be an important source of fixed nitrogen under conditions that favor their development [see illustration on page 136]. They may be a significant source in rice paddies and other environments favoring their growth. In natural ecosystems with mixed vegetation the symbiotic associations involving such plant genera as *Alnus* (the alders) and *Ceanothus* (the buckthorns) are important suppliers of fixed nitrogen.

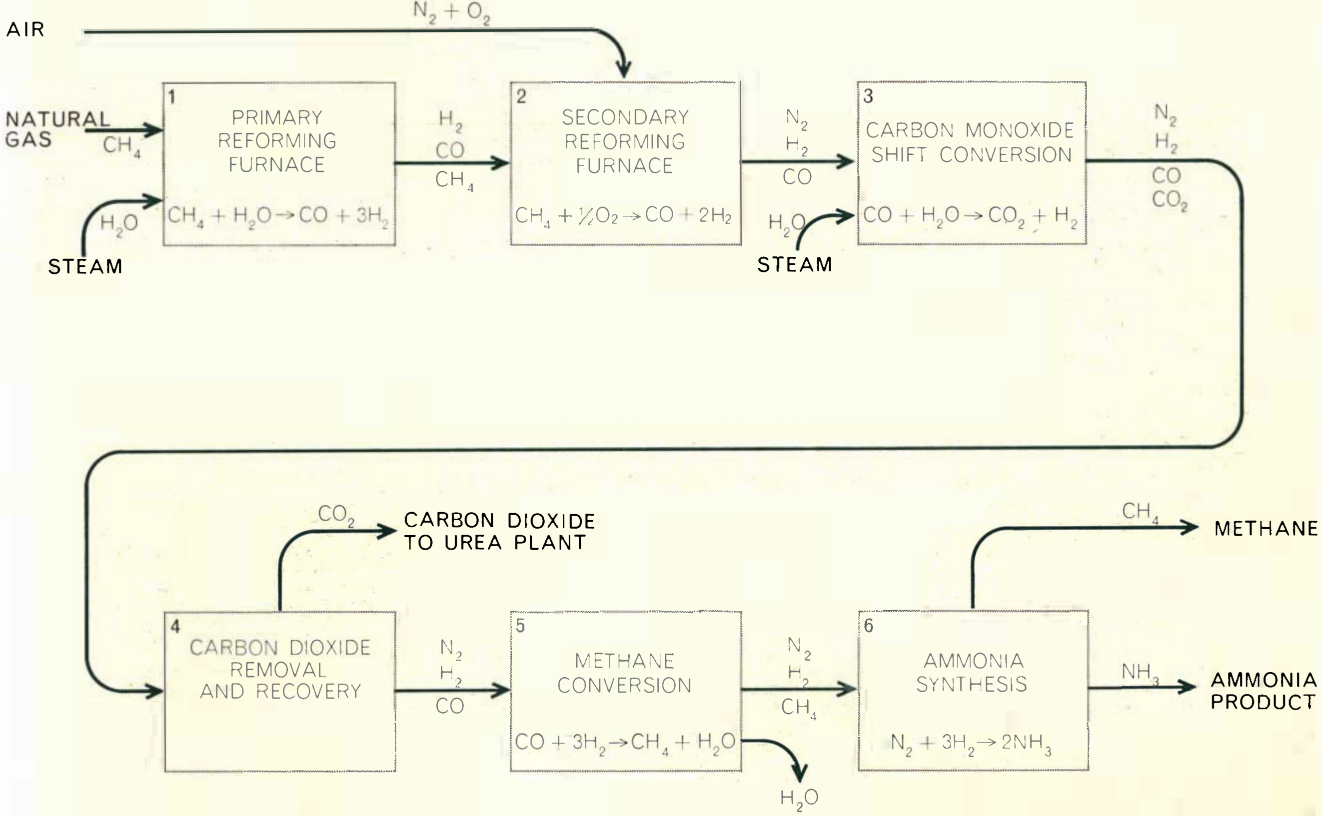
For the earth as a whole, however, the greatest natural source of fixed nitrogen is probably the legumes. They are certainly the most important from an agronomic standpoint and have therefore been the most closely studied. The input of nitrogen from the microbial symbionts of alfalfa and other leguminous crops can easily amount to 350 kilograms per hectare, or roughly 100 times the annual rate of fixation attainable by nonsymbiotic organisms in a natural ecosystem.

Recommendations for increasing the world's food supply usually emphasize increasing the cultivation of legumes not only to enrich the soil in nitrogen but also because legumes (for example peas and beans) are themselves a food crop containing a good nutritional balance of amino acids. There are, however, several obstacles to carrying out such recommendations. The first is custom and taste. Many societies with no tradition of growing and eating legumes are reluctant to adopt them as a basic food.

For the farmer legumes can create a more immediate problem: the increased yields made possible by the extra nitrogen lead to the increased consumption of other essential elements, notably potassium and phosphorus. As a consequence farmers often say that legumes are "hard on the soil." What this really means is that the large yield of such crops places

REACTION	ENERGY YIELD (KILOCALORIES)
DENITRIFICATION	
1 $C_6H_{12}O_6 + 6KNO_3 \longrightarrow 6CO_2 + 3H_2O + 6KOH + 3N_2O$ GLUCOSE; POTASSIUM NITRATE; POTASSIUM HYDROXIDE; NITROUS OXIDE	545
2 $5C_6H_{12}O_6 + 24KNO_3 \longrightarrow 30CO_2 + 18H_2O + 24KOH + 12N_2$ NITROGEN	570 (PER MOLE OF GLUCOSE)
3 $5S + 6KNO_3 + 2CaCO_3 \longrightarrow 3K_2SO_4 + 2CaSO_4 + 2CO_2 + 3N_2$ SULFUR; POTASSIUM SULFATE; CALCIUM SULFATE	132 (PER MOLE OF SULFUR)
RESPIRATION	
4 $C_6H_{12}O_6 + 6O_2 \longrightarrow 6CO_2 + 6H_2O$ CARBON DIOXIDE; WATER	686
AMMONIFICATION	
5 $CH_2NH_2COOH + 1\frac{1}{2}O_2 \longrightarrow 2CO_2 + H_2O + NH_3$ GLYCINE; OXYGEN; AMMONIA	176
NITRIFICATION	
6 $NH_3 + 1\frac{1}{2}O_2 \longrightarrow HNO_2 + H_2O$ NITROUS ACID	66
7 $KNO_2 + \frac{1}{2}O_2 \longrightarrow KNO_3$ POTASSIUM NITRITE	17.5
NITROGEN FIXATION	
8 $N_2 \longrightarrow 2N$ "ACTIVATION" OF NITROGEN	-160
9 $2N + 3H_2 \longrightarrow 2NH_3$	12.8

ENERGY YIELDS OF REACTIONS important in the nitrogen cycle show the various means by which organisms can obtain energy and thereby keep the cycle going. The most profitable are the denitrification reactions, which add electrons to nitrate nitrogen, whose valence is plus 5, and shift it either to plus 1 (as in N_2O) or zero (as in N_2). In the process glucose (or sulfur) is oxidized. Reactions No. 1 and No. 2 release nearly as much energy as conventional respiration (*No. 4*), in which the agent for oxidizing glucose is oxygen itself. The ammonification reaction (*No. 5*) is one of many that release ammonium for nitrification. The least energy of all, but still enough to provide the sole energetic support for certain bacteria, is released by the nitrification reactions (*No. 6 and No. 7*), which oxidize nitrogen. Only nitrogen fixation, which is accomplished in two steps, calls for an input of energy. The true energy cost of nitrogen fixation to an organism is unknown, however.



INDUSTRIAL AMMONIA PROCESS is based on the high-pressure catalytic fixation method invented in 1914 by Fritz Haber and Karl Bosch, which supplied Germany with nitrates for explosives in World War I. This flow diagram is based on the process developed by the M. W. Kellogg Company. As in most modern plants, the hydrogen for the basic reaction is obtained from methane, the chief constituent of natural gas, but any hydrocarbon source will do. In Step 1 methane and steam react to produce a gas rich in hydrogen. In Step 2 atmospheric nitrogen is introduced; the oxygen accompanying it is converted to carbon monoxide by partial combustion with methane. The carbon monoxide reacts with steam in Step 3. The carbon dioxide is removed in Step 4 and can be used elsewhere to convert some of the ammonia to urea, which has the formula $CO(NH_2)_2$. The last traces of carbon monoxide are converted to methane in Step 5. In Step 6 nitrogen and hydrogen combine at elevated temperature and pressure, in the presence of a catalyst, to form ammonia. A portion of the ammonia product can readily be converted to nitric acid by reacting it with oxygen. Nitric acid and ammonia can then be combined to produce ammonium nitrate, which, like urea, is another widely used fertilizer.

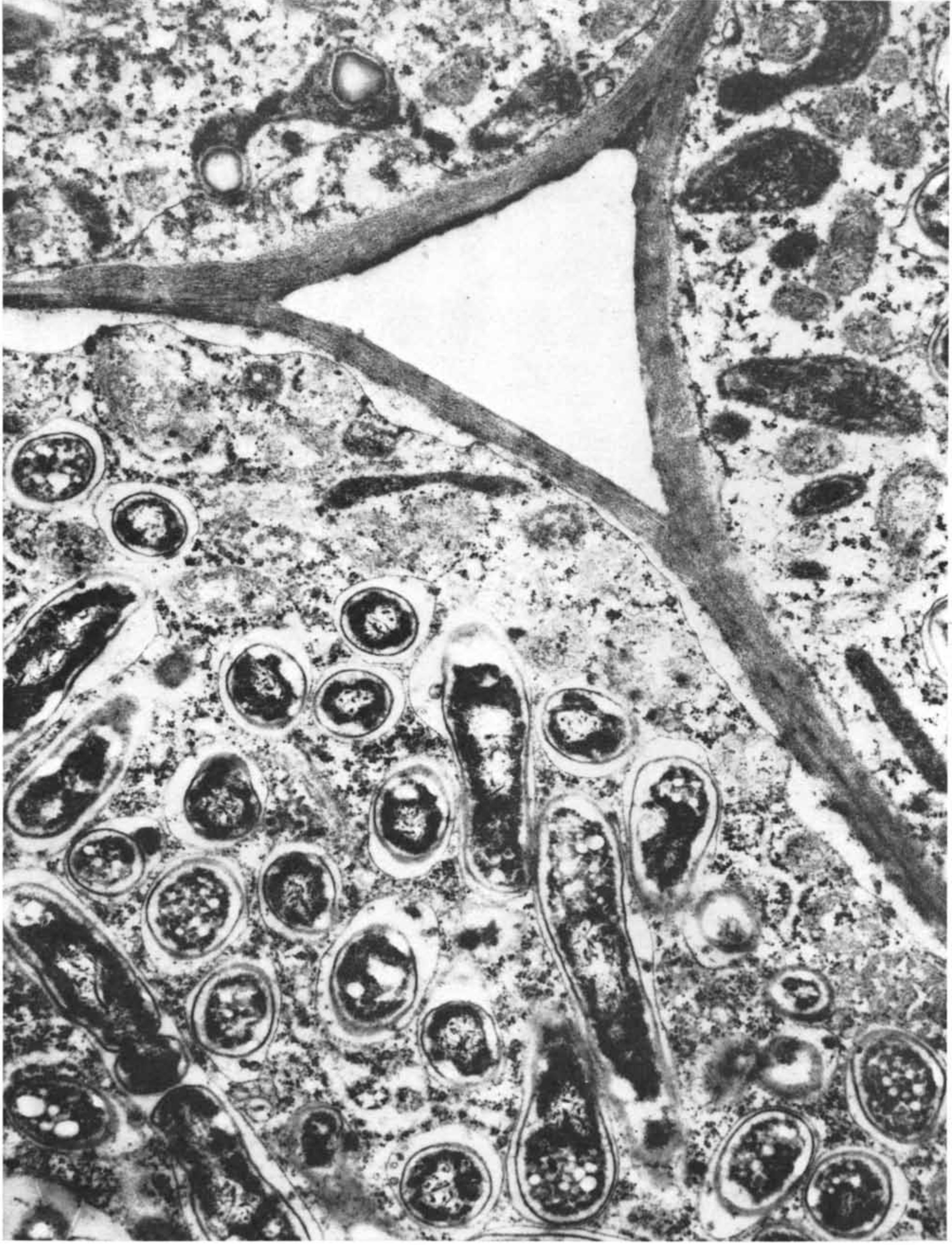
a high demand on all minerals, and unless the minerals are supplied the full benefit of the crop is not realized.

Symbiotic nitrogen fixers have a greater need for some micronutrients (for example molybdenum) than most plants do. It is now known that molybdenum is directly incorporated in the nitrogen-fixing enzyme nitrogenase. In Australia there were large areas where legumes refused to grow at all until it was discovered that the land could be made fertile by the addition of as little as two ounces of molybdenum per acre. Cobalt turns out to be another essential micronutrient for the fixation of nitrogen. The addition of only 10 parts per trillion of cobalt in a culture solution can make the difference between plants that are stunted and obviously in need of nitrogen and plants that are healthy and growing vigorously.

Although legumes and their symbionts are energetic fixers of nitrogen, there are indications that the yield of a legume crop can be increased still further by direct application of fertilizer instead of depending on the plant to supply all its own needs for fixed nitrogen. Additional experiments are needed to determine just how much the yield can be increased and how this increase compares with the industrial fixation of nitrogen in terms of energy investment. Industrial processes call for some 6,000 kilocalories per kilogram of nitrogen fixed, which is very little more than the theoretical minimum. The few controlled studies with which I am familiar suggest that the increase in crop yield achieved by the addition of a kilogram of nitrogen amounts to about the same number of calories. This comparison suggests that one can exchange the calories put into industrial fixation of nitrogen for the calories contained in food. In actuality this trade-off applies to the entire agricultural enterprise. The energy required for preparing, tilling and harvesting a field and for processing and distributing the product is only slightly less than the energy contained in the harvested crop.

Having examined the principal reactions that propel the nitrogen cycle, we are now in a position to view the process as a whole and to interpret some of its broad implications. As other authors in this issue of *Scientific American* have explained, one must be cautious in trying to present a worldwide inventory of a particular element in the biosphere and in indicating annual flows from one part of a cycle to another. The balance sheet for nitrogen [*see top illustration on page 145*] is particularly crude because we do not have enough information to assign accurate estimates to the amounts of nitrogen that are fixed and subsequently returned to the atmosphere by biological processes.

Another source of uncertainty involves the amount of nitrogen fixed by ionizing phenomena in the atmosphere. Although one can measure the amount of fixed nitrogen in rainfall, one is forced to guess



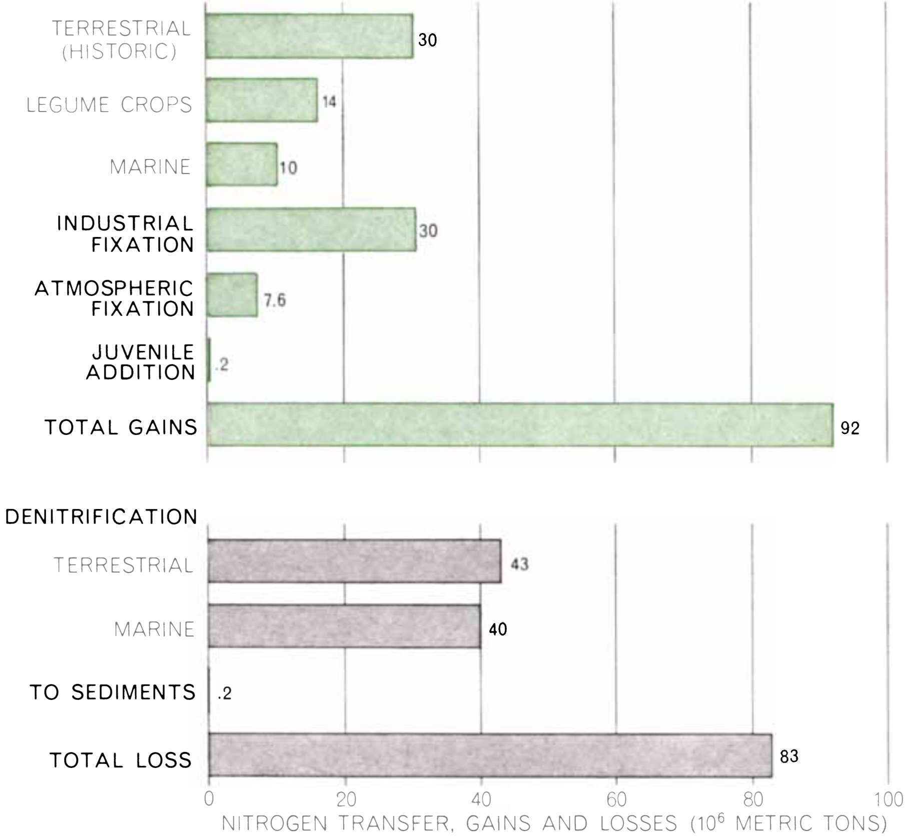
CROSS SECTION OF SOYBEAN ROOT NODULE, enlarged 22,000 diameters, shows portions of three cells that have been infected by the nitrogen-fixing bacterium *Rhizobium japonicum.* More than two dozen bacteria are visible, each surrounded by a membrane. After the bacteria have divided, within a few days, each membrane will contain four to six "bacteroids." This electron micrograph was made by D. J. Goodchild and F. J. Bergersen of the Commonwealth Scientific and Industrial Research Organization in Australia.

how much represents nitrogen that has entered the atmosphere from the land or the sea, either as ammonia or as oxides of nitrogen. Because the ocean is slightly alkaline it could release ammonia at a low rate, but that rate is almost impossible to estimate. Land areas are a more likely source of nitrogen oxides, and some reasonable estimates of the rate of loss are possible. One can say that the total amount of fixed nitrogen delivered to the earth by rainfall is of the order of 25 million metric tons per year. My own estimate is that 70 percent of this total is previously fixed nitrogen cycling through the biosphere, and that only 30 percent is freshly fixed by lightning and other atmospheric phenomena.

Another factor that is difficult to estimate is the small but steady loss of nitrogen from the biosphere to sedimentary rocks. Conversely, there is a continuous delivery of new nitrogen to the system by the weathering of igneous rocks in the crust of the earth. The average nitrogen content of igneous rocks, however, is considerably lower than that of sedimentary rocks, and since the quantities of the two kinds of rock are roughly equal, one would expect a net loss of nitrogen from the biosphere through geologic time. Conceivably this loss is just about balanced by the delivery of "juvenile" nitrogen to the atmosphere by volcanic action. The amount of fixed nitrogen reintroduced in this way probably does not exceed two or three million tons per year.

Whereas late-19th-century scientists worried that denitrifying bacteria were exhausting the nitrogen in the soil, we must be concerned today that denitrification may not be keeping pace with nitrogen fixation, considering the large amounts of fixed nitrogen that are being introduced in the biosphere by industrial fixation and the cultivation of legumes. It has become urgent to learn much more about exactly where and under what circumstances denitrification takes place.

We know first of all that denitrification does not normally proceed to any great extent under aerobic conditions. Whenever free oxygen is available, it is energetically advantageous for an organism to use it to oxidize organic compounds rather than to use the oxygen bound in nitrate salts. One can conclude that there must be large areas in the biosphere where conditions are sufficiently anaerobic to strongly favor the denitrification reaction. Such conditions exist wherever the input of organic materials



BALANCE SHEET FOR NITROGEN CYCLE, based on the author's estimates, indicates that nitrogen is now being introduced into the biosphere in fixed form at the rate of some 92 million metric tons per year (*colored bars*), whereas the total amount being denitrified and returned to the atmosphere is only about 83 million tons per year. The difference of some nine million tons may represent the rate at which fixed nitrogen is building up in the biosphere: in the soil, in ground-water reservoirs, in rivers and lakes and in the ocean.

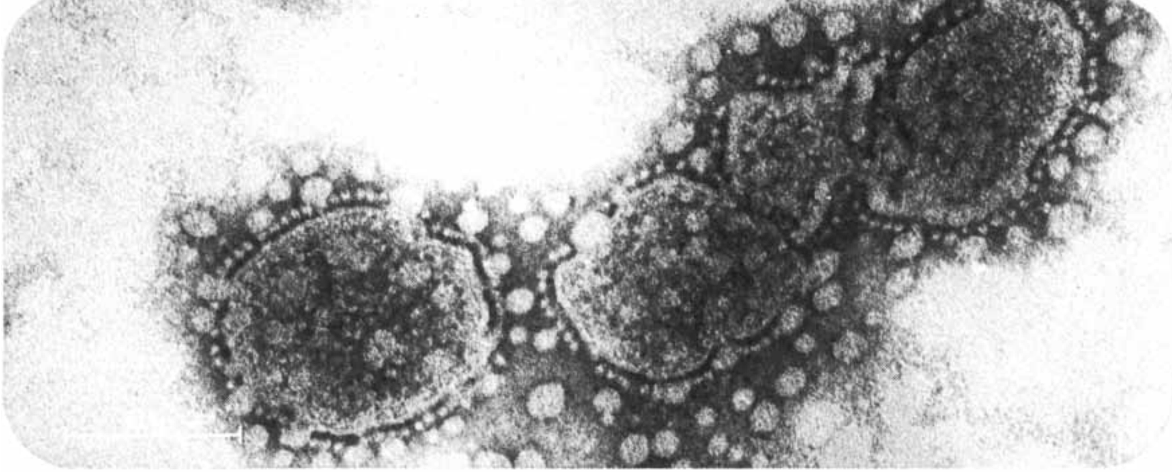
ASSOCIATIONS OF TREES AND BACTERIA are important fixers of nitrogen in natural ecosystems. The ginkgo tree (*left*), a gymnosperm, has shown little outward change in millions of years. The alder (*right*), an angiosperm, is common in many parts of the world.

exceeds the input of oxygen for their degradation. Typical areas where the denitrification process operates close to the surface are the arctic tundra, swamps and similar places where oxygen input is limited. In many other areas where the input of organic material is sizable, however, denitrification is likely to be proceeding at some point below the surface, probably close to the level of the water table.

There are even greater uncertainties regarding the nitrogen cycle in the ocean. It is known that some marine organisms do fix nitrogen, but quantitative information is scanty. A minimum rate of denitrification can be deduced by estimating the amount of nitrate carried into the ocean by rivers. A reasonable estimate is 10 million metric tons per year in the form of nitrates and perhaps twice that amount in the form of organic material, a total of about 30 million tons. Since the transfer of nitrogen into sediments is slight, one can conclude that, at least before man's intervention in the nitrogen cycle, the ocean was probably capable of denitrifying that amount of fixed nitrogen.

The many blanks in our knowledge of the nitrogen cycle are disturbing when one considers that the amount of nitrogen fixed industrially has been doubling about every six years. If we add to this extra nitrogen the amounts fixed by the cultivation of legumes, it already exceeds (by perhaps 10 percent) the amount of nitrogen fixed in nature. Unless fertilizers and nitrogenous wastes are carefully managed, rivers and lakes can become loaded with the nitrogen carried in runoff waters. In such waterways and in neighboring ground-water systems the nitrogen concentration could, and in some cases already does, exceed the levels acceptable for human consumption. Under some circumstances bacterial denitrification can be exploited to control the buildup of fixed nitrogen, but much work has to be done to develop successful management techniques.

The problem of nitrogen disposal is aggravated by the nitrogen contained in the organic wastes of a steadily increasing human and domestic-animal population. Ideally this waste nitrogen should be recycled back to the soil, but efficient and acceptable means for doing so remain to be developed. At present it is economically sounder for the farmer to keep adding industrial fertilizers to his crops. The ingenuity that has been used to feed a growing world population will have to be matched quickly by an effort to keep the nitrogen cycle in reasonable balance.



How the two photosystems came to light

We have to go back to square one, to find the period in which Philips first showed an interest in light. 79 years later, we find them still hard at it. Having thoroughly explored many aspects, they have now turned to the biological effects of light.

Photosynthesis is the process by which green plants use light energy to convert water and carbon dioxide into carbohydrate and oxygen. The light energy is absorbed by chlorophyll and other photosynthetic pigments generating a reducing agent, $NADPH_2$, and an energy-rich compound ATP. Both components are needed for the light independent reduction of CO_2 to carbohydrate.

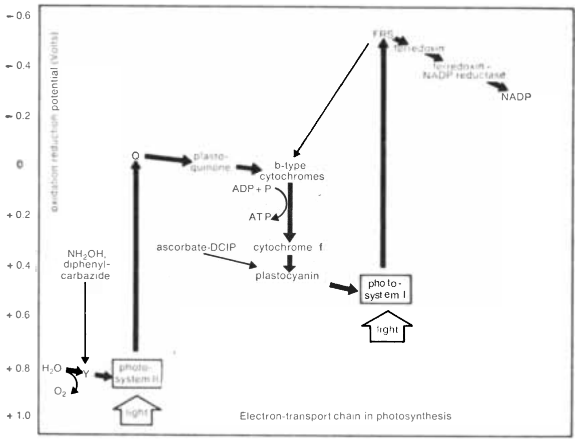
Photosynthesis actually occurs in the chloroplasts of the plant cell. These organelles contain a lamellar system, embedded in a matrix. The light reactions take place in the lamellae and the CO_2 reduction occurs in the matrix region of the chloroplast.

It is widely accepted that two light reactions, arranged in series, provide the energy for the uphill flow of electrons from water to NADP (see diagram). Light reaction II produces a strong oxidant, Y^+, which oxidizes H_2O to O_2, and a weak reductant Q^-. The chemical nature of Y and Q is not precisely known. Light reaction I yields a weak oxidant, oxidized plastocyanin, and a strong reductant, reduced FRS (ferredoxin reducing substance). FRS transfers its electron to ferredoxin and NADP is reduced to $NADPH_2$ in the presence of the enzyme ferredoxin-NADP reductase. In the downhill flow of electrons from the b-type cytochromes to cytochrome f, sufficient energy is made available to convert a molecule of ADP into ATP. There is evidence of a cyclic flow of electrons around photosystem I, also resulting in ATP formation.

As the chloroplast itself is still a complicated system, Dr. J. S. C. Wessels and his group at Philips Research Laboratories, Eindhoven, the Netherlands, studied whether subchloroplast particles were able to perform the photosynthetic light reactions. By fragmenting chloroplasts with low concentrations of the non-ionic detergent digitonin, they obtained vesicles, ranging in size from 50-200nm, surrounded by stalked knobs about 9nm in diameter (see electron-micrograph, made by Mrs. A. Dorsman using a Philips electron microscope). These vesicles, which are formed by the constriction of the chloroplast lamellae, are still able to produce $NADPH_2$ and ATP in the light. The knobs proved to be essential for the ATP synthesizing activity. Higher concentrations of digitonin were found to disrupt the vesicles and release small chlorophyll-containing particles. Two types of particle have been isolated by means of density gradient centrifugation. Both types were still photoactive and Dr. Wessels was able to show that they correspond to the two photosystems.

As a matter of fact the photosystem I particles reduce NADP in the light if they are provided with ferredoxin, ferredoxin-NADP reductase, plastocyanin and the electron donor couple ascorbate-dichlorophenolindophenol (DCIP). The photosystem II particles are able to carry out a photoreduction of DCIP in the presence of hydroxylamine or diphenylcarbazide as the electron donor.

Further studies of the chemical and physical properties of the separate photosystems should provide more information on the mechanism of the two light reactions of photosynthesis and might ultimately lead to planned intervention in plant metabolism.



Electron-transport chain in photosynthesis

In the Research Laboratories of the Philips group of companies, scientists work together in many fields of science. Among these are: Acoustics, Cryogenics, Information Processing, Mechanics, Nuclear Physics, Perception, Solid State, Telecommunications and Television.

PHILIPS

MINERAL CYCLES

Although the biosphere is mainly composed of hydrogen, carbon, nitrogen and oxygen, other elements are essential constituents of living matter. Notable among them are phosphorus and sulfur

by Edward S. Deevey, Jr.

The periodic table lists more than 100 chemical elements. Yet ecologists have defined the biosphere as the locus of interaction of only four of them: hydrogen, carbon, nitrogen and oxygen. In the periodic table these four are numbered 1, 6, 7 and 8. This definition, although it deals handsomely with much of the chemistry of life, turns out to be a little too restrictive. But when we enlarge it to include phosphorus and sulfur, as we do here, we have gone no farther up the table than element No. 16. From this it should be apparent that no element lighter than sulfur can be ignored, either by ecologists or by anyone else. The fact is that most human problems—all environmental ones, anyway—arise from the exceptional reactivity of six of the 16 lightest elements.

Because our definition of the biosphere is based more on reactivity than on atomic number, it is a minimum definition. It is not intended to exclude heavier elements that react with the primary six. As a matter of empirical fact it is known that no element lighter than iron and cobalt, elements No. 26 and No. 27, is unimportant to the biosphere. Beyond copper, No. 29, there are a few conspicuously reactive elements such as the heavy halogens bromine and iodine. Most of the heavies are metals, such as gold, mercury and lead (Nos. 79, 80 and 82), however, and their main effect on the lightweight biosphere is to depress it. Toward the end of the periodic table are some famously overweight metals whose tendency to lighten themselves has disastrous effects on any light substances that get in the way.

In order to understand how it is that many elements interact with the essential six, one must briefly reflect on the biosphere as a whole. Because the biosphere is so reactive, its influence on the hydrosphere, the lithosphere and the atmosphere is inversely proportional to its mass. This mass is very small. An average square centimeter of the earth's surface supports a tiny amount of biosphere: 580 milligrams, less than the weight of two aspirin tablets. A roughly equivalent mass is found in the same area of hydrosphere a single centimeter deep, or in a paper-thin slice of lithosphere. Still, from a worm's-eye view the biosphere has real substance, particularly on land, where it amounts to 200 oven-dry tons on an average hectare.

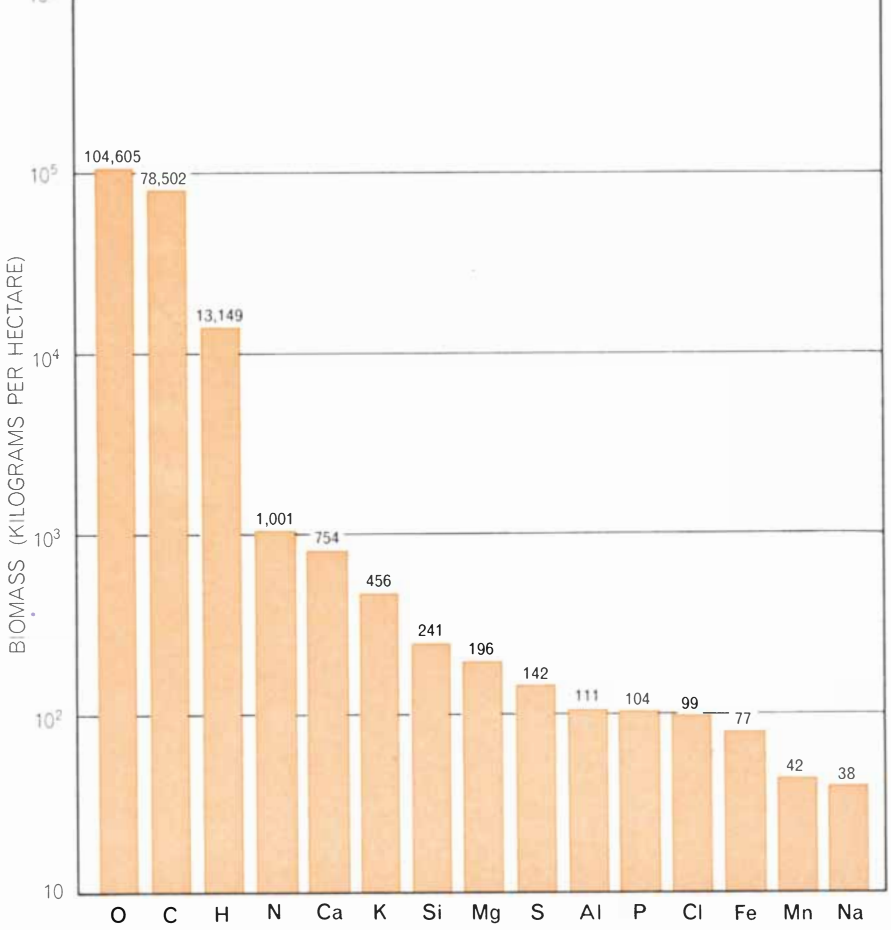
A glance at a partial list of the elements that compose the biosphere shows why hydrogen, oxygen, carbon and nitrogen dominate conceptions of biosphere chemistry. Together these elements constitute all but a tiny fraction of the average terrestrial vegetation, which in turn constitutes more than 99 percent of the world's standing crop. The quantities are shown in the chart on the next page, based on a splendid compilation by L. E. Rodin and N. I. Basilevich. What I have done is to weight their chemical analyses in proportion to the kinds of land area they represent. The weighting factors, for desert, forest, tundra and so on, are the same ones I used to calculate the earth's production of carbon in an earlier article ["The Human Population," by Edward S. Deevey, Jr.; Scientific American, September, 1960]. Incidentally, on the basis of this new calculation terrestrial carbon production comes out at 65×10^9 tons of carbon per year, about 15 percent more than the figure I computed before.

What chemical compounds do these elements form? The standard way to determine the chemical composition of an organic substance is to burn it and collect the products. The list of components that results from this destructive procedure expresses some obvious facts, such as the familiar one that the biosphere is mainly carbon dioxide and water. Nitrogen, a major constituent of protein, seems surprisingly scarce (about five parts per 1,000 by weight) until we remember that the biosphere is chiefly wood, that is, not protein but the carbohydrate cellulose.

The destructive procedure would also leave a smudge, about 12 parts per 1,000 of the total, loosely called ash. Its dominant elements calcium, potassium, silicon and magnesium have important biochemical functions. One atom of magnesium, for instance, lies at the center of every molecule of chlorophyll, and silicon, the stuff of sand, is obviously useful for building hard structures. Iron and manganese also play central roles in the biosphere, a fact that could not be guessed from their position in our chart. In biochemistry as in geochemistry the importance of these elements is in governing oxidation-reduction reactions, but the masses involved are small. As for the major cations—ions of such elements as calcium, potassium, magnesium and sodium—new insights have just begun to flood in with their discovery in rainwater.

There are many other metallic elements that appear in trace amounts. Not all of them are listed in the chart because some could be accidental con-

SULFUR-FIXING BACTERIUM shown in the electron micrograph on the opposite page is one of five species that make sulfur available to the biosphere. This bacterium, *Desulfovibrio salexigens*, metabolizes the sulfates in seawater and releases the sulfur as hydrogen sulfide. This sulfur enters the atmosphere and is used by other forms of life. The micrograph enlarges the bacterium 31,000 diameters. It was made by Judith A. Murphy of the University of Illinois.



COMPOSITION OF THE BIOSPHERE is dominated by oxygen, carbon and hydrogen, as is indicated by the bars in this logarithmic chart. The units are kilograms per hectare of land surface. Key to the symbols for the chemical elements is at the bottom of the page.

taminants. There remain two, sulfur and phosphorus, each amounting to more than 10 percent of the nitrogen, that do not look like contaminants. To ignore these elements as "traces" or even to think of them as "ash" or "inorganic" elements is to misconstrue the chemical architecture of the biosphere.

A listing of elements and compounds does not reveal that architecture. There is a big difference between a finished house and a pile of building materials. Nevertheless, a list is a useful point of departure. If it is made with care, it can protect ecologists from the kind of mistake that architects sometimes make, such as forgetting the plumbing.

When a list contains as much information as a shopping list—when it shows amounts as well as kinds of materials—some conclusions can be drawn from the relative proportions. (As a former bureaucrat I have learned that a "laundry list" contains even more ambiguous information than a "shopping list"; good bureaucrats keep both.) If a housewife's shopping list showed a pound of coffee, four pork chops and 100 pounds of sugar, for example, we would know that madame is either hoarding or running a private business. If she also wants a ton of flour, she is evidently baking, not distilling. The inclusion of two dozen light bulbs would suggest that she works mainly at night, but the listing of 10 dozen light bulbs would point to a faulty generator.

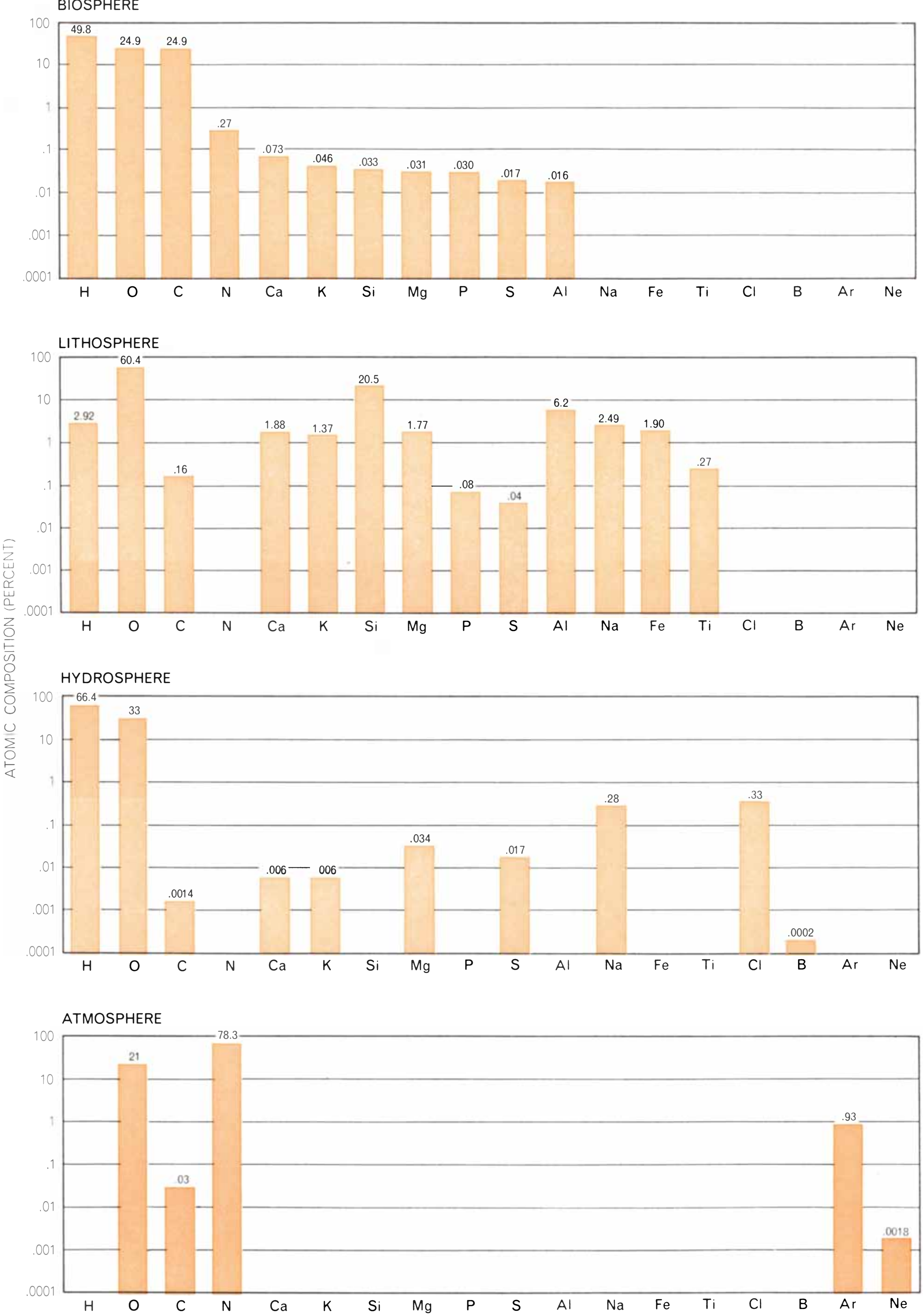
As it happens, this kind of semiquantitative ratiocination was applied to ash, and to biogeochemistry, by the master of nonobvious deduction, Sherlock Holmes. Unfortunately no copy of his analytical results (the monograph on cigar ash, cited in Chapter 4 of "A Study in Scarlet") has yet come to light. If the charts on the opposite page can serve as a substitute, we can cast a Holmesian eye over the list. Our thinking will be more productive if we compare the composition of the biosphere with the composition of the lithosphere, the hydrosphere and the atmosphere. For this comparison all four of the "spheres" in the chart are converted from parts by weight to atoms per 100 atoms. (The masses of the four spheres being very different, these percentages will give no idea of the earth's mean or total composition.)

At first glance the four spheres do not seem to belong in the same universe. Not surprisingly, the lithosphere turns out to be a slightly metallic aluminum silicate. ("Here is no water but only rock/Rock and no water and the sandy road," as T. S. Eliot put it in "The Waste Land.") The biosphere, in sharp contrast, is both wet and carbonaceous. A single class of compounds, formaldehyde (CH_2O) and its polymers, including cellulose, could make up more than 98 percent of the total (by weight). Still, even when it is dried in an oven at 110 degrees Celsius, life is mainly hydrogen and oxygen, in close approximation to the proportions known as water. In other words, the biosphere is notably carboxylated: it is both more hydrated and chemically more reduced (hydrogenated) than is the lithosphere from which, in some sense, it came. Among the 10 most abundant elements of the lithosphere there is no obvious source for life's carbon. Hydrogen is also fairly far down the list for rock (and would be farther down if I had not copied some old figures from Frank W. Clarke's *The Data of Geochemistry*, which overweight the acidic rocks of continents).

Even the elementary Dr. Watson might conclude that life's hydrogen comes from some inorganic hydrate—water, for instance—and indeed the hydrosphere provides an ample and ready supply. This will not work for carbon, though, and in trying to account for carboxylation we can make a deduction that is truly elementary in the Holmesian, or nonobvious, sense. We begin

Al	ALUMINUM	Cl	CHLORINE	Mn	MANGANESE	P	PHOSPHORUS
Ar	ARGON	Fe	IRON	N	NITROGEN	S	SULFUR
B	BORON	H	HYDROGEN	Na	SODIUM	Si	SILICON
C	CARBON	K	POTASSIUM	Ne	NEON	Ti	TITANIUM
Ca	CALCIUM	Mg	MAGNESIUM	O	OXYGEN		

RELATIVE AMOUNTS OF ELEMENTS in the biosphere, the lithosphere, the hydrosphere and the atmosphere are presented in the charts on the opposite page. Here, however, amounts are given not as kilograms per hectare but as atoms per 100 atoms. Here again scale is logarithmic to show less abundant elements, which otherwise could not be compared.



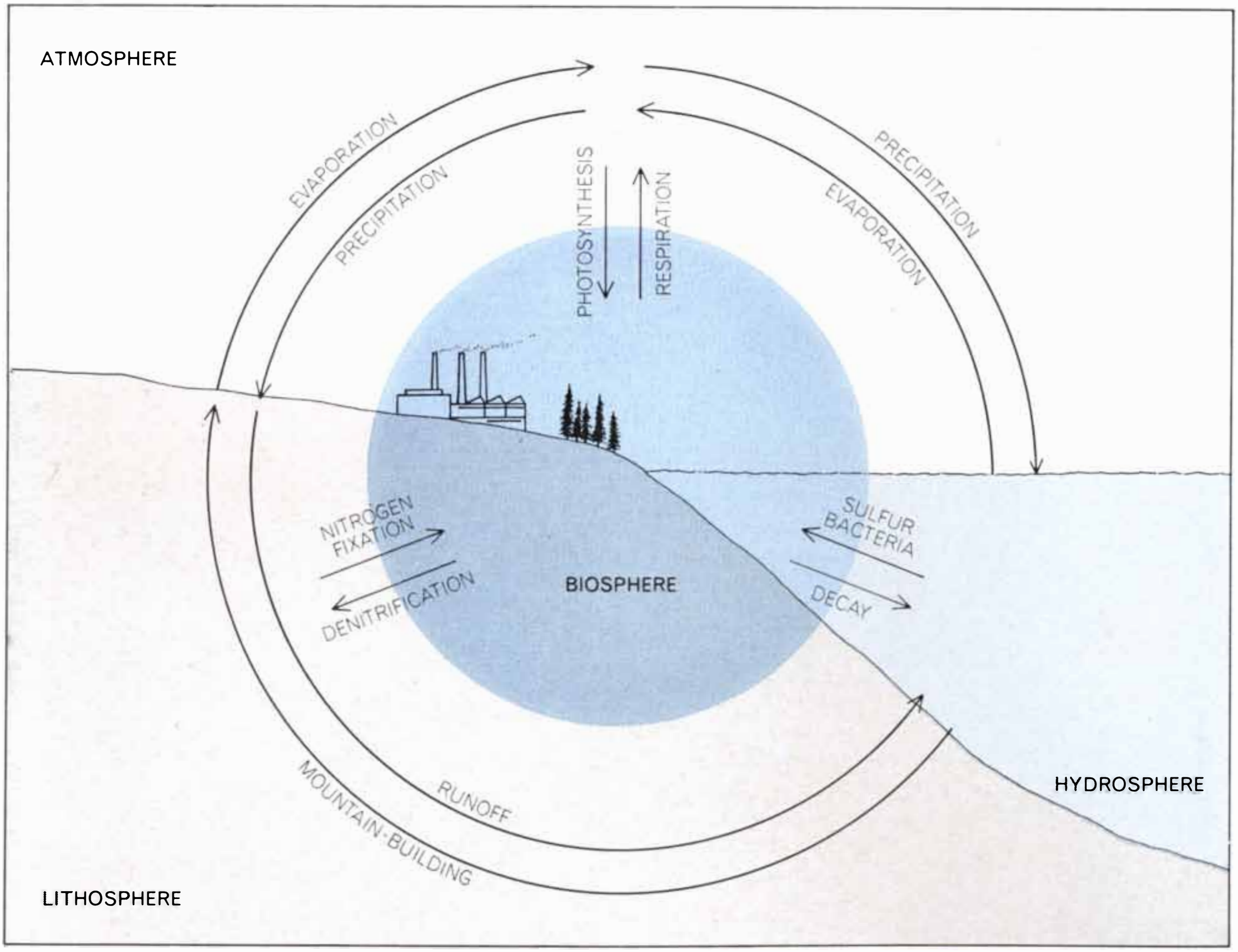
BIOSPHERE
49.8
24.9
24.9
.27
.073
.046
.033
.031
.030
.017
.016
LITHOSPHERE
2.92
60.4
.16
1.88
1.37
20.5
1.77
.08
.04
6.2
2.49
1.90
.27
HYDROSPHERE
66.4
33
.0014
.006
.006
.034
.017
.28
.33
.0002
ATMOSPHERE
21
.03
78.3
.93
.0018
100
10
1
.1
.01
.001
.0001
H O C N Ca K Si Mg P S Al Na Fe Ti Cl B Ar Ne
ATOMIC COMPOSITION (PERCENT)

again by noting that life is mainly aqueous, and also that it concentrates carbon in proportions far greater than those in any accessible source. Is it possible that these facts are related? If they are, what do we know about water that throws any light on this relation and on the behavior of carbon? (At this point a lesser detective might reach for the carbonated water and pause for a reply.)

Instead of guessing, Holmes would proceed with his review of the evidence. Water, of course, is continuously recycled near the earth's surface, by runoff, evaporation and condensation. That is, it flows in rivers from the lithosphere to the hydrosphere, and it returns to rewash the land by way of the atmosphere. Any water-soluble elements are certain to track this cycle at least partway, from land to sea, although they may find the sea to be a sink, as boron does. If they are to get out, they can reach the land as part of an uplifted sea bottom, but that is a chancy mechanism. Recycling is both faster and surer if the element is volatile as well as soluble, so that one of its compounds can move landward through the atmosphere as water does.

In the biosphere there are at least three elements besides those of water—carbon, nitrogen and sulfur—that fall in this doubly mobile class. Among their airborne compounds are carbon dioxide (CO_2), methane (CH_4), free nitrogen (N_2), ammonia (NH_3), hydrogen sulfide (H_2S) and sulfur dioxide (SO_2). It is interesting that when carbon, nitrogen and sulfur are recycled, their valence changes. It may not be an accident that all three are more reduced in the biosphere than they are in the external world. Be that as it may, they all seem to belong to the biosphere, which is otherwise mainly water. Hence all three must be recycled together, *along with the water* (said Holmes with an air of quiet triumph), if the earth is to sustain its most unusual hydrate. ("And what is that?" I asked. "Why, *carbohydrate*, of course," said Holmes.)

I call this deduction nonobvious, because in an obvious variant it has become so familiar as to inhibit thought. The outlines of the carbon cycle, in organisms at any rate, have been evident since Joseph Priestley's day. The critical step, "obviously," is the photosynthetic reduction of carbon dioxide. That reaction is a hydrogenation, yielding formaldehyde. Its source of hydrogen is the dehydrogenation of water, with the liberation of oxygen. The chemical energy thus captured, by a process unique to green plants, becomes available, inside



CARBOXYLATION CYCLE supplies the biosphere with carbon, oxygen, hydrogen, nitrogen and sulfur by carrying them from the lithosphere, the hydrosphere and the atmosphere. Curved arrows at upper right and left represent any or all of these five elements that travel from the atmosphere to the lithosphere or to the hydrosphere by precipitation, or back to the atmosphere by evaporation. Curved arrows at bottom indicate direct routes between the lithosphere and the hydrosphere such as runoff, mountain-building and the hydration of minerals. Biosphere (*color*) captures these elements by providing alternative routes. Top pair of straight arrows show exchange between the biosphere and the atmosphere, carbon, for example, being exchanged by photosynthesis and respiration. Pair of straight arrows at right show exchange between the biosphere and the hydrosphere, that of sulfur being mediated by bacteria. Pair of arrows at left indicate soil-biosphere exchanges including nitrogen fixation and denitrification by microorganisms.

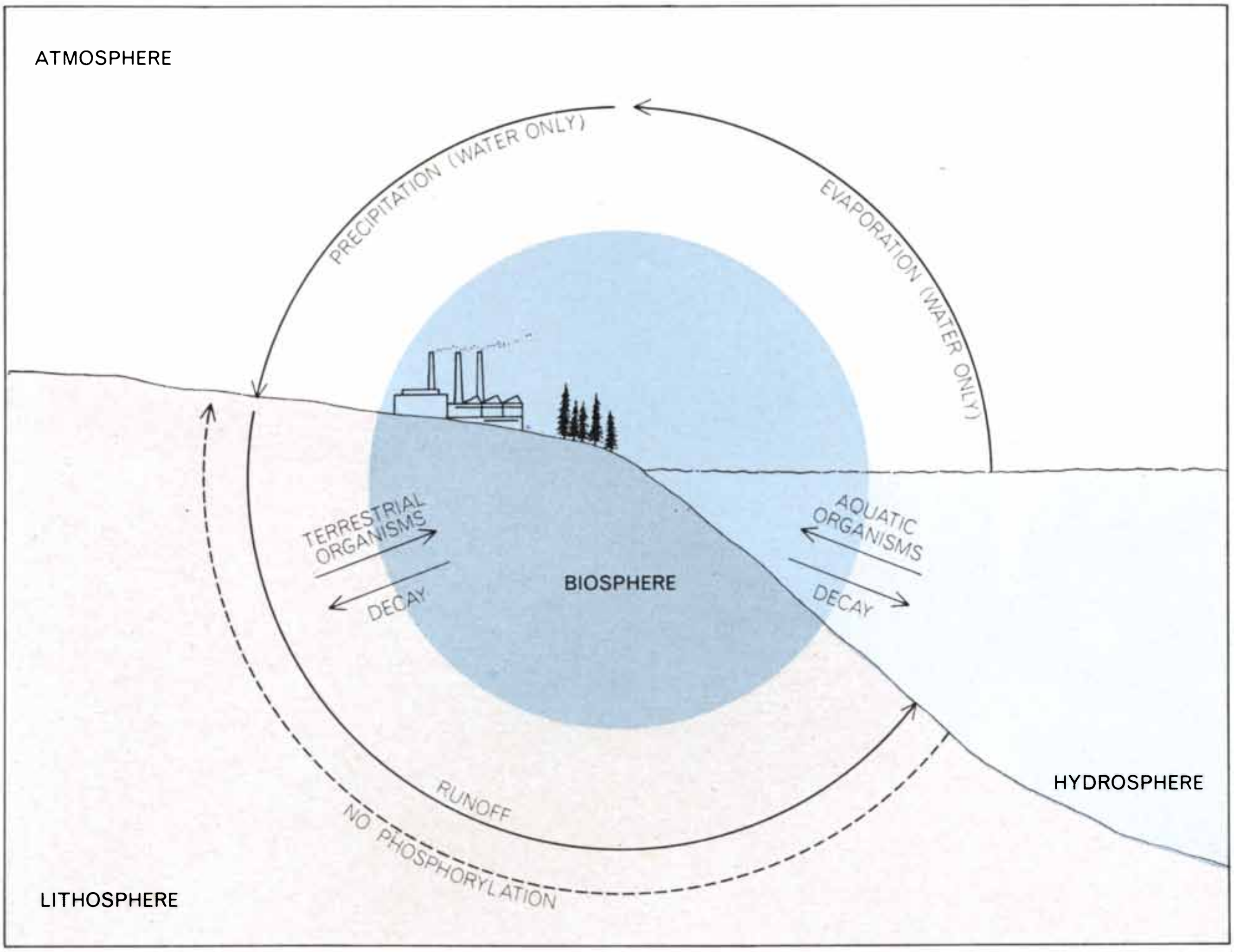
it not?). After its utilization, which includes consumption by animals, the reoxidized carbon dioxide can rejoin any geochemical cycles it likes.

All other vital reactions? Well, not quite all. The chemical reduction of nitrogen is one hydrogenation essential to green plants that they cannot perform for themselves. As one result, even elementary textbooks admit, the carbon and nitrogen cycles are necessarily interdependent. Without microorganisms that take nitrogen from the air and hydrogenate it (they can use carbon dioxide as a carbon source), all the nitrogen in the biosphere would soon appear in the atmosphere in stable, oxidized form. (The textbooks concede this point somewhat grudgingly, because much of the biological nitrogen cycle operates below the oxidation state of free nitrate and nitrite to amino acids and ammonia.)

If, as it turns out, sulfur too is recycled by way of the hydrologic cycle but independently of green plants, it becomes necessary to look beyond carbon and water for the clue to carboxylation. In other words, some biologists are not unlike architects who forget about the plumbing. In their preoccupation with carbon dioxide reduction as the starting point for cell biochemistry they tend to forget two other hydrogenations, those of sulfur and nitrogen, that are just as important.

A check is needed here, to be sure that these two elements are really intrinsic to the biosphere. In the case of sulfur the figures show it to be very scarce, and if it is a contaminant, the whole however, is no contaminant; no protein can be made without it. In fact, sulfur is the "stiffening" in protein. A protein cannot perform its function unless it is folded and shaped in a particular way. This three-dimensional structure is maintained by bonds between sulfur atoms that link one segment of a protein molecule to another. Without these sulfur bonds a protein would coil randomly, like a carelessly dropped rope.

The reason for the apparent scarcity of sulfur is the low protein content of woody tissue; any animal body contains much more. Cod-meal protein, for example, with 2.26 percent of the sulfurous amino acid methionine, has the empirical formula $H_{555}C_{265}O_{174}N_{83}S$. Although other proteins differ in the proportions, the substance of the biosphere must always contain these five elements.



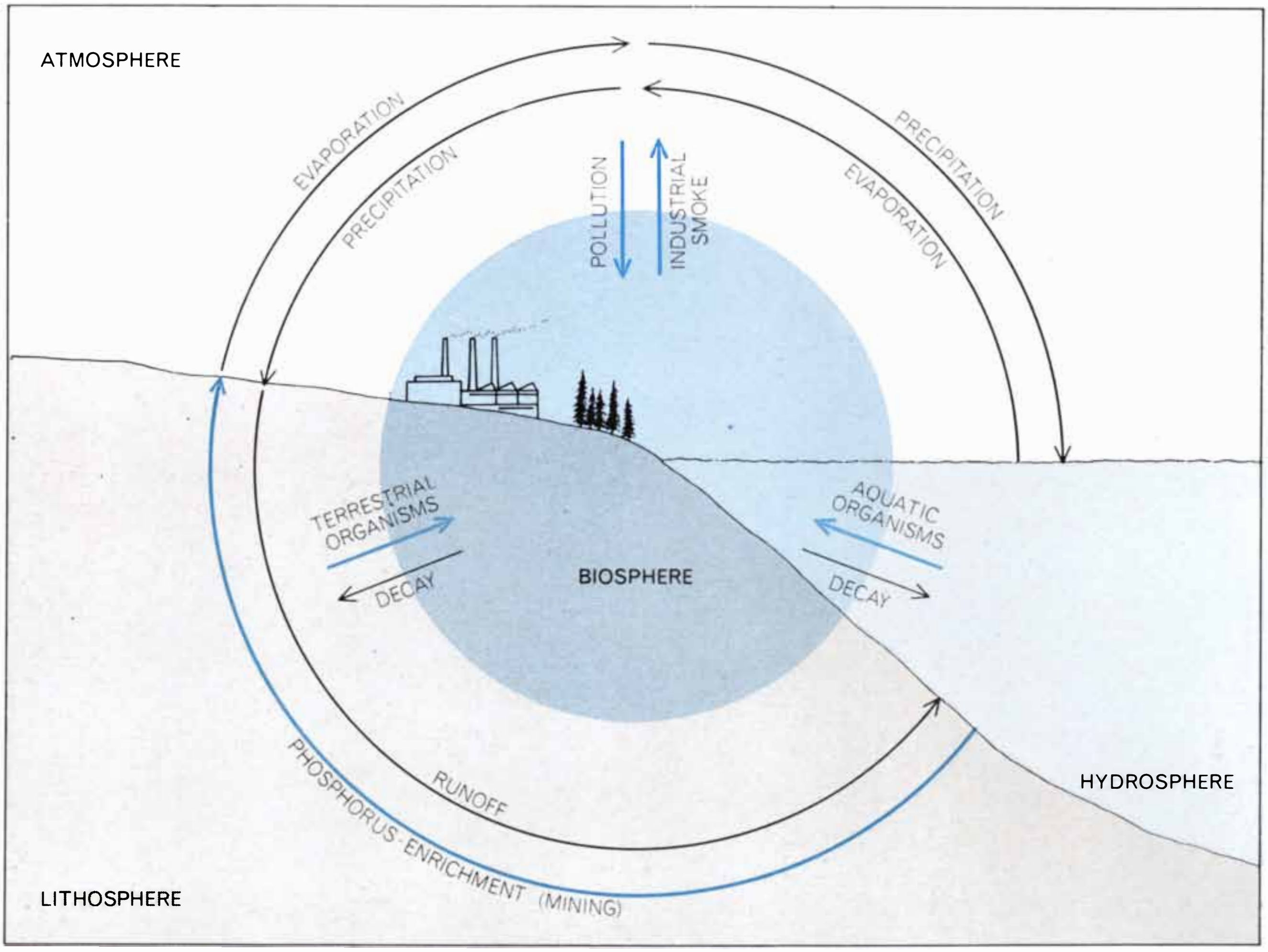
SOLUBLE-ELEMENT CYCLE is followed by minerals such as phosphorus that dissolve in water but are not volatile, that is, they are not carried into the air by evaporation (*curved arrow at right*). The curved arrow at bottom shows that phosphorus is washed from the lithosphere into the hydrosphere by runoff from rainfall (*curved arrow at top left*). The broken curved arrow at bottom indicates that phosphorus in the hydrosphere does not normally return to the lithosphere and that therefore the ocean would become a phosphorus sink. The upper straight arrows at right and left, however, show that the organisms of the biosphere impede this development by absorbing some phosphorus. The straight arrows pointing from the biosphere to the lithosphere and to the hydrosphere indicate the decay of organic matter. On land the soluble-element cycle is continued when decay returns phosphorus to the lithosphere. Without an atmospheric link from ocean to land, however, the cycle is actually a one-way flow with interruptions.

It has been known for many years that sulfur is recycled from the sea back to the land by way of the atmosphere. Calculations confirming this fact by Erik Eriksson of the International Meteorological Institution show that the world's rocks contain too little sulfur, by a factor of about three, to account for the sulfate delivered annually by the world's rivers. About three-quarters of the total budget (in 1940) is therefore inferred to have come from the atmosphere. Of this amount about a third, or a quarter of the total, can have come from industrial sources—better known these days as "sulfur dioxide pollution." The other two-thirds, or half the total budget as of 1940, must take some more natural route from the hydrosphere.

When Eriksson wrote, in 1959, the question was still open, whether the cycled sulfur reaches the land as an aerosol from sea spray or as hydrogen sulfide (H_2S). If the principal volatile compound is a sulfide, it must be made by sulfate-reducing bacteria, because no other "room temperature" source of sulfide is known. M. LeRoy Jensen and Noboyuki Nakai, then working at Yale University, settled this question in favor of the bacteria, by showing that atmospheric sulfur, although it falls in rain as sulfate, contains less of the heavy isotope sulfur 34 than seawater sulfate does. What the natural isotopic label shows is that the sulfate in rain entered the atmosphere not as sea spray but as sulfide, there to be oxidized to sulfur dioxide. After dissolution in rainwater, sulfate (and sulfuric acid) are formed.

The principle of the Jensen-Nakai demonstration is worth noticing, because it applies to the cycling of carbon as well as of sulfur, and barring some technical difficulties it could also apply to nitrogen. The route followed through oxidation-reduction reactions by ordinary sulfur (sulfur 32) is analogous to the route followed by ordinary carbon (carbon 12) in photosynthesis. These lighter, more mobile isotopes appear preferentially in reduced compounds such as hydrogen sulfide, methane and formaldehyde. At equilibrium in a closed system the oxidation products (carbon dioxide or sulfate) have correspondingly more of the heavier isotopes carbon 13 and sulfur 34 without change in the total mass. If, however, a reduced and isotopically light product escapes, as hydrogen sulfide does from the hydrosphere, equilibrium is not attained, and if the gaseous product is trapped and reoxidized in a separate system, the oxide (sulfur dioxide in this case) remains light.

Exactly where within the hydrosphere



EUTROPHICATION OF THE BIOSPHERE is the intensive cycling of phosphorus, nitrogen and sulfur. Colored curved arrow at bottom represents beginning of the process: the human use of phosphorus as fertilizer, which returns phosphorus to the lithosphere, thereby reversing the phosphorus cycle. Colored straight arrows at left and right indicate that phosphorus added to the lithosphere (and to phosphorus already present) is then taken up by phytoplankton and other organisms as well as by crops. Other straight arrows at right and left show that phosphorus and other elements return to the lithosphere and hydrosphere by decay. Once phosphorus is plentiful, scarcity of nitrogen and sulfur may limit eutrophication. Arrows at top represent carbon dioxide, nitrate and sulfate from industrial activity rising into atmosphere and falling in rain. They may promote eutrophication of dry land since vegetation may reabsorb them from air and soil. Curved arrows indicate routes followed by elements that are both soluble and volatile.

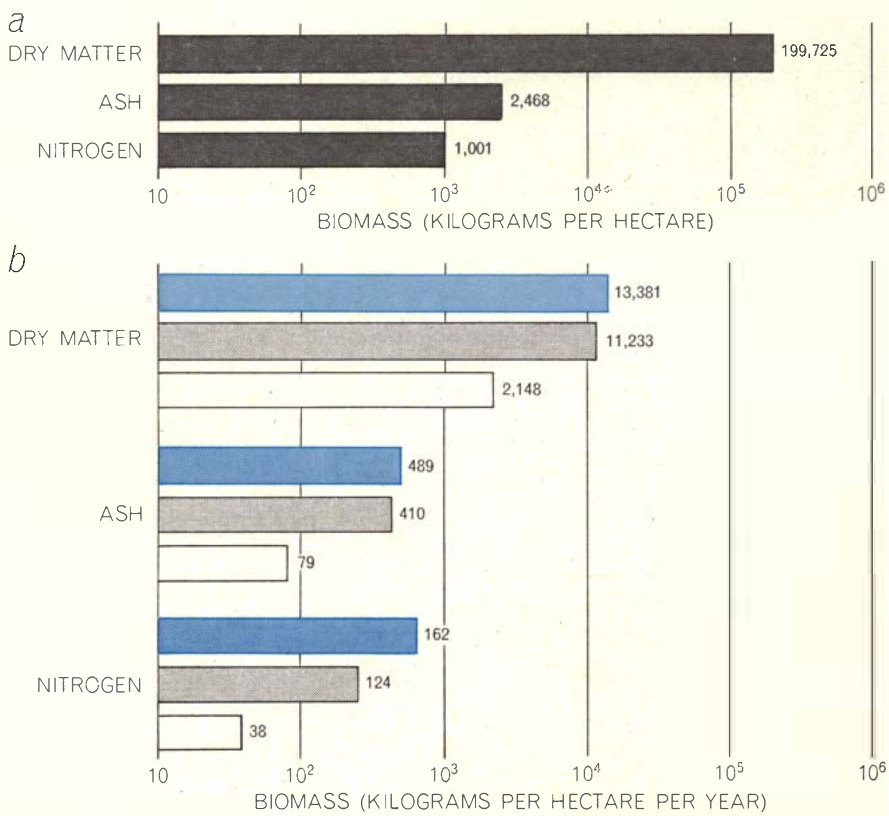
clear. The known ones are obligate anaerobes, and their habitat is mud. Swamps, marshes and the floor of eutrophic lakes must all be important, and they may be quantitatively more important than the blue mud of estuaries and continental shelves. The sulfur metabolism of such large systems is not easy to study, even with isotopic tools. Minze Stuiver, now at the University of Washington, injected radioactively labeled sulfate ions into one eutrophic lake, Linsley Pond in Connecticut. Sulfate reduction proved to be intense, as had been expected. This lake, however, has quite a bit of ferrous iron in its deeper waters, and more in the mud itself. In the presence of the ferrous iron all the labeled sulfide was firmly held in the mud as ferrous sulfide, and no hydrogen sulfide escaped. At least for the duration of the radioactive label, with its half-life of 89 days, this mass of mud was not a source of atmospheric sulfur but a sink.

It follows from all of this that the cycling of sulfur in nature is no less relevant to carboxylation than the cycling of carbon and nitrogen. Without downgrading photosynthesis, we can say that carbon fixation is only one of at least three critical steps in the global synthesis of protein. All three are hydrogenations, achieved with the aid of enzymes, which are themselves proteins, and therefore occur only in the biosphere. Of the three reductions, however, only the reduction of carbon calls for green plants and sunlight. The other two, the reduction of nitrogen and of sulfur, are accomplished anaerobically, by microbes. Thus the locus of the nitrogen and sulfur reductions is, broadly speaking, oxygen-deficient soil and mud. Both loci are separated spatially from that airy, sunlit world where green plants (addicted, like human societies, to the external disposal of wastes) are thoughtlessly liberating oxygen.

With three critical steps for five elements, moving through four "spheres" of abstract space, one feels the need for a picture—a "systems model"—just to keep track of the relations. The two-dimensional analogue on page 152 is simple but adequate. Although it fails to specify fluxes, or any chemical quantities, it provides a mental framework for the movement of five elements: hydrogen, oxygen, carbon, nitrogen and sulfur, either alone or in combinations such as water, nitrate, the dioxides of carbon and sulfur, and carbohydrate. The synthetic output is the biosphere, with the

	(KILOGRAMS PER HECTARE)	(KILOGRAMS PER HECTARE)	(KILOGRAMS PER HECTARE)
CALCIUM (Ca^{++})	2.8	3.0	+0.2
MAGNESIUM (Mg^{++})	1.1	1.8	+0.7
SODIUM (Na^{+})	2.1	4.2	+2.1
POTASSIUM (K^{+})	1.8	1.1	−0.7
CHLORIDE (Cl^{-})	2.8	4.1	+1.3
SULFATE (SO_4^{--})	30.0	29.4	−0.6
AMMONIUM (NH_4^{+})	2.1	0.3	−1.8
NITRATE (NO_3^{-})	6.7	4.8	−1.9
SILICON DIOXIDE (SiO_2)	1.9	20.9	+19.0
ALUMINUM (Al^{+++})	--	1.4	+
BICARBONATE (HCO_3^{-})	0	0.7	+0.7
TOTAL	51.4	71.7	+20.3

EUTROPHICATION OF DRY LAND is indicated by the imbalance between the quantity of certain ions falling from the atmosphere on the forest at Watershed No. 6 at Hubbard Brook in New Hampshire and the output of these ions in the brook itself. Input (*smaller arrows at left*) of some elements such as calcium, magnesium and sodium is smaller than the output (*larger arrows at right*). The input of potassium, ammonium, sulfate and nitrate, however, is larger (*larger arrows at left*) than output of these substances (*smaller arrows*). The excess of input indicates that the forest is utilizing these four substances as it grows.



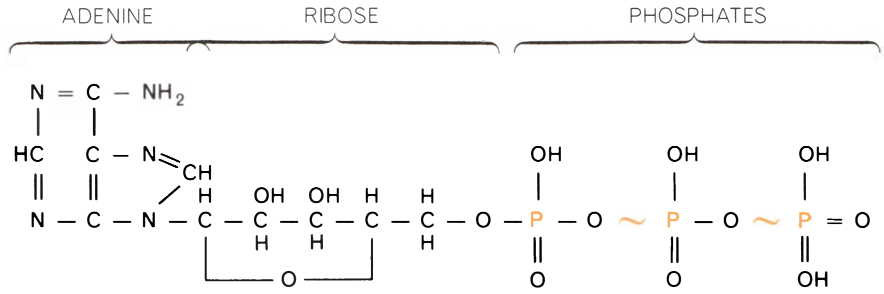
OTHER EVIDENCE FOR EUTROPHICATION is provided by studies of the earth's standing crop on dry land. In *a* biomass, or weighable dry matter that includes ash and nitrogen, totals about 200,000 kilograms per hectare. In *b* the first set of bars shows that the dry matter increases in an average year by 13,381 kilograms per hectare (*color*). About 11,000 kilograms is lost in the form of litter fall (*gray*) such as fallen leaves and branches, giving a "mean increment" of 2,148 kilograms per hectare (*open bar*). The second set of bars shows that ash increases by 489 kilograms per hectare (*color*) but is reduced by litter fall (*gray*) to 79 kilograms (*open bar*). The third set of bars shows that nitrogen increases by 162 kilograms (*color*), a gain that is reduced by litter fall (*gray*) to 38 kilograms per hectare.

empirical composition of protein. The central or regulatory position of the biosphere in this model follows from the fact that for all five elements it is both a source and a temporary sink. For any element that might be tempted to cycle around the edges of the model, the biosphere provides several high-energy alternatives. The most interesting of these are the reductions of carbon, nitrogen and sulfur, each concentrated at a different interface, two being out of immediate contact with air. Water, although it is able in principle to cycle independently, is the source of the hydrogen that energizes the biosphere, and cannot long avoid the biospheric loop as long as the biosphere functions.

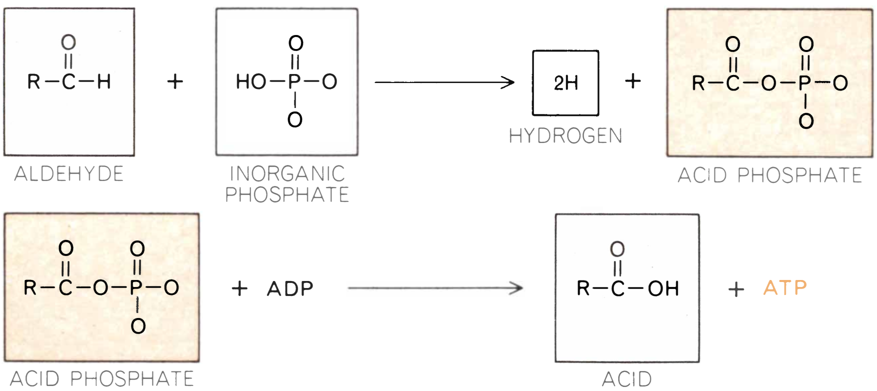
It is easy to be bemused by so fascinating a model. Its function, however, is to clarify thought. If further thought disrupts the model, nothing is lost but a few lines on paper. More or less instantly, by reference to the table of biospheric composition, we can see that the model is incomplete. Phosphorus has been left out, along with calcium, potassium, silicon and magnesium, four elements that are commoner in the biosphere than sulfur is. Will any or all of these cycle tamely through the model, or will they disrupt it beyond repair?

For phosphorus, but not yet for the others, the answer is clear: With one significant modification, the model can accommodate phosphorus. First, let us be sure, as we made sure for sulfur, that phosphorus is necessary to the biosphere. It is not a constituent of protein, but no protein can be made without it. The "high-energy phosphate bond," reversibly moving between adenosine diphosphate (ADP) and adenosine triphosphate (ATP), is the universal fuel for all biochemical work within the cell. The photosynthetic fixation of carbon would be a fruitless tour de force if it were not followed by the phosphorylation of the sugar produced. Thus although neither ADP nor ATP contains much phosphorus, one phosphorus atom per molecule of adenosine is absolutely essential. No life (including microbial life) is possible without it.

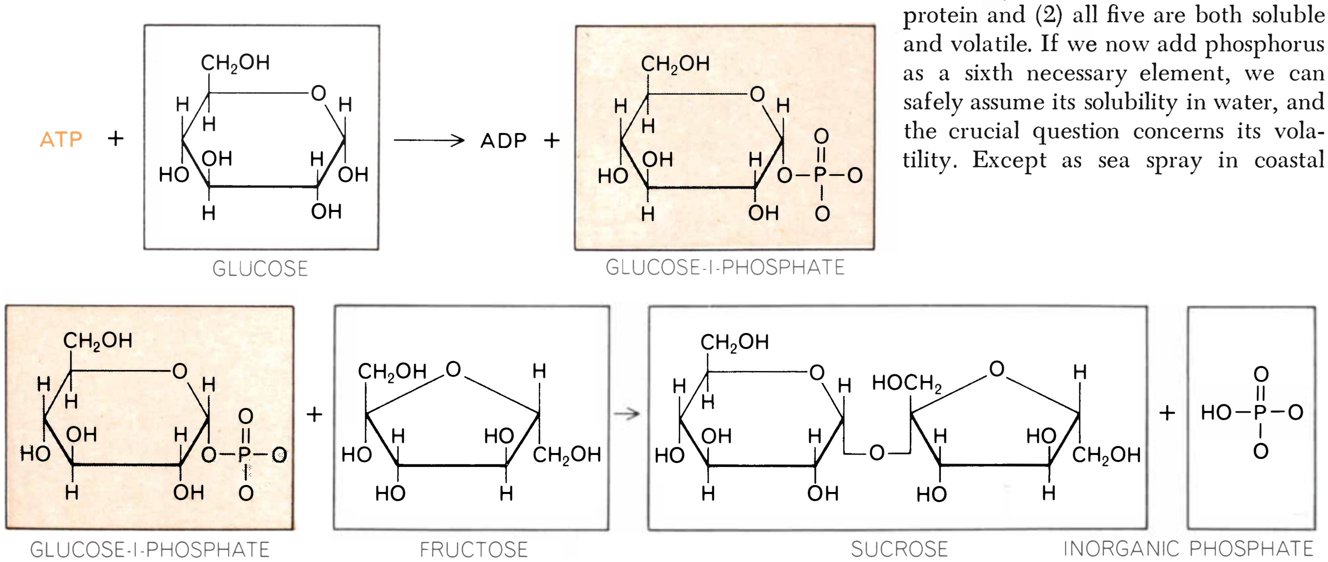
Our provisional model of the biosphere has been constructed on two explicit assumptions: (1) the biosphere necessarily contains the five elements of protein and (2) all five are both soluble and volatile. If we now add phosphorus as a sixth necessary element, we can safely assume its solubility in water, and the crucial question concerns its volatility. Except as sea spray in coastal



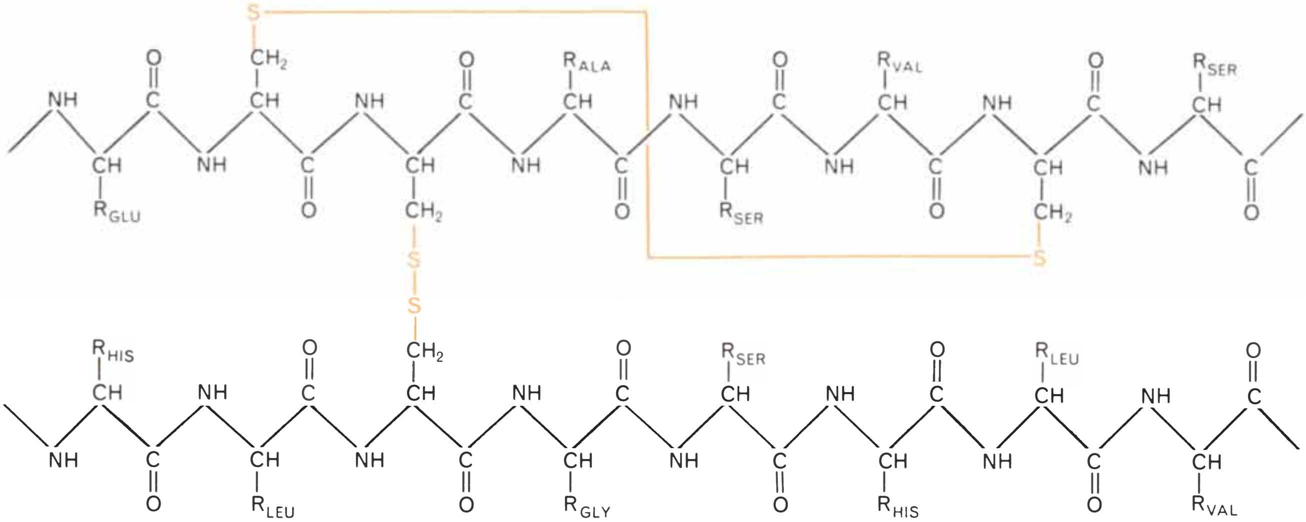
UNIVERSAL FUEL of living matter is adenosine triphosphate (ATP). High-energy phosphate bonds of ATP (~) each store 12,000 calories and release 7,500 calories when broken.



PRODUCTION OF ATP, shown in generalized form, consists of two stages. The first stage begins as aldehyde reacts with an inorganic phosphate to produce hydrogen and acid phosphate. In second stage (*bottom*) acid phosphate (*shading*) reacts with ADP (adenosine diphosphate) to make an organic acid and ATP (*color*). *R* stands for radicals, or side groups.



SYNTHESIS OF SUCROSE is an example of a reaction for which ATP (*color*) supplies energy. The reaction begins at upper left as the ATP molecule combines with glucose molecule, releasing 7,500 calories. The reaction produces ADP and glucose-1-phosphate. In a second stage of the reaction (*bottom*) glucose-1-phosphate combines with fructose, yielding sucrose and inorganic phosphate.



BASIC FUNCTION OF SULFUR in living matter appears to be to provide a linkage between the polypeptide chains in a protein molecule. These linkages help the protein maintain its three-dimensional shape so that it can perform its function. In this segment of a bovine insulin molecule disulfide bonds (*color*) are formed between sulfur atoms, which are present in the amino acid cystine. Cystine is a subunit of both polypeptide chains. Because the molecule is displayed in two dimensions it is flattened. Therefore the bond between the top and bottom cystine groups on the upper chain appears broken. In the normal three-dimensional state, however, this chain is twisted and folded because of the disulfide bond in a way indicated by the colored line that joins the two sulfur atoms. (The other bond is one of two that links the chains.) The shape of the insulin molecule maintained by these bonds enables it to control the metabolism of sugar. The other amino acids in this molecular segment, whose side chains are indicated by the letter *R*, are glutamic acid (GLU), alanine (ALA), serine (SER), valine (VAL), histidine (HIS), leucine (LEU) and glycine (GLY).

zones, or as dust in the vicinity of exposed phosphate rock, phosphorus is unknown in the atmosphere; none of its ordinary compounds has any appreciable vapor pressure. It therefore tracks the hydrologic cycle only partway, from the lithosphere to the hydrosphere, and in a world uncomplicated by a biosphere the ocean would be its only sink. In terms of my model this amounts to uncoupling the atmospheric reservoir (except for water), omitting the half-arrow showing the return of phosphorus from the hydrosphere to the lithosphere and leaving the biosphere's phosphorus as a feedback loop, diverting some of the one-way flow from rock to ocean. Geometrically at least, the model is general enough to accommodate these changes, some version of which will be needed if any permanent sinks are discovered in the system.

For any soluble but nonvolatile element a closed natural cycle is possible only through the biosphere. The model hints at the reason why many elements—vanadium, cobalt, nickel and molybdenum among them—are best known in aquatic organisms and cycle mainly within the hydrosphere. Now, however, the model, nonquantitative though it is, suggests something else. If the biosphere demands such an element as phosphorus (and the cases of iron and manganese should be similar), two alternative inferences are permissible, depending on the magnitudes of reservoirs and fluxes. If the lithosphere contains an ample supply of phosphorus, or if the flux to the hydrospheric sink is large, the biosphere can take off what it needs and waste the rest. It is commonly believed such elements as sodium and calcium are thus wasted by terrestrial vegetation, although ecologists are beginning to doubt it. On the other hand, if the quantity is scanty or the flux small, the element will be in critically short supply. And if short supply is chronic, the output of the entire system could be expected to be adjusted to the rate of exploitation of one critical element, much as the performance of a bureaucracy is closely geared to the supply of paper clips.

In undisturbed nature the chronic shortage of phosphorus is notorious; that is what most people mean by "soil infertility." In the lithosphere phosphorus is scarcer than carbon, and in the hydrosphere, because phosphorus falls in the parts-per-billion range, it fails to show up at all in the chart of constituents on page 151. Apart from its natural scarcity, phosphorus is freely soluble only in acid solution or under reducing conditions. On the surface of an alkaline and oxidized earth it tends to be immobilized as calcium phosphate or ferric phosphate. In lake waters, where the output of carbohydrate is thriftily attuned to phosphorus concentrations of the order of 50 micrograms per liter, doubling the phosphorus input commonly doubles the standing crop of plankton and pondweeds.

Under these conditions the situation in a lake changes drastically. If phosphorus is plentiful, nitrate may become the critically short nutrient for a crop that needs about 15 atoms of nitrogen for one of phosphorus. Blue-green algae may then take over the plankton because by reducing atmospheric nitrogen they escape the dependence that other algae have on nitrate. Meanwhile, judging from much recent experience, the phosphorus input will probably have doubled again—but the subject under discussion is no longer undisturbed nature. What started as "cottage eutrophication," by seepage from a few septic tanks, has been escalated into a noisome mess by "treated" sewage and polyphosphate detergents. To conserve biogeochemical parity the atmosphere has begun to deliver into lakes nitrate and sulfate from the combustion of fossil fuels.

It would be wrong to read too much into a systems model. "Conserving biogeochemical parity" is just a figure of speech, technically hyperbole, and ironical at that. After all, the pollution of the air by nitrate and sulfate is quite independent—technologically, spatially and politically—of the pollution of water by phosphorus. If the accelerated phosphorus cycle in lakes takes advantage of these added inputs, we dare not say that nitrate and sulfate have been drawn into the biosphere from the atmosphere, as U.S. power was drawn to a Canadian circuit breaker in the Northeast blackout of 1965. What the model tells us is that matters can look that way from the standpoint of the biosphere. If the lake segment of the phosphorus cycle is accelerated to the point where nitrogen and sulfur are as critical as phosphorus used to be, and if there is a new source of nitrate and sulfate in the atmosphere, the atmosphere is adequately coupled to all other subsystems to ensure the success of the newly accelerated loop. The loop, known as eutrophication, is thus amplified from a lacustrine nuisance to a systems problem, and around such lakes as Lake Erie it threatens to become a cancer in the global ecosystem.

The trouble started, of course, when the world's one-way phosphorus cycle was first reversed and then accelerated by human activity. Since bird guano was discovered on desert islands, later to be supplemented in fertilizers by phosphate rock, marine phosphate has been restored to the lithosphere in ever increasing amounts. As a device for growing people in ever increasing numbers the practice cannot be faulted, but if people are to continue to flourish in the biosphere, they will have to pay more attention to scarce resources. Phosphorus is much too valuable to be thoughtlessly shared with blue-green algae.

The term eutrophication, which means enrichment, usually inadvertent, is not ordinarily applied to forests and deserts. I dare to extend it to the terrestrial biosphere because two new lines of evidence have suddenly appeared to suggest that the known pollution of air by nitrate and sulfate also encourages the bloom on dry land. The first line of evidence comes from Hubbard Brook, N.H., where F. Herbert Bormann of the Yale School of Forestry and Gene E. Likens of Cornell University have had six forested watersheds under close study since 1963. What interests us here is the difference, per hectare of ecosystem, between the input of ions in rainfall (plus dry fallout, if any) and the output as measured at a dam at the foot of each drainage basin.

Among the common ions entering and leaving Watershed No. 6 at Hubbard Brook, chloride and three positive ions—calcium, magnesium and sodium—show an excess of output over input, presumably derived from the local rocks and soil. These four ions conform, if only barely, to the idea that the biosphere wastes excess salts on their way to the sea. In contrast, potassium and ammonium (NH_4) and the two major negative ions, sulfate and nitrate, are avidly held by this segment of the biosphere, as is indicated by the fact that their input exceeds their output. In the case of potassium all but 700 grams per hectare is captured. Collectively the "nonvolatile" minerals, including silica, that fall from the clear New Hampshire sky amounted to some 13 kilograms per hectare in a typical year. With sulfate, nitrate and ammonium added, the total reached 51.4 kilograms per hectare.

The second line of evidence indicates that the biosphere as a whole is becoming larger. Ecologists expect to find growth in secondary forests, but climax vegetation should be in a steady state, with annual gains balancing losses. According to figures I have recompiled from Rodin and Basilevich, the mean world vegetation is not yet at climax. After the known quantity of dead leaves, branches and other litter is subtracted from the net production of new tissue, the difference is always positive, at an average 2,148 kilograms of new biomass per hectare of land per year. With ash making up 1.2 percent of this biomass, about 26 kilograms of ash is annually withdrawn from an average hectare to sustain the increment of carbohydrate. The input of airborne elements at Hubbard Brook could provide this ash twice over, with no contribution from the local lithosphere.

This comparison is impressionistic, and it may be misleading. Apart from industrial sulfate, which (as sulfuric acid) is perhaps as likely to corrode the biosphere as to nourish it, the world's vegetation may be in no danger of instant eutrophication. (If the biosphere is really becoming larger, the input of industrial carbon dioxide may constitute another major nutrient.) The modes of recycling discovered at Hubbard Brook are nonetheless astonishing. Added to what we know or can safely infer about other volatile elements, such studies underscore the necessity of a global view of biochemistry. What can be said with assurance is that there is a unique and nearly ubiquitous compound, with the empirical formula $H_{2960}O_{1480}C_{1480}N_{16}P_{1.8}S$, called living matter. Its synthesis, on an oxidized and uncarboxylated earth, is the most intricate feat of chemical engineering ever performed—and the most delicate operation that people have ever tampered with.

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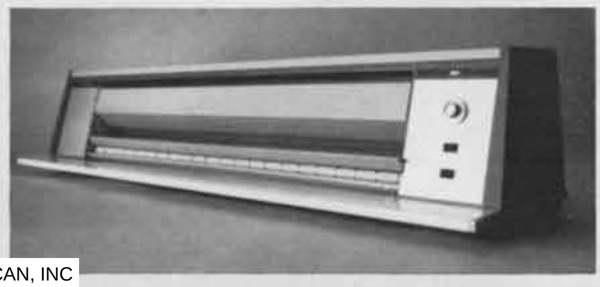


Human Food Production as a Process in the Biosphere

Human population growth is mainly the result of increases in food production. This relation raises the question: How many people can the biosphere support without impairment of its overall operation?

by Lester R. Brown

Throughout most of man's existence his numbers have been limited by the supply of food. For the first two million years or so he lived as a predator, a herbivore and a scavenger. Under such circumstances the biosphere could not support a human population of more than 10 million, a population smaller than that of London or Afghanistan today. Then, with his domestication of plants and animals some 10,000 years ago, man began to shape the biosphere to his own ends.

As primitive techniques of crop production and animal husbandry became more efficient the earth's food-producing capacity expanded, permitting increases in man's numbers. Population growth in turn exerted pressure on food supply, compelling man to further alter the biosphere in order to meet his food needs. Population growth and advances in food production have thus tended to be mutually reinforcing.

It took two million years for the human population to reach the one-billion mark, but the fourth billion now being added will require only 15 years: from 1960 to 1975. The enormous increase in the demand for food that is generated by this expansion in man's numbers, together with rising incomes, is beginning to have disturbing consequences. New signs of stress on the biosphere are reported almost daily. The continuing expansion of land under the plow and the evolution of a chemically oriented modern agriculture are producing ominous alterations in the biosphere not just on a local scale but, for the first time in history, on a global scale as well. The natural cycles of energy and the chemical elements are clearly being affected by man's efforts to expand his food supply.

Given the steadily advancing demand for food, further intervention in the biosphere for the expansion of the food supply is inevitable. Such intervention, however, can no longer be undertaken by an individual or a nation without consideration of the impact on the biosphere as a whole. The decision by a government to dam a river, by a farmer to use DDT on his crops or by a married couple to have another child, thereby increasing the demand for food, has repercussions for all mankind.

The revolutionary change in man's role from hunter and gatherer to tiller and herdsman took place in circumstances that are not well known, but some of the earliest evidence of agriculture is found in the hills and grassy plains of the Fertile Crescent in western Asia. The cultivation of food plants and the domestication of animals were aided there by the presence of wild wheat, barley, sheep, goats, pigs, cattle and horses. From the beginnings of agriculture man naturally favored above all other species those plants and animals that had been most useful to him in the wild. As a result of this favoritism he has altered the composition of the earth's plant and animal populations. Today his crops, replacing the original cover of grass or forest, occupy some three billion acres. This amounts to about 10 percent of the earth's total land surface and a considerably larger fraction of the land capable of supporting vegetation, that is, the area excluding deserts, polar regions and higher elevations. Two-thirds of the cultivated cropland is planted to cereals. The area planted to wheat alone is 600 million acres—nearly a million square miles, or an area equivalent to the U.S. east of the Mississippi. As for the influence of animal husbandry on the earth's animal populations, Hereford and Black Angus cattle roam the Great Plains, once the home of an estimated 30 to 40 million buffalo; in Australia the kangaroo has given way to European cattle; in Asia the domesticated water buffalo has multiplied in the major river valleys.

Clearly the food-producing enterprise has altered not only the relative abundance of plant and animal species but also their global distribution. The linkage of the Old and the New World in the 15th century set in motion an exchange of crops among various parts of the world that continues today. This exchange greatly increased the earth's capacity to sustain human populations, partly because some of the crops trans-

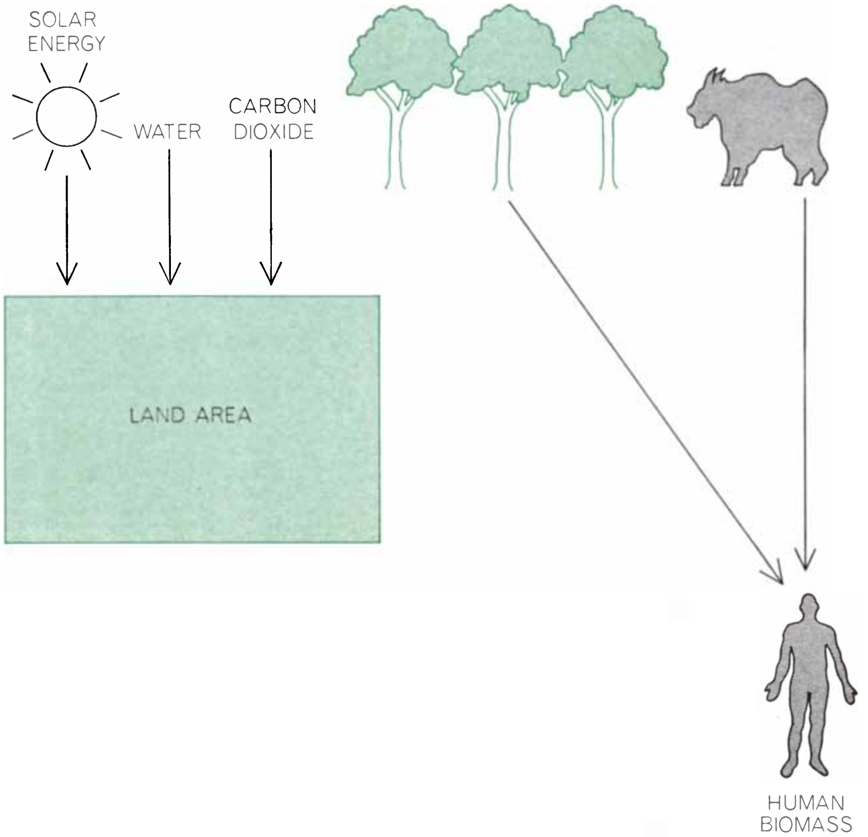
EXPERIMENTAL FARM in Brazil, one of thousands around the world where improvements in agricultural technology are pioneered, is seen as an image on an infrared-sensitive film in the aerial photograph on the opposite page. The reflectance of vegetation at near-infrared wavelengths of .7 to .9 micron registers on the film in false shades of red that are proportional to the intensity of the energy. The most reflective, and reddest, areas (*bottom*) are land still uncleared of forest cover. Most of the tilled fields, although irregular in shape, are contour-plowed. Regular patterns (*left and bottom right*) are citrus-orchard rows. The photograph was taken by a National Aeronautics and Space Administration mission in cooperation with the Brazilian government in a joint study of the assessment of agricultural resources by remote sensing. The farm is some 80 miles northwest of São Paulo.

ported elsewhere turned out to be better suited there than to their area of origin. Perhaps the classic example is the introduction of the potato from South America into northern Europe, where it greatly augmented the food supply, permitting marked increases in population. This was most clearly apparent in Ireland, where the population increased rapidly for several decades on the strength of the food supply represented by the potato. Only when the potato-blight organism (*Phytophthora infestans*) devastated the potato crop was population growth checked in Ireland.

The soybean, now the leading source of vegetable oil and principal farm export of the U.S., was introduced from China several decades ago. Grain sorghum, the second-ranking feed grain in the U.S. (after corn), came from Africa as a food store in the early slave ships. In the U.S.S.R. today the principal source of vegetable oil is the sunflower, a plant that originated on the southern Great Plains of the U.S. Corn, unknown in the Old World before Columbus, is now grown on every continent. On the other hand, North America is indebted to the Old World for all its livestock and poultry species with the exception of the turkey.

To man's accomplishments in exploiting the plants and animals that natural evolution has provided, and in improving them through selective breeding over the millenniums, he has added in this century the creation of remarkably productive new breeds, thanks to the discoveries of genetics. Genetics has made possible the development of cereals and other plant species that are more tolerant to cold, more resistant to drought, less susceptible to disease, more responsive to fertilizer, higher in yield and richer in protein. The story of hybrid corn is only one of many spectacular examples. The breeding of short-season corn varieties has extended the northern limit of this crop some 500 miles.

Plant breeders recently achieved a historic breakthrough in the development of new high-yielding varieties of wheat and rice for tropical and subtropical regions. These wheats and rices, bred by Rockefeller Foundation and Ford Foundation scientists in Mexico and the Philippines, are distinguished by several characteristics. Most important, they are short-statured and stiff-strawed, and are highly responsive to chemical fertilizer. They also mature earlier. The first of the high-yielding rices, IR-8, matures in 120 days as against 150 to 180 days for other varieties.

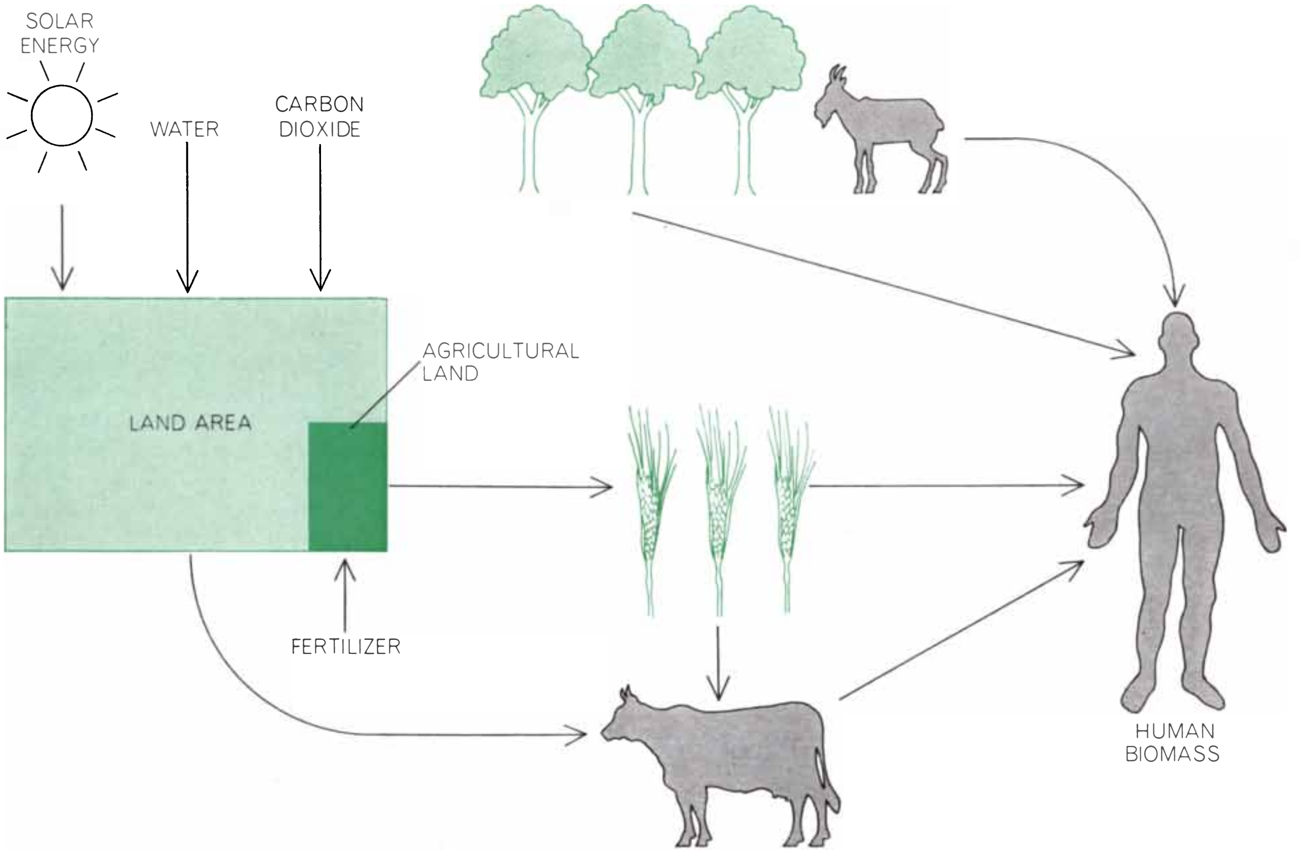


IMPACT OF THE AGRICULTURAL REVOLUTION on the human population is outlined in these two diagrams. The diagram at left shows the state of affairs before the invention of agriculture: the plants and animals supported by photosynthesis on the total land area could support a human population of only about 10 million. The diagram at right shows

Another significant advance incorporated into the new strains is the reduced sensitivity of their seed to photoperiod (length of day). This is partly the result of their cosmopolitan ancestry: they were developed from seed collections all over the world. The biological clocks of traditional varieties of cereals were keyed to specific seasonal cycles, and these cereals could be planted only at a certain time of the year, in the case of rice say at the onset of the monsoon season. The new wheats, which are quite flexible in terms of both seasonal and latitudinal variations in length of day, are now being grown in developing countries as far north as Turkey and as far south as Paraguay.

The combination of earlier maturity and reduced sensitivity to day length creates new opportunities for multiple cropping in tropical and subtropical regions where water supplies are adequate, enabling farmers to harvest two, three and occasionally even four crops per year. Workers at the International Rice Research Institute in the Philippines regularly harvest three crops of rice per year. Each acre they plant yields six tons annually, roughly three times the average yield of corn, the highest-yielding cereal in the U.S. Thousands of farmers in northern India are now alternating a crop of early-maturing winter wheat with a summer crop of rice, greatly increasing the productivity of their land. These new opportunities for farming land more intensively lessen the pressure for bringing marginal land under cultivation, thus helping to conserve precious topsoil. At the same time they increase the use of agricultural chemicals, creating environmental stresses more akin to those in the advanced countries.

The new dwarf wheats and rices are far more efficient than the traditional varieties in their use of land, water, fertilizer and labor. The new opportunities for multiple cropping permit conversion of far more of the available solar energy into food. The new strains are not the solution to the food problem, but they are removing the threat of massive famine in the short run. They are buying time for the stabilization of population, which is ultimately the only solution to the food crisis. This "green revolution"



the state of affairs after the invention of agriculture. The 10 percent of the land now under the plow, watered and fertilized by man, is the primary support for a human population of 3.5 billion. Some of the agricultural produce is consumed directly by man; some is consumed indirectly by first being fed to domestic animals. Some of the food for domestic animals, however, comes from land not under the plow (*curved arrow at bottom left*). Man also obtains some food from sources other than agriculture, such as fishing.

may affect the well-being of more people in a shorter period of time than any technological advance in history.

The progress of man's expansion of food production is reflected in the way crop yields have traditionally been calculated. Today the output of cereals is expressed in yield per acre, but in early civilizations it was calculated as a ratio of the grain produced to that required for seed. On this basis the current ratio is perhaps highest in the U.S. corn belt, where farmers realize a four-hundredfold return on the hybrid corn seed they plant. The ratio for rice is also quite high, but the ratio for wheat, the third of the principal cereals, is much lower, possibly 30 to one on a global basis.

The results of man's efforts to increase the productivity of domestic animals are equally impressive. When the ancestors of our present chickens were domesticated, they laid a clutch of about 15 eggs once a year. Hens in the U.S. today average 220 eggs per year, and the figure is rising steadily as a result of continuing advances in breeding and feeding. When cattle were originally domesticated, they probably did not produce more than 600 pounds of milk per year, barely enough for a calf. (It is roughly the average amount produced by cows in India today.) The 13 million dairy cows in the U.S. today average 9,000 pounds of milk yearly, outproducing their ancestors 15 to one.

Most such advances in the productivity of plant and animal species are recent. Throughout most of history man's efforts to meet his food needs have been directed primarily toward bringing more land under cultivation, spreading agriculture from valley to valley and continent to continent. He has also, however, invented techniques to raise the productivity of land already under cultivation, particularly in this century, when the decreasing availability of new lands for expansion has compelled him to turn to a more intensive agriculture. These techniques involve altering the biosphere's cycles of energy, water, nitrogen and minerals.

Modern agriculture depends heavily on four technologies: mechanization, irrigation, fertilization and the chemical control of weeds and insects. Each of these technologies has made an important contribution to the earth's increased capacity for sustaining human populations, and each has perturbed the cycles of the biosphere.

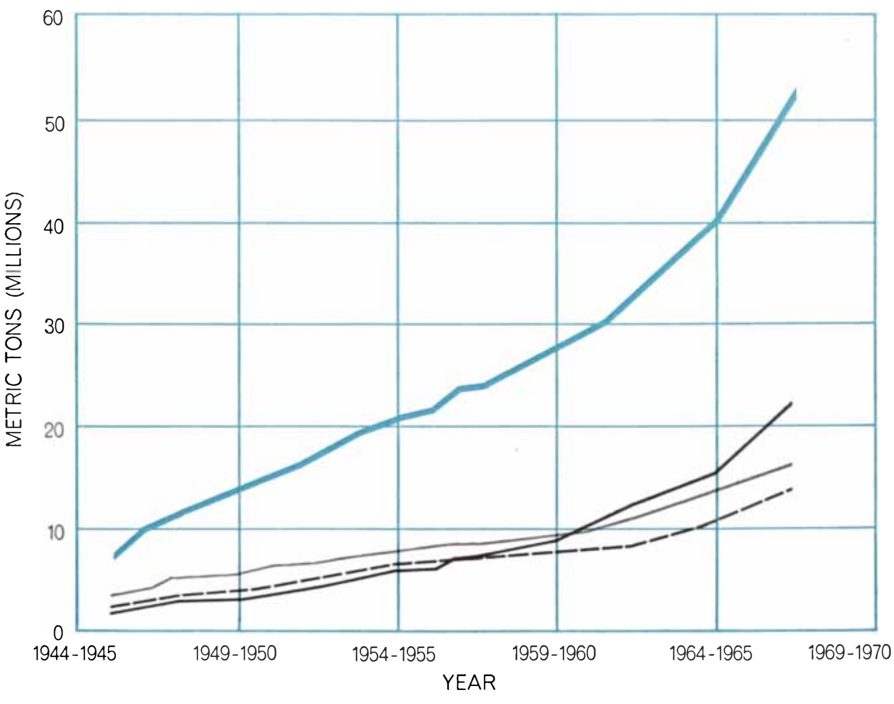
At least as early as 3000 B.C. the farmers of the Middle East learned to harness draft animals to help them till the soil. Harnessing animals much stronger than himself enabled man to greatly augment his own limited muscle power. It also enabled him to convert roughage (indigestible by humans) into a usable form of energy and thus to free some of his energy for pursuits other than the quest for food. The invention of the internal-combustion engine and the tractor 5,000 years later provided a much greater breakthrough. It now became possible to substitute petroleum (the product of the photosynthesis of aeons ago) for oats, corn and hay grown as feed for draft animals. The replacement of horses by the tractor not only provided the farmer with several times as much power but also released 70 million acres in the U.S. that had been devoted to raising feed for horses.

In the highly mechanized agriculture of today the expenditure of fossil fuel energy per acre is often substantially greater than the energy yield embodied in the food produced. This deficit in the output is of no immediate consequence, because the system is drawing on energy in the bank. When fossil fuels become scarcer, man will have to turn to some other source of motive energy for agriculture: perhaps nuclear energy or some means, other than photosynthesis, of harnessing solar energy. For the present and for the purposes of agriculture the energy budget of the biosphere is still favorable: the supply of solar energy—both the energy stored in fossil fuels and that taken up daily and converted into food energy by crops—enables an advanced nation to be fed with only 5 percent of the population directly employed in agriculture.

The combination of draft animals and mechanical power has given man an enormous capacity for altering the earth's surface by bringing additional land under the plow (not all of it suited for cultivation). In addition, in the poorer countries his expanding need for fuel has forced him to cut forests far in excess of their ability to renew themselves. The areas largely stripped of forest include mainland China and the subcontinent of India and Pakistan, where much of the population must now use cow dung for fuel. Although statistics are not available, the proportion of mankind using cow dung as fuel to prepare meals may far exceed the proportion using natural gas. Livestock populations providing draft power, food and fuel tend to increase along with human populations, and in many poor countries the needs of livestock for forage far exceed its self-renewal, gradually denuding the countryside of grass cover.

As population pressure builds, not only is more land brought under the plow but also the land remaining is less suited to cultivation. Once valleys are filled, farmers begin to move up hillsides, creating serious soil-erosion problems. As the natural cover that retards runoff is reduced and soil structure deteriorates, floods and droughts become more severe.

Over most of the earth the thin layer of topsoil producing most of man's food is measured in inches. Denuding the land of its year-round natural cover of grass or forest exposes the thin mantle of life-sustaining soil to rapid erosion by wind and water. Much of the soil ultimately washes into the sea, and some of it is lifted into the atmosphere. Man's actions are causing the topsoil to be removed faster than it is formed. This unstable relationship between man and the land from which he derives his subsistence obviously cannot continue indefinitely.



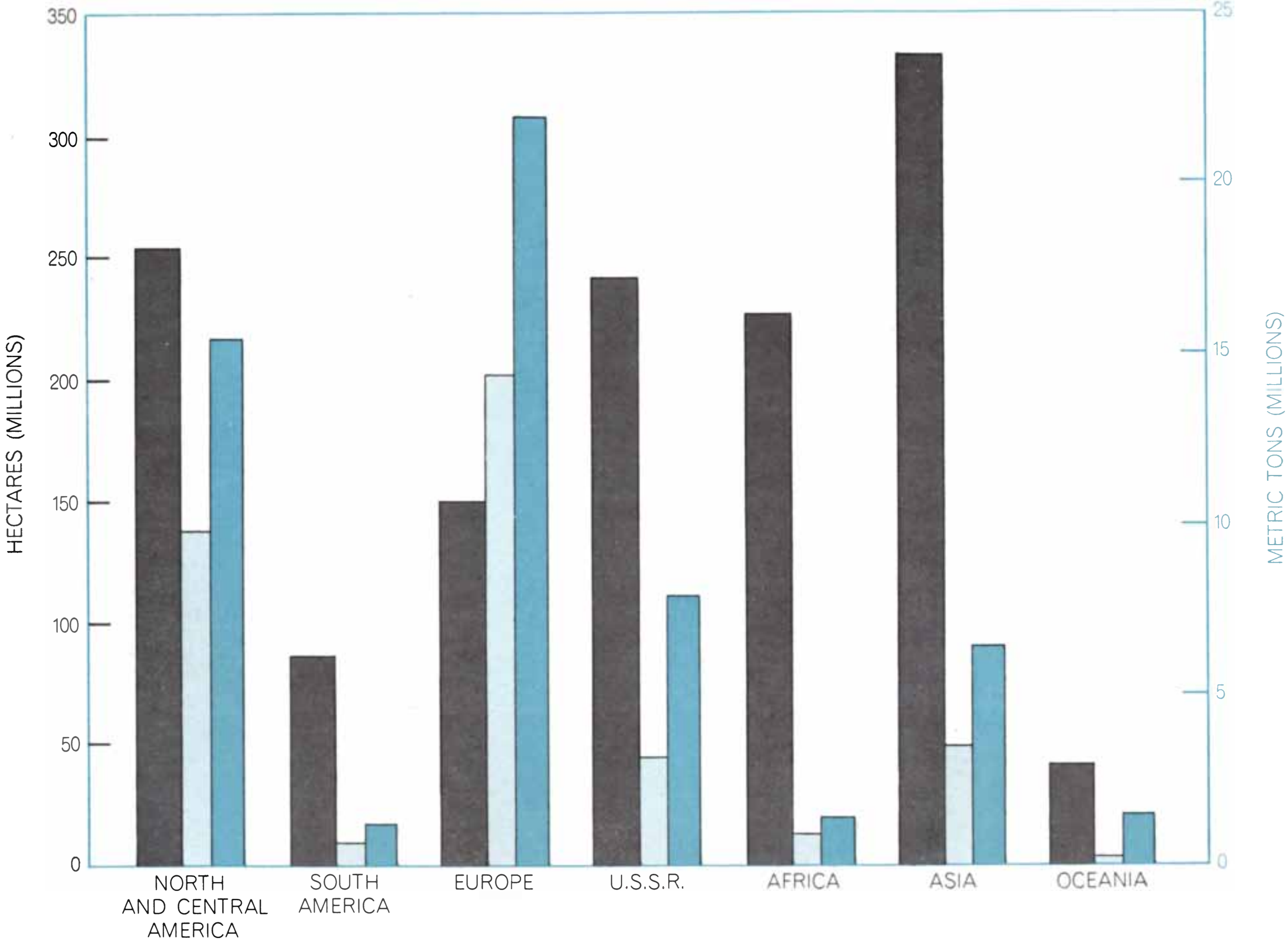
FERTILIZER CONSUMPTION has increased more than fivefold since the end of World War II. The top line in the graph (*color*) shows the tonnage of all kinds of fertilizers combined. The lines below show the tonnages of the three major types: nitrogen (*black*), now the leader, phosphate (*gray*) and potash (*broken line*). Figures, from the most recent report by the UN Food and Agriculture Organization, omit fertilizer consumption in China.

Robert R. Brooks of Williams College, an economist who spent several years in India, gives a wry description of the process occurring in the state of Rajasthan, where tens of thousands of acres of rural land are being abandoned yearly because of the loss of topsoil: "Overgrazing by goats destroys the desert plants which might otherwise hold the soil in place. Goatherds equipped with sickles attached to 20-foot poles strip the leaves of trees to float downward into the waiting mouths of famished goats and sheep. The trees die and the soil blows away 200 miles to New Delhi, where it comes to rest in the lungs of its inhabitants and on the shiny cars of foreign diplomats."

Soil erosion not only results in a loss of soil but also impairs irrigation systems. This is illustrated in the Mangla irrigation reservoir, recently built in the foothills of the Himalayas in West Pakistan as part of the Indus River irrigation system. On the basis of feasibility studies indicating that the reservoir could be expected to have a lifetime of at least 100 years, $600 million was invested in the construction of the reservoir. Denuding and erosion of the soil in the watershed, however, accompanying a rapid growth of population in the area, has already washed so much soil into the reservoir that it is now expected to be completely filled with silt within 50 years.

A historic example of the effects of man's abuse of the soil is all too plainly visible in North Africa, which once was the fertile granary of the Roman Empire and now is largely a desert or near-desert whose people are fed with the aid of food imports from the U.S. In the U.S. itself the "dust bowl" experience of the 1930's remains a vivid lesson on the folly of overplowing. More recently the U.S.S.R. repeated this error, bringing 100 million acres of virgin soil under the plow only to discover that the region's rainfall was too scanty to sustain continuous cultivation. Once moisture reserves in the soil were depleted the soil began to blow.

Soil erosion is one of the most pressing and most difficult problems threatening the future of the biosphere. Each year it is forcing the abandonment of millions of acres of cropland in Asia, the Middle East, North Africa and Central America. Nature's geological cycle continuously produces topsoil, but its pace is far too slow to be useful to man. Someone once defined soil as rock on its way to the sea. Soil is produced by the weathering of rock and the process takes several centuries to form an inch of topsoil. Man is managing to destroy the topsoil



TONS OF FERTILIZER used in seven world areas are compared with the amount of agricultural land in each area. Two tonnages are shown in each instance: the amount used in 1962–1963 (*light color*) and the amount used in 1967–1968 (*solid color*). The greatest use of fertilizer occurs in Europe, the least fertilized area is Africa and the greatest percentage increase in the period was in Australia and New Zealand. Figures, from the Food and Agriculture Organization, omit China, North Korea and North Vietnam.

in some areas of the world in a fraction of this time. The only possible remedy is to find ways to conserve the topsoil more effectively.

The dust-bowl era in the U.S. ended with the widespread adoption of conservation practices by farmers. Twenty million acres were fallowed to accumulate moisture and thousands of miles of windbreaks were planted across the Great Plains. Fallow land was alternated with strips of wheat ("strip-cropping") to reduce the blowing of soil while the land was idle. The densely populated countries of Asia, however, are in no position to adopt such tactics. Their food needs are so pressing that they cannot afford to take large areas out of cultivation; moreover, they do not yet have the financial resources or the technical skills for the immense projects in reforestation, controlled grazing of cattle, terracing, contour farming and systematic management of watersheds that would be required to preserve their soil.

The significance of wind erosion goes far beyond the mere loss of topsoil. As other authors in this issue have observed, a continuing increase in particulate matter in the atmosphere could affect the earth's climate by reducing the amount of incoming solar energy. This particulate matter comes not only from the technological activities of the richer countries but also from wind erosion in the poorer countries. The poorer countries do not have the resources for undertaking the necessary effort to arrest and reverse this trend. Should it be established that an increasing amount of particulate matter in the atmosphere is changing the climate, the richer countries would have still another reason to provide massive capital and technical assistance to the poor countries, joining with them to confront this common threat to mankind.

Irrigation, which agricultural man began to practice at least as early as 6,000 years ago, even earlier than he harnessed animal power, has played its great role in increasing food production by bringing into profitable cultivation vast areas that would otherwise be unusable or only marginally productive. Most of the world's irrigated land is in Asia, where it is devoted primarily to the production of rice. In Africa the Volta River of Ghana and the Nile are dammed for irrigation and power purposes. The Colorado River system of the U.S. is used extensively for irrigation in the Southwest, as are scores of rivers elsewhere. Still to be exploited for irrigation are the Mekong of southeastern Asia and the Amazon.

During the past few years there has been an important new irrigation development in Asia: the widespread installation of small-scale irrigation systems on individual farms. In Pakistan and India, where in many places the water table is close to the surface, hundreds of thousands of tube wells with pumps have been installed in recent years. Interestingly, this development came about partly as an answer to a problem that had been presented by irrigation itself.

Like many of man's other interventions in the biosphere, his reshaping of the hydrologic cycle has had unwanted side effects. One of them is the raising of the water table by the diversion of river water onto the land. Over a period of time the percolation of irrigation water downward and the accumulation of this water underground may gradually raise the water table until it is within a few feet or even a few inches of the surface. This not only inhibits the growth of plant roots by waterlogging but also results in the surface soil's becoming salty as water evaporates through it, leaving a concentrated deposit of salts in the upper few inches. Such a situation developed in West Pakistan after its fertile plain had been irrigated with water from the Indus for a century. During a visit by President Ayub to Washington in 1961 he appealed to President Kennedy for help: West Pakistan was losing 60,000 acres of fertile cropland per year because of waterlogging and salinity as its population was expanding 2.5 percent yearly.

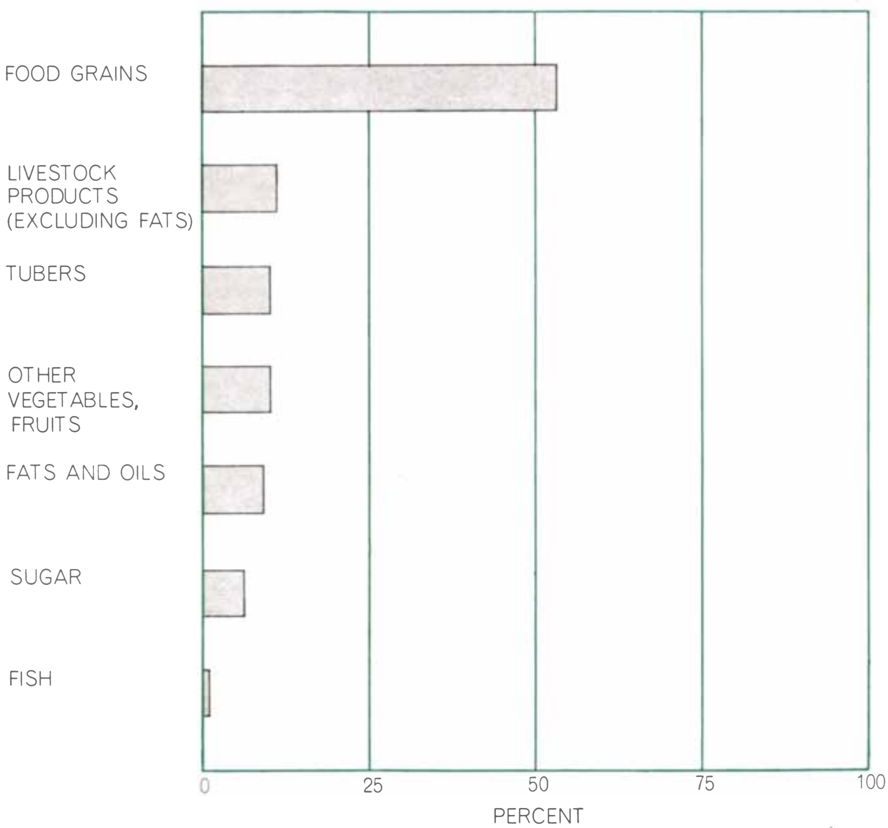
This same sequence, the diversion of river water into land for irrigation, followed eventually by waterlogging and salinity and the abandonment of land, had been repeated many times throughout history. The result was invariably the decline, and sometimes the disappearance, of the civilizations thus intervening in the hydrologic cycle. The remains of civilizations buried in the deserts of the Middle East attest to early experiences similar to those of contemporary Pakistan. These civilizations, however, had no one to turn to for foreign aid. An interdisciplinary U.S. team led by Roger Revelle, then Science Adviser to the Secretary of the Interior, studied the problem and proposed among other things a system of tube wells that would lower the water table by tapping the ground water for intensive irrigation. Discharging this water on the surface, the wells would also wash the soil's salt downward. The stratagem worked, and the salty, waterlogged land of Pakistan is steadily being reclaimed.

Other side effects of river irrigation are not so easily remedied. Such irrigation has brought about a great increase in the incidence of schistosomiasis, a disease that is particularly prevalent in the river valleys of Africa and Asia. The disease is produced by the parasitic larva of a blood fluke, which is harbored by aquatic snails and burrows into the flesh of people standing in water or in water-soaked fields. The Chinese call schistosomiasis "snail fever"; it might also be called the poor man's emphysema, because, like emphysema, this extremely debilitating disease is environmentally induced through conditions created by man. The snails and the fluke thrive in perennial irrigation systems, where they are in close proximity to large human populations. The incidence of the disease is rising rapidly as the world's large rivers are harnessed for irrigation, and today schistosomiasis is estimated to afflict 250 million people. It now surpasses malaria, the incidence of which is declining, as the world's most prevalent infectious disease.

As a necessity for food production water is of course becoming an increasingly crucial commodity. The projected increases in population and in food requirements will call for more and more water, forcing man to consider still more massive and complex interventions in the biosphere. The desalting of seawater for irrigation purposes is only one major departure from traditional practices. Another is a Russian plan to reverse the flow of four rivers currently flowing northward and emptying into the Arctic Ocean. These rivers would be diverted southward into the semiarid lands of southern Russia, greatly enlarging the irrigated area of the U.S.S.R. Some climatologists are concerned, however, that the shutting off of the flow of relatively warm water from these four rivers would have far-reaching implications for not only the climate of the Arctic but also the climatic system of the entire earth.

The growing competition for scarce water supplies among states and among various uses in the western U.S. is also forcing consideration of heroic plans. For example, a detailed engineering proposal exists for the diversion of the Yukon River in Alaska southward across Canada into the western U.S. to meet the growing need for water for both agricultural and industrial purposes. The effort would cost an estimated $100 billion.

Representing an even greater intervention in the biosphere is the prospect that man may one day consciously alter the earth's climatic patterns, shifting some of the rain now falling on the oceans to the land. Among the steps needed for the realization of such a scheme are the construction of a comprehensive model of the earth's climatic system and the development of a computational facility capable of simulating



WORLDWIDE FOOD ENERGY comes in different amounts from different products. Cereals outstrip other foodstuffs; wheat and rice each supply a fifth of mankind's food energy.

and manipulating the model. The required information includes data on temperatures, humidity, precipitation, the movement of air masses, ocean currents and many other factors that enter into the weather. Earth-orbiting satellites will doubtless be able to collect much of this information, and the present generation of advanced computers appears to be capable of carrying out the necessary experiments on the model. For the implementation of the findings, that is, for the useful control of rainfall, there will of course be a further requirement: the project will have to be managed by a global and supranational agency if it is not to lead to weather wars among nations working at cross purposes. Some commercial firms are already in the business of rainmaking, and they are operating on an international basis.

The third great technology that man has introduced to increase food production is the use of chemical fertilizers. We owe the foundation for this development to Justus von Liebig of Germany, who early in the 19th century determined the specific requirements of nitrogen, phosphorus, potassium and other nutrients for plant growth. Chemical fertilizers did not come into widespread use, however, until this century, when the pressure of population and the disappearance of new frontiers compelled farmers to substitute fertilizer for the expansion of cropland to meet growing food needs. One of the first countries to intensify its agriculture, largely by the use of fertilizers, was Japan, whose output of food per acre has steadily risen (except for wartime interruptions) since the turn of the century. The output per acre of a few other countries, including the Netherlands, Denmark and Sweden, began to rise at about the same time. The U.S., richly endowed with vast farmlands, did not turn to the heavy use of fertilizer and other intensive measures until about 1940. Since then its yields per acre, assisted by new varieties of grain highly responsive to fertilizer, have also shown remarkable gains. Yields of corn, the production of which exceeds that of all other cereals combined in the U.S., have nearly tripled over the past three decades.

Experience has demonstrated that in areas of high rainfall the application of chemical fertilizers in conjunction with other inputs and practices can double, triple or even quadruple the productivity of intensively farmed soils. Such levels of productivity are achieved in Japan and the Netherlands, where farmers apply up to 300 pounds of plant nutrients per acre per year. The use of chemical fertilizers is estimated to account for at least a fourth of man's total food supply. The world's farmers are currently applying 60 million metric tons of plant nutrients per year, an average of nearly 45 pounds per acre for the three billion acres of cropland. Such application, however, is unevenly distributed. Some poor countries do not yet benefit from the use of fertilizer in any significant amounts. If global projections of population and income growth materialize, the production of fertilizer over the remaining three decades of this century must almost triple to satisfy food demands.

Can the projected demand for fertilizer be met? The key ingredient is nitrogen, and fortunately man has learned how to speed up the fixation phase of the nitrogen cycle [see "The Nitrogen Cycle," by C. C. Delwiche, page 136]. In nature the nitrogen of the air is fixed in the soil by certain microorganisms, such as those present in the root nodules of leguminous plants. Chemists have now devised various ways of incorporating nitrogen from the air into inorganic compounds and making it available in the form of nitrogen fertilizers. These chemical processes produce the fertilizer much more rapidly and economically than the growing of leguminous-plant sources such as clover, alfalfa or soybeans. More than 25 million tons of nitrogen fertilizer is now being synthesized and added to the earth's soil annually.

The other principal ingredients of chemical fertilizer are the minerals potassium and phosphorus. Unlike nitrogen, these elements are not replenished by comparatively fast natural cycles. Potassium presents no immediate problem; the rich potash fields of Canada alone are estimated to contain enough potassium to supply mankind's needs for centuries to come. The reserves of phosphorus, however, are not nearly so plentiful as those of potassium. Every year 3.5 million tons of phosphorus washes into the sea, where it remains as sediment on the ocean floor. Eventually it will be thrust above the ocean surface again by geologic uplift, but man cannot wait that long. Phosphorus may be one of the first necessities that will prompt man to begin to mine the ocean bed.

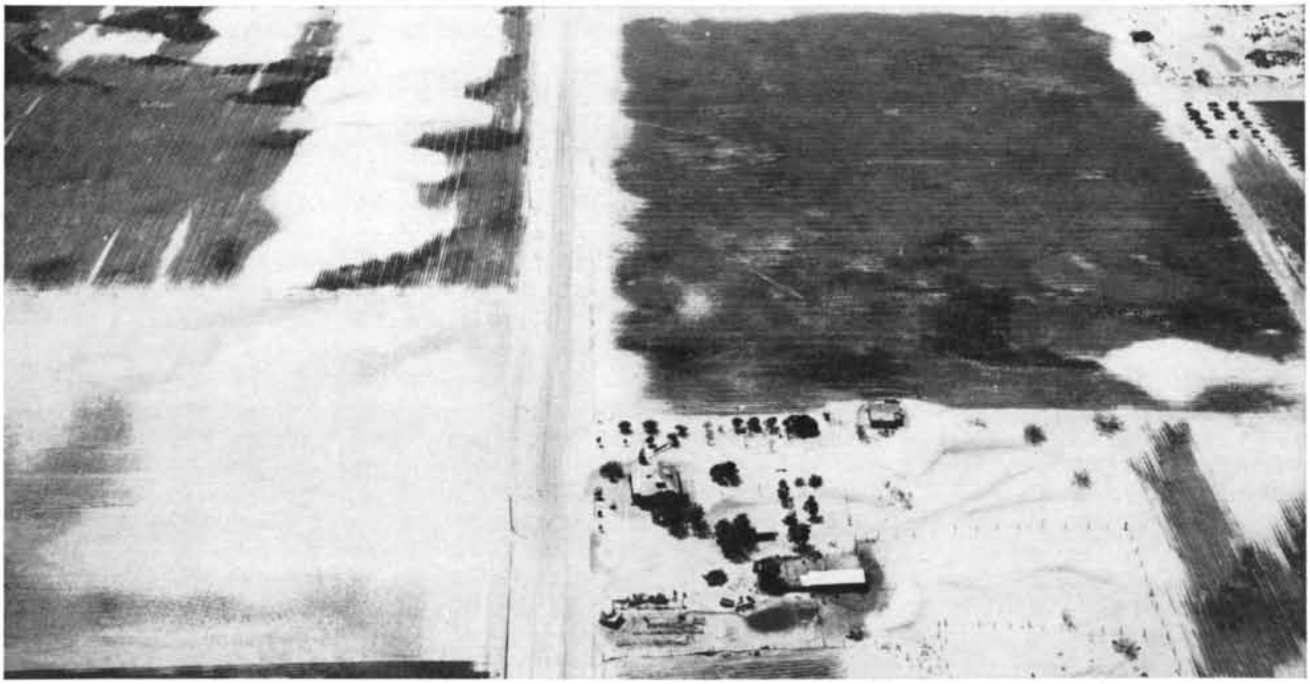
The great expansion of the use of fertilizers in this century has benefited mankind enormously, but the benefits are not unalloyed. The runoff of chemical fertilizers into rivers, lakes and underground waters creates two important hazards. One is the chemical pollution of drinking water. In certain areas in Illinois and California the nitrate content of well water has risen to a toxic level. Excessive nitrate can cause the physiological disorder methemoglobinemia, which reduces the blood's oxygen-carrying capacity and can be particularly dangerous to children under five. This hazard is of only local dimensions and can be countered by finding alternative sources of drinking water. A much more extensive hazard, profound in its effects on the biosphere, is the now well-known phenomenon called eutrophication.

Inorganic nitrates and phosphates discharged into lakes and other bodies of fresh water provide a rich medium for the growth of algae; the massive growth of the algae in turn depletes the water of oxygen and thus kills off the fish life. In the end the eutrophication, or overfertilization, of the lake slowly brings about its death as a body of fresh water, converting it into a swamp. Lake Erie is a prime example of this process now under way.

How much of the now widespread eutrophication of fresh waters is attributable to agricultural fertilization and how much to other causes remains an open question. Undoubtedly the runoff of nitrates and phosphates from farmlands plays a large part. There are also other important contributors, however. Considerable amounts of phosphate, coming mainly from detergents, are discharged into rivers and lakes from sewers carrying municipal and industrial wastes. And there is reason to believe that in some rivers and lakes most of the nitrate may come not from fertilizers but from the internal-combustion engine. It is estimated that in the state of New Jersey, which has heavy automobile traffic, nitrous oxide products of gasoline combustion, picked up and deposited by rainfall, contribute as much as 20 pounds of nitrogen per acre per year to the land. Some of this nitrogen washes into the many rivers and lakes of New Jersey and its adjoining states. A way must be found to deal with the eutrophication problem because even in the short run it can have damaging effects, affecting as it does the supply of potable water, the cycles of aquatic life and consequently man's food supply.

Recent findings have presented us with a related problem in connection with the fourth technology supporting man's present high level of food production: the chemical control of diseases, insects and weeds. It is now clear that the use of DDT and other chlorinated hydrocarbons as pesticides and herbicides is beginning to threaten many species of animal life, possibly including man. DDT today is found in the tissues

EXPERIMENTAL PLANTINGS at the International Rice Research Institute in the Philippine Republic are seen in an aerial photograph. IR-8, a high-yield rice, was bred here.



RUINED FARM in the "dust bowl" area of the U.S. in the 1930's is seen in an aerial photograph. The farm is near Union in Terry County, Tex. The wind has eroded the powdery, drought-parched topsoil and formed drifts among the buildings and across the fields.

of animals over a global range of life forms and geography from penguins in Antarctica to children in the villages of Thailand. There is strong evidence that it is actually on the way to extinguishing some animal species, notably predatory birds such as the bald eagle and the peregrine falcon, whose capacity for using calcium is so impaired by DDT that the shells of their eggs are too thin to avoid breakage in the nest before the fledglings hatch. Carnivores are particularly likely to concentrate DDT in their tissues because they feed on herbivores that have already concentrated it from large quantities of vegetation. Concentrations of DDT in mothers' milk in the U.S. now exceed the tolerance levels established for foodstuffs by the Food and Drug Administration.

It is ironic that less than a generation after 1948, when Paul Hermann Müller of Switzerland received a Nobel prize for the discovery of DDT, the use of the insecticide is being banned by law in many countries. This illustrates how little man knows about the effects of his intervening in the biosphere. Up to now he has been using the biosphere as a laboratory, sometimes with unhappy results.

Several new approaches to the problem of controlling pests are now being explored. Chemists are searching for pesticides that will be degradable, instead of long-lasting, after being deposited on vegetation or in the soil, and that will be aimed at specific pests rather than acting as broad-spectrum poisons for many forms of life. Much hope is placed in techniques of biological control, such as are exemplified in the mass sterilization (by irradiation) of male screwworm flies, a pest of cattle that used to cost U.S. livestock producers $100 million per year. The release of 125 million irradiated male screwworm flies weekly in the U.S. and in adjoining areas of Mexico (in a cooperative effort with the Mexican government) is holding the fly population to a negligible level. Efforts are now under way to get rid of the Mexican fruit fly and the pink cotton bollworm in California by the same method.

Successes are also being achieved in breeding resistance to insect pests in various crops. A strain of wheat has been developed that is resistant to the Hessian fly; resistance to the corn borer and the corn earworm has been bred into strains of corn, and work is in progress on a strain of alfalfa that resists aphids and leafhoppers. Another promising approach, which already has a considerable history, is the development of insect parasites, ranging from bacteria and viruses to wasps that lay their eggs in other insects. The fact remains, however, that the biological control of pests is still in its infancy.

I have here briefly reviewed the major agricultural technologies evolved to meet man's increasing food needs, the problems arising from them and some possible solutions. What is the present balance sheet on the satisfaction of human food needs? Although man's food supply has expanded several hundredfold since the invention of agriculture, two-thirds of mankind is still hungry and malnourished much of the time. On the credit side a third of mankind, living largely in North America, Europe, Australia and Japan, has achieved an adequate food supply, and for the remaining two-thirds the threat of large-scale famine has recently been removed, at least for the immediate future. In spite of rapid population growth in the developing countries since World War II, their peoples have been spared from massive famine (except in Biafra in 1969–1970) by huge exports of food from the developed countries. As a result of two consecutive monsoon failures in India, a fifth of the total U.S. wheat crop was shipped to India in both 1966 and 1967, feeding 60 million Indians for two years.

Although the threat of outright famine has been more or less eliminated for the time being, human nutrition on the global scale is still in a sorry state. Malnutrition, particularly protein deficiency, exacts an enormous toll from the physical and mental development of the young in the poorer countries. This was dramatically illustrated when India held tryouts in 1968 to select a team to represent it in the Olympic games that year. Not a single Indian athlete, male or female, met the minimum standards for qualifying to compete in any of the 36 track and field events in Mexico City. No doubt this was partly due to the lack of support for athletics in India, but poor nutrition was certainly also a large factor. The young people of Japan today are visible examples of what a change can be brought about by improvement in nutrition. Well-nourished from infancy, Japanese teen-agers are on the average some two inches taller than their elders.

Protein is as crucial for children's mental development as for their physical development. This was strikingly shown in a recent study extending over several years in Mexico: children who had been severely undernourished before the age of five were found to average 13 points lower in I.Q. than a carefully selected control group. Unfortunately no amount of feeding or education in later life can repair the setbacks to development caused by undernourishment in the early years. Protein shortages in the poor countries today are depreciating human resources for at least a generation to come.

Protein constitutes the main key to human health and vigor, and the key to the protein diet at present is held by grain consumed either directly or indirectly (in the form of meat, milk and eggs). Cereals, occupying more than 70 percent of the world's cropland, provide 52 percent of man's direct energy intake. Eleven percent is supplied by livestock products such as meat, milk and eggs, 10 percent by potatoes and other tubers, 10 percent by fruits and vegetables, 9 percent by animal fats and vegetable oils, 7 percent by sugar and 1 percent by fish. As in the case of the total quantity of the individual diet, however, the composition of the diet varies greatly around the world. The difference is most marked in the per capita use of grain consumed directly and indirectly.

The two billion people living in the poor countries consume an average of about 360 pounds of grain per year, or about a pound per day. With only one pound per day, nearly all must be consumed directly to meet minimal energy requirements; little remains for feeding to livestock, which may convert only a tenth of their feed intake into meat or other edible human food. The average American, in contrast, consumes more than 1,600 pounds of grain per year. He eats only about 150 pounds of this directly in the form of bread, breakfast cereal and so on; the rest is consumed indirectly in the form of meat, milk and eggs. In short, he enjoys the luxury of the highly inefficient animal conversion of grain into tastier and somewhat more nutritious proteins.

Thus the average North American currently makes about four times as great a demand on the earth's agricultural ecosystem as someone living in one of the poor countries. As the income levels in these countries rise, so will their demand for a richer diet of animal products. For the increasing world population at the end of the century, which is expected to be twice the 3.5 billion of today, the world production of grain would have to be doubled merely to maintain present consumption levels. This increase, combined with the projected improvement in diet associated with gains in income over the next three decades, could nearly triple the demand for grain, requiring that the food supply increase more over the next three decades than it has in the 10,000 years since agriculture began.

There are ways in which this pressure can be eased somewhat. One is the breeding of higher protein content in grains and other crops, making them nutritionally more acceptable as alternatives to livestock products. Another is the development of vegetable substitutes for animal products, such as are already available in the form of oleomargarine, soybean oil, imitation meats and other replacements (about 65 percent of the whipped toppings and 35 percent of the coffee whiteners now sold in U.S. supermarkets are nondairy products). Pressures on the agricultural ecosystem would thus drive high-income man one step down in the food chain to a level of more efficient consumption of what could be produced by agriculture.

What is clearly needed today is a cooperative effort—more specifically, a world environmental agency—to monitor, investigate and regulate man's interventions in the environment, including those made in his quest for more food. Since many of his efforts to enlarge his food supply have a global impact, they can only be dealt with in the context of a global institution. The health of the biosphere can no longer be separated from our modes of political organization. Whatever measures are taken, there is growing doubt that the agricultural ecosystem will be able to accommodate both the anticipated increase of the human population to seven billion by the end of the century and the universal desire of the world's hungry for a better diet. The central question is no longer "Can we produce enough food?" but "What are the environmental consequences of attempting to do so?"

In this age of affluence, we have more of everything. Including more trash. 182,000,000 tons a year. And what to do with it is a real problem.

Burning it produces smoke and fly ash. Open dumps breed insects and disease.

Many cities bury their problem. It's cheaper, cleaner, more efficient and healthier.

And waste burial, or sanitary landfill, is a good way to turn low value land into a community asset. Los Angeles County reclaimed an abandoned strip mine with sanitary landfill.

The result is the lush, 87-acre South Coast Botanical Garden.

Find out what you can do in your community. Write for the free booklet, "What can you do with refuse?" to: Caterpillar Tractor Co., Dept. 718SA, 100 N.E. Adams St., Peoria, Illinois 61602.

Or ask your local Caterpillar Dealer to show you the film, "The trouble with trash."

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IS OPEN FOR

We call it Vega 2300.

We also call it ''the little car that does everything well.''

Because it does.

Vega moves well, stops well, steers well, rides well, handles well, responds well, passes well, travels well, parks well, wears well, and is priced well under what you'd expect to pay for such a talented little car.

In our highway tests, Vega has been getting gas mileage in the neighborhood of the little imports, which isn't a bad neighborhood.

Yet unlike your average little car, ours steps right out when you step on the gas.

The engine is a specially designed overhead cam four with a lightweight aluminum alloy block. It turns slowly and quietly at turnpike speeds, with power to spare.

Disc brakes are standard in the front. So are bucket seats, except on the truck.

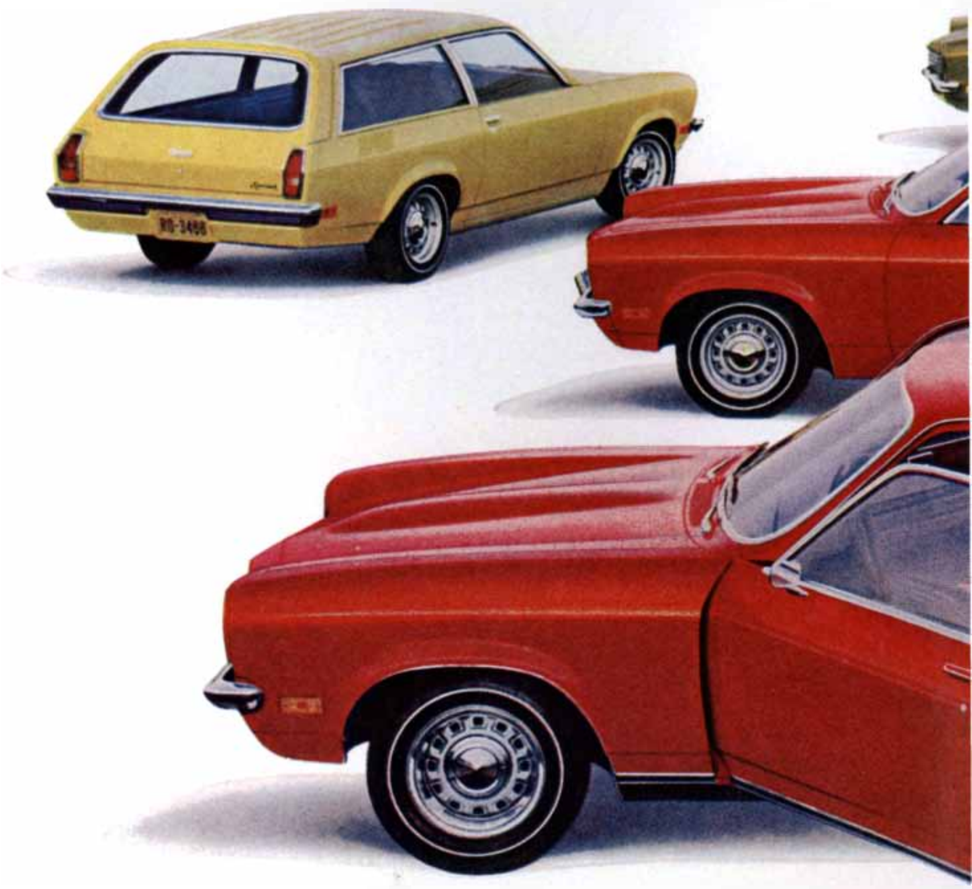
How we doing so far?

Numbers speak louder than words.

The wheelbase is 97 inches.

Total length is just under 170 inches, or nearly four feet shorter than a full-size Chevrolet.

Height is just over 51 inches, six inches



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Fuel economy: about 25 mpg, with the standard transmission, in our highway tests.

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What it all adds up to is a lot of little car.

Three cars and a truck.

Vega turned out so well that we couldn't turn out just one.

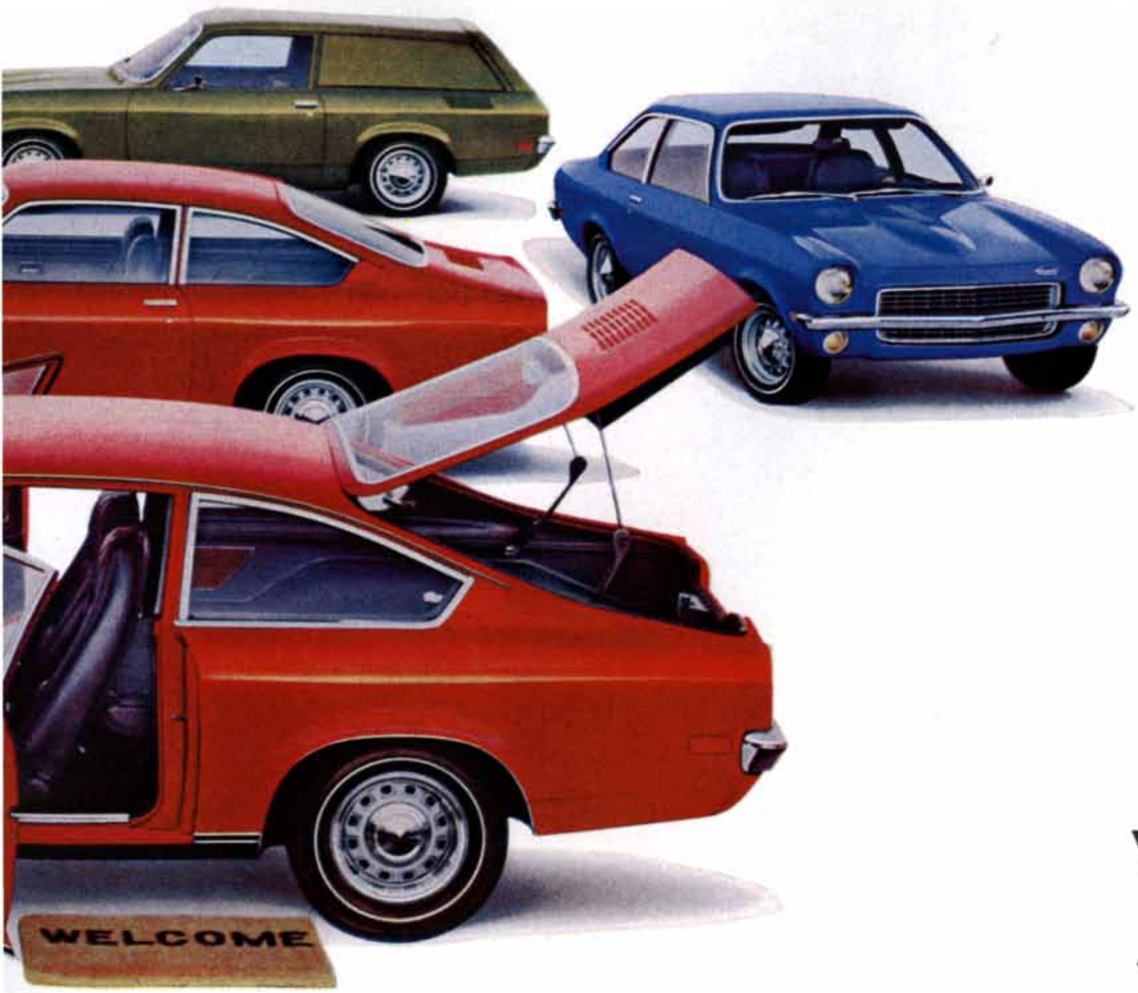
So we're turning out four: the sporty little hatchback coupe shown open and closed in the foreground below; the sedan, on the right; the Kammback wagon, on the left; and the little panel truck, in the rear.

Oh, and a special GT version of the coupe and wagon which we'll show you later on.

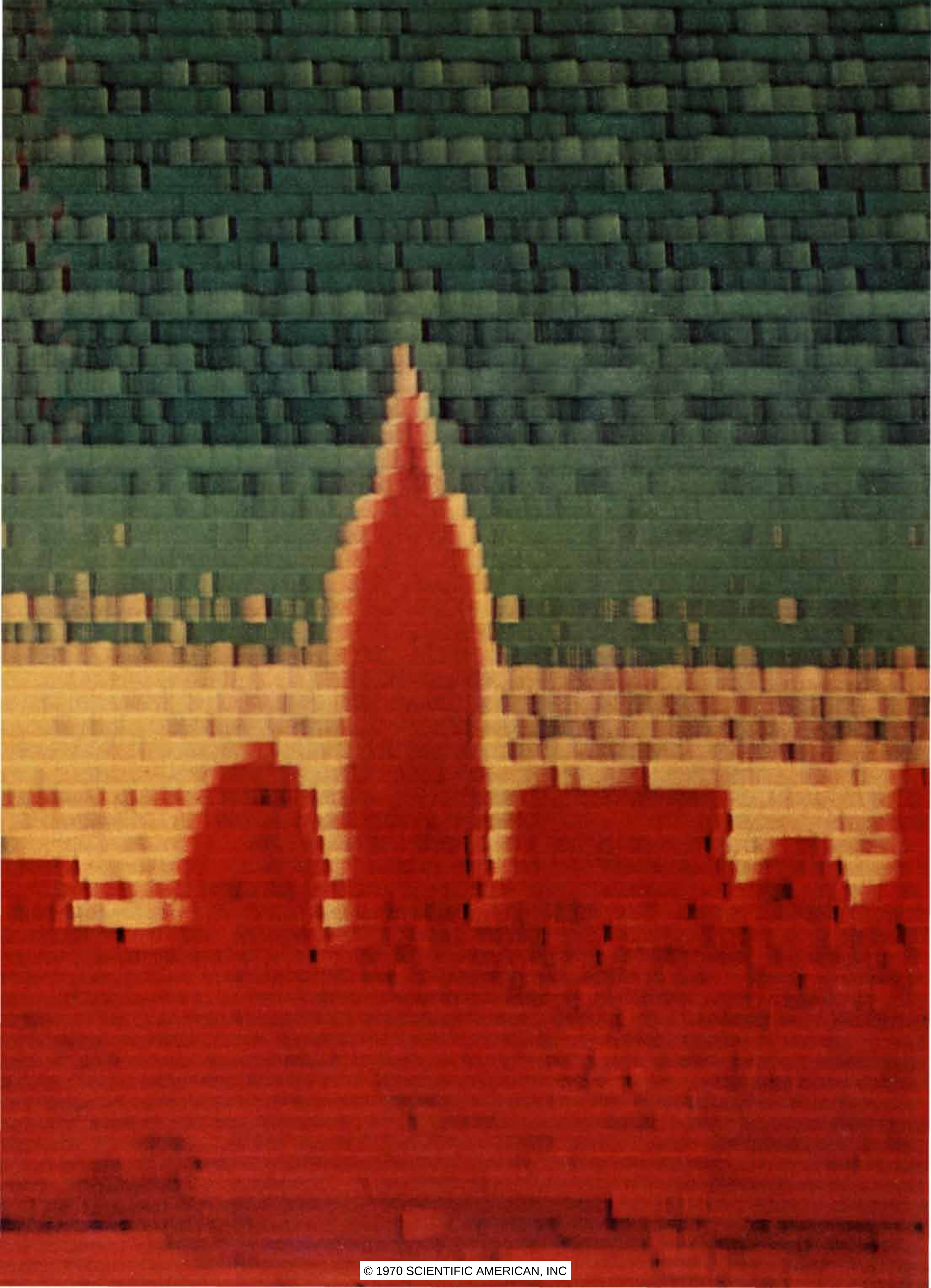
September 10th is Opening Day.

All 6,300 Chevrolet dealers are handling Vega, so you shouldn't have to go very far to see and drive one.

Chevy's new little car is open for business. Look into it.



VEGA
CHEVROLET



Human Energy Production as a Process in the Biosphere

In releasing the energy stored in fossil and nuclear fuels man accelerates slow cycles of nature. The waste products of power generation then interact with the fast cycles of the biosphere

by S. Fred Singer

As other articles in this issue of *Scientific American* have noted, the earth in general and the biosphere in particular have grand-scale pathways of energy metabolism. For example, solar energy falls on the earth, green plants utilize a tiny fraction of it to manufacture energy-rich compounds and some of these compounds are stored in the earth's crust as what we have come to call fossil fuels. The primary fission fuel uranium and the potential fusion fuel deuterium were originally "cooked" in the interior of stars. In releasing the energy of these chemical and nuclear fuels man is in effect racing the slow cycles of nature, with inevitable effects on the cycles themselves.

Before 1800 the power available to human societies was limited to solar energy that had only recently been radiated to the earth. The most direct form of such power was human or animal power; the energy came from the metabolism of food, which is to say from the biological oxidation of compounds storing solar energy. The burning of wood or oils of animal or vegetable origin to provide light and heat also represented the conversion of recently stored solar energy. By the same token the use of moving air or falling water to drive mills or pumps constituted the use of recently arrived solar energy. Among the other limitations of such power sources was the fact that they could not be readily transported and that their energy could not be transmitted any considerable distance.

This picture has of course changed completely since 1800, and it has assumed significant new dimensions in the past two decades with the advent of nuclear power. The most striking measure of these changes is the increased per capita consumption of energy in the developed countries. Indeed, the correlation between a nation's per capita use of energy and its level of economic development is almost linear [*see illustration on page 178*]. The minimum per capita consumption of energy is what is required in food for a man to stay alive, namely about 2,000 kilocalories or 100 watts (thermal) per day. Today the per capita use of energy in the U.S. is 10,000 watts per day, and the figure is rising by some 2.5 percent per year.

Hand in hand with the advance in the rate of energy consumption has gone the introduction of the new sources of energy: fossil and nuclear fuels. In contrast to the sources used before 1800, fossil and nuclear fuels represent energy that reached the earth millions and even some billions of years ago. Except occasionally for political reasons, it matters little where the new fuels are found; they can be transported readily, and the energy produced from them can be transmitted over great distances.

On first consideration it might seem that fossil and nuclear fuels are fundamentally different, in that the energy of one is released by oxidation, or burning, and the energy of the other is released by fission or fusion. In a deeper sense, however, the two kinds of fuel are closely related. Fossil fuels store the radiant energy originally produced by nuclear reactions in the interior of the sun. Nuclear fuels store energy produced by another set of nuclear reactions in the interior of certain stars. When such stars exploded, they showered into space the elements that had been synthesized within them. These elements then went into the formation of younger stars such as the sun, together with its family of planets.

The production of fossil fuels is based on the carbon cycle that has been described in the article by Bert Bolin [*page 124*]. In the process of photosynthesis plants use radiant energy from the sun to convert carbon dioxide and water into carbohydrates, at the same time releasing oxygen into the atmosphere. When the plant materials decompose or are eaten by animals, the process is reversed: oxygen is used to convert carbohydrates into energy plus carbon dioxide and water.

The amount of carbon dioxide involved in photosynthesis annually is about 110 billion tons, or roughly 5 percent of the carbon dioxide in the atmosphere. The consumption of carbon dioxide through photosynthesis is matched to one part in 10,000 by the annual release of carbon dioxide to the atmosphere through oxidation. Under normal conditions the amounts of carbon dioxide and oxygen in the atmosphere re-

WASTE HEAT that is an inevitable accompaniment of the human use of energy is evident in the thermal infrared image of New York on the opposite page. The thermogram was made with a Barnes thermograph that depicts emissions of energy on a color scale ranging from black for the coolest objects through green, yellow and red to red-purple for the hottest ones. Some of the emissions represent solar energy stored in the walls of buildings, but a large fraction is waste heat from the human consumption of energy. The rectangular elements of the image result from digitized output of thermograph. Empire State Building is at center.

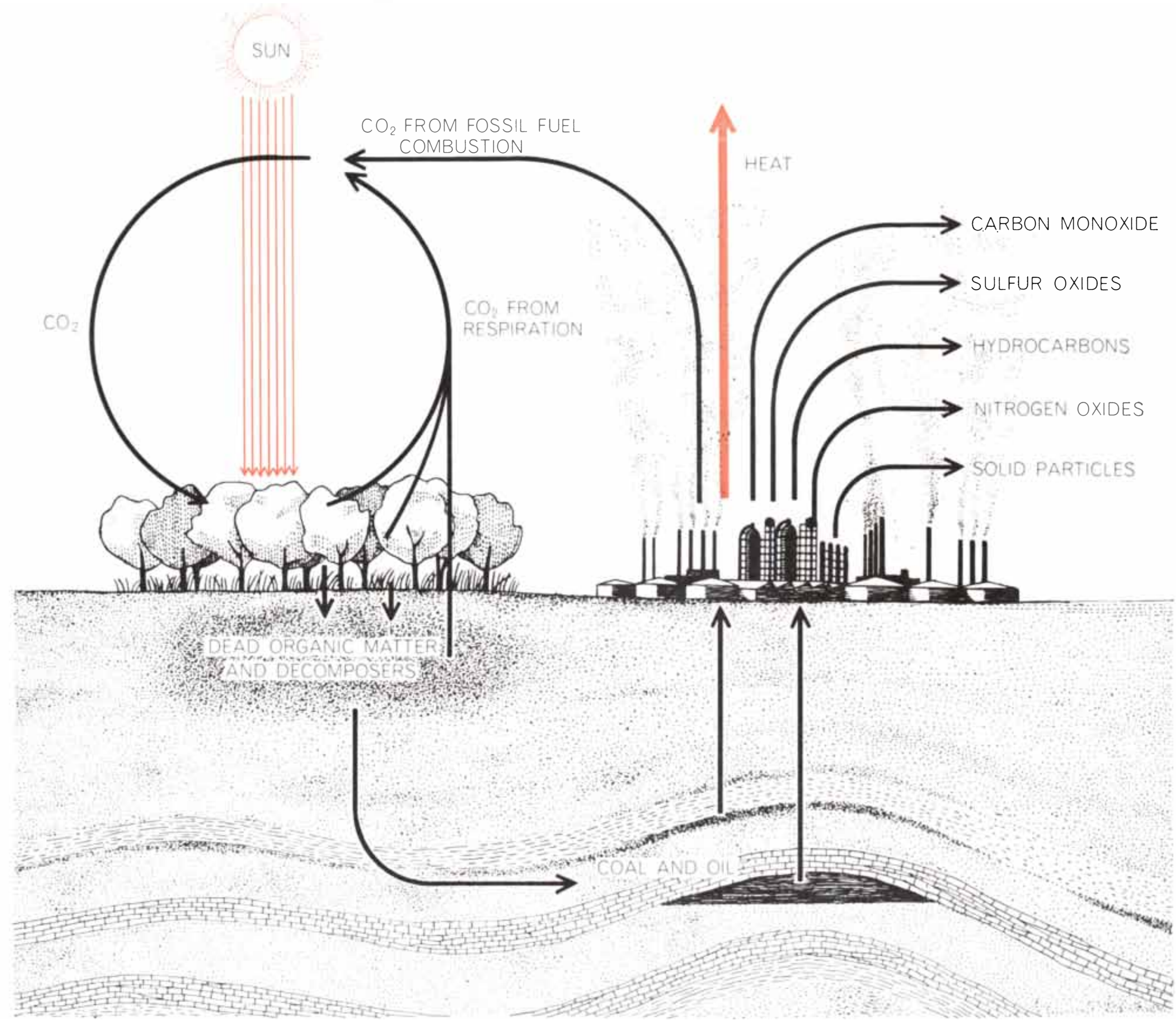
main approximately in equilibrium from year to year.

There are, however, small long-term imbalances in the carbon cycle, and it is owing to them that the fossil fuels being exploited today all derive from plants and animals that lived long ago. Over a span of geologic history extending back into the Cambrian period of some 500 million years ago, a small fraction of these organisms have been buried in sediments or mud under conditions that prevented complete oxidation. Various chemical changes have transformed them into fossil fuels: coal, oil, natural gas, lignite, tar and asphalt. Although the same geological processes are still operative, they function over vast periods of time, and so the amount of new fossil fuel that is likely to be produced during the next few thousand years is inconsequential. Therefore one can assume that the existing fossil fuels constitute a nonrenewable resource.

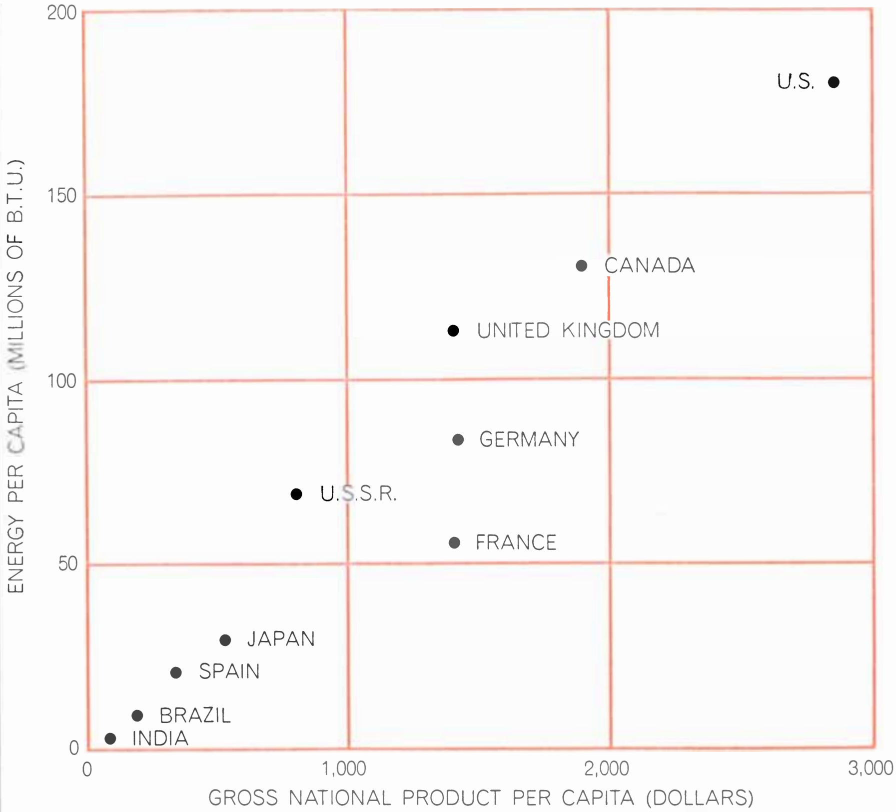
Coal has been burned for some eight centuries, but it was consumed in negligible amounts until early in the 19th century. Since the middle of that century the rise in the consumption of coal has been spectacular: in 1870 the world production rate of coal was about 250 million metric tons per year, whereas this year it will be about 2.8 billion tons. The rate of increase, however, is lower now than it was at the beginning of the period, having declined from an average of 4.4 percent per year to 3.6 percent, largely because of the rapid increase in the fraction of total industrial energy contributed by oil and gas. In the U.S. that fraction rose from 7.9 percent in 1900 to 67.9 percent in 1965, whereas the contribution of coal declined from 89 percent to 27.9 percent.

World production of crude oil was negligible as recently as 1890; now it is close to 12 billion barrels per year. The rise in the rate of production has been nearly 7 percent per year, so that the amount of oil extracted has doubled every 10 years. As yet there is no sign of a deceleration in this rate.

Nonetheless, the finiteness of the earth's fossil fuel supplies gives rise to the question of how long they will last. M. King Hubbert of the U.S. Geological Survey has estimated that the earth's



ENERGY CYCLE involved in the combustion of fossil fuels begins with solar energy employed in photosynthesis millions of years ago. A small fraction of the plants is buried under conditions that prevent complete oxidation. The material undergoes chemical changes that transform it into coal, oil and other fuels. When they are burned to release their stored energy, only part of the energy goes into useful work. Much of the energy is returned to the atmosphere as heat, together with such by-products of combustion as carbon dioxide and water vapor. Other emissions in fossil fuel combustion are listed at right in the relative order of their volume.



CLOSE RELATION between a nation's consumption of energy and its gross national product is depicted on the basis of a study made by the Office of Science and Technology in 1961. Most of the nations covered beyond the 10 shown would be in the lower left-hand rectangle.

coal supply can serve as a major source of industrial energy for another two or three centuries. His estimate for petroleum is 70 to 80 years. However much these periods may be stretched by unforeseen discoveries and improved technology, the end of the fossil fuel era will inevitably come. From the perspective of that time—perhaps the 23rd century—the period of exploitation of fossil fuels will be seen as only a brief episode in the span of human history.

This year the U.S. will consume some 685,000 million million B.T.U. of energy, most of it derived from fossil fuels. (One short ton of coal has a thermal value of 25.8 million B.T.U. The thermal value of one barrel of oil is 5.8 million B.T.U.) Industry takes more than 35 percent of the total energy consumption. About a third of industry's share is in the form of electricity, which, as of 1960, was generated roughly 50 percent from coal, 20 percent from water power, 20 percent from natural gas and 10 percent from oil.

The nation's homes use almost as much energy as industry does. A major consumer is space heating, which for the average home requires as much energy as the average family car: about 70 million B.T.U. per year, or the equivalent of 900 gallons of oil. The other domestic uses are for cooking, heating water, lighting and air conditioning.

Transportation accounts for 20 percent of the annual energy consumption, mainly in the form of gasoline for automobiles. Another 10 percent goes for commercial consumption in stores, offices, hotels, apartment houses and the like. Agriculture probably consumes no more than 1 percent of all the energy, chiefly for the operation of tractors and for running irrigation and drainage equipment.

Looking at the use of fossil fuels from another viewpoint, one finds that most of the coal goes into the generation of electricity. Oil and natural gas tend to be used directly, either for heating purposes or to provide motive power for vehicles. Fossil fuels are also used as the raw materials for the petrochemical industry. Notwithstanding that industry's rapid growth, however, it still accounts for less than 2 percent of the annual consumption of fossil fuels.

Clearly the production of energy from fossil fuels on the scale typical of a modern industrial nation represents an enormous amount of combustion, with

Gas Energy helps put the brakes on air pollution.

Through the development of a natural Gas fuel system for cars and trucks. So congestion in the streets won't have to mean congestion in the air.

In fact, these systems are being developed right now. In California, Massachusetts, Georgia, Arkansas, Texas, and Ohio.

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Why use natural Gas in city traffic? In Southern California, tests show that carbon monoxide emissions are reduced 90%. Reactive hydrocarbons 90%. Nitrogen oxides 90%. And clean-burning Gas costs much less than gasoline.

Air pollution is a complex problem, but Gas Energy is helping our cities solve it. Developing economical Gas incineration systems to keep industrial wastes out of the air was one part of the solution. And this new dual-fuel system is another.

But is this really so surprising? After all, Gas is pure energy

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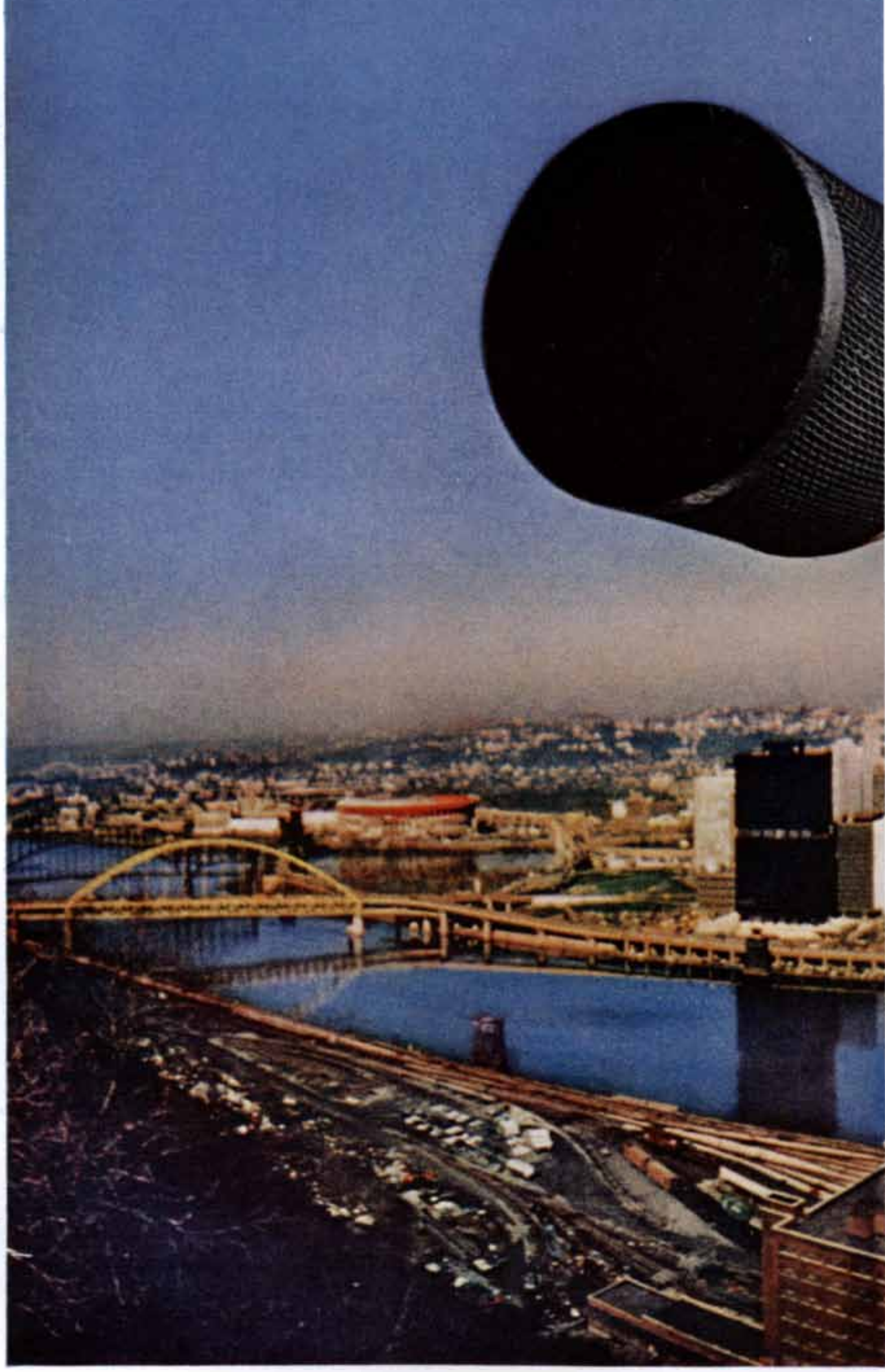
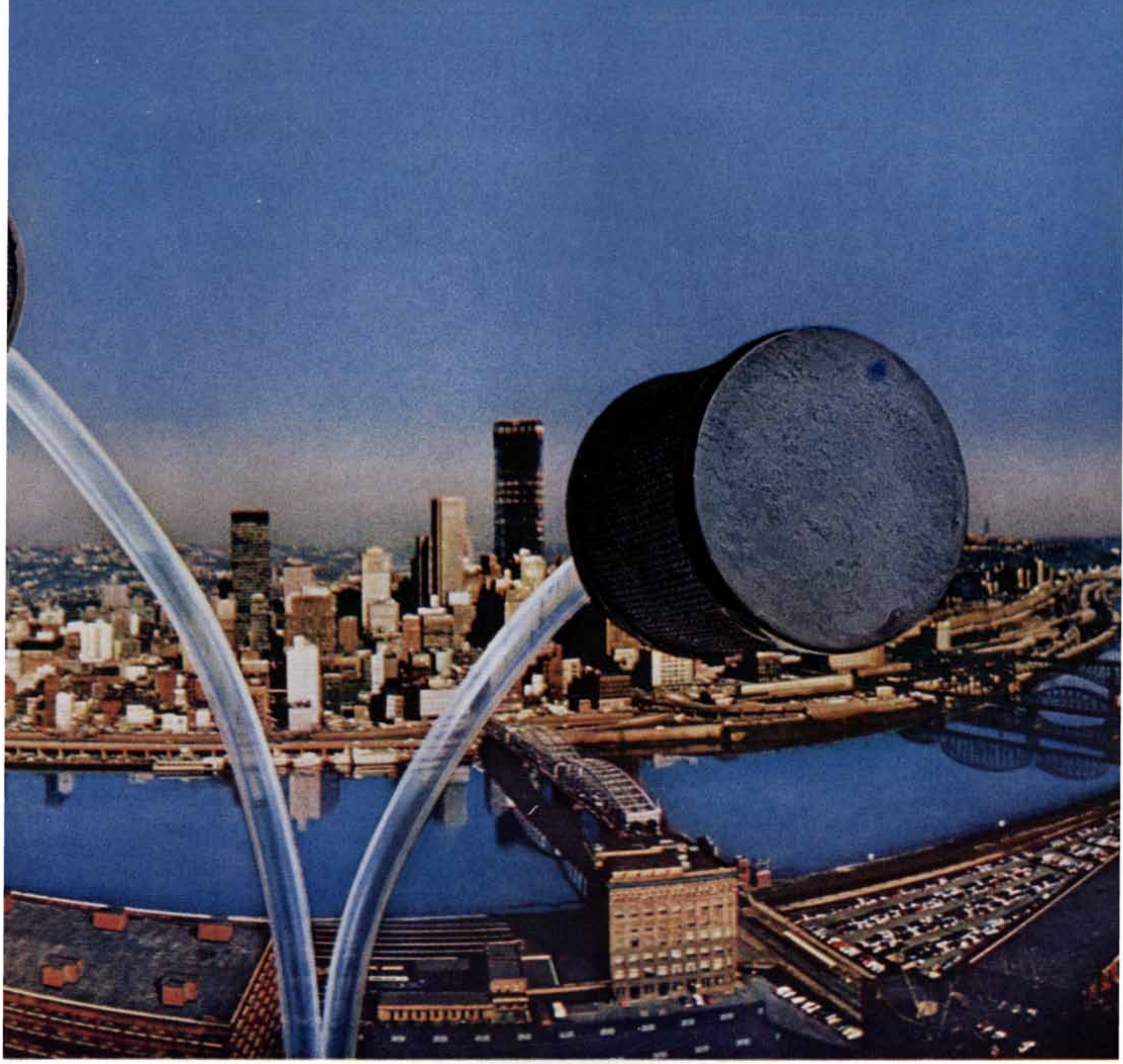
IBM's Dennis Leonetti, who began working on Allegheny County's long-standing air-pollution project in 1967, at the site of a planned sensing station.



They're keeping an eye on unseen pollutants in a city's air.

Once a 3-white-shirt-a-day city, Pittsburgh did a remarkable job of cleaning up its visible air pollution. But how do you fight the stuff you can't see? Dennis Leonetti's story is another example of how IBM, its people or products often play a part in tackling today's problems.



"Air taken in through 'sniffers' like these is continuously analyzed for pollutants. Readings are then fed into a central computer."

"There were days when Pittsburgh was dark by noon. And some people wore three shirts a day," reflects Dennis Leonetti, IBM Marketing Representative to the Allegheny County Bureau of Air Pollution Control.

"They really did a remarkable job of cleaning up the visible pollution. As far back as 1962, a U.S. Public Health Service study, covering thirteen cities, showed that Pittsburgh had less 'dust' than eleven of them. Only Salt Lake City had clearer air.

"But the most difficult part of the job is still ahead.

"What we're after now are the pollutants you can't see. Carbon monoxide. Sulphur dioxide. And what's called fine particulate, the stuff that stays suspended in the air.

"By this summer, the County will have seven sensing stations with 52 sensors. The final plan calls for seventeen stations with 103 sensors.

"These 'sniffers' take continuous readings of pollutant levels, which, along with weather data, are fed into the computer over telephone lines.

"Readings are printed out every five minutes. But when a pollutant exceeds a specified level, the printout appears in red and the computer automatically requests new readings every fifteen seconds.

"A system like this can pinpoint excess pollutants and their sources. And give pollution authorities an opportunity to take appropriate action.

"What's more, we'll eventually be able to use it as an early warning system—spotting dangerous conditions *before* critical pollution levels are reached.

"Nobody's looking for any awards yet. We haven't eliminated air pollution. But what we're doing will help here. And, we hope, in other cities as well."

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attendant effects on the biosphere. By far the greatest effect is the emission of carbon dioxide. Combustion also injects a number of pollutants into the air. In the U.S. the five most common air pollutants, listed in the order of their annual tonnage, are carbon monoxide, sulfur oxides, hydrocarbons, nitrogen oxides and solid particles. The major sources are automobiles, industry, electric power plants, space heating and refuse disposal. The burning of fossil fuels also produces effects on water: chemical effects when the air pollutants are washed down by water and thermal effects arising from the dispersal of waste heat from thermal power plants.

Carbon dioxide is the only combustion product whose increase has been documented on a worldwide basis. The injection of large quantities of carbon dioxide into the atmosphere in the past few decades has been extremely sudden in relation to important natural time scales. For example, although the surface of the sea can adjust to changes in the level of carbon dioxide in the atmosphere in about five years, the deeper layers require some hundreds or thousands of years to adjust. If the oceans were perfectly mixed at all times, carbon dioxide added to the atmosphere would distribute itself about five-sixths in the water and about one-sixth in the air. In actuality the distribution is about equal.

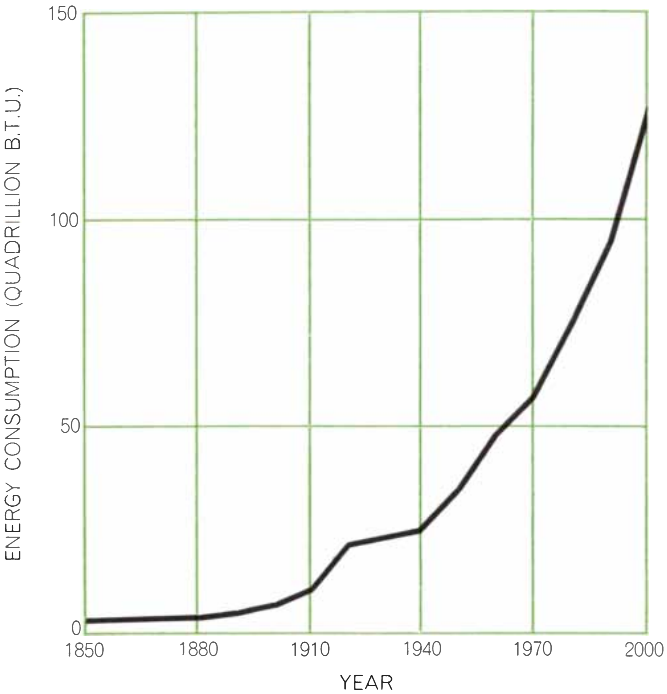
It appears that between 1860 and the present the concentration of carbon dioxide in the atmosphere has increased from about 290 parts per million to about 320 parts per million, an increase of more than 10 percent. Precise measurements by Charles D. Keeling of the Scripps Institution of Oceanography have established that the carbon dioxide content increased by six parts per million between 1958 and 1968. Reasonable projections indicate an increase of 25 percent (over 1970) to about 400 parts per million by the turn of the century and to between 500 and 540 parts per million by 2020.

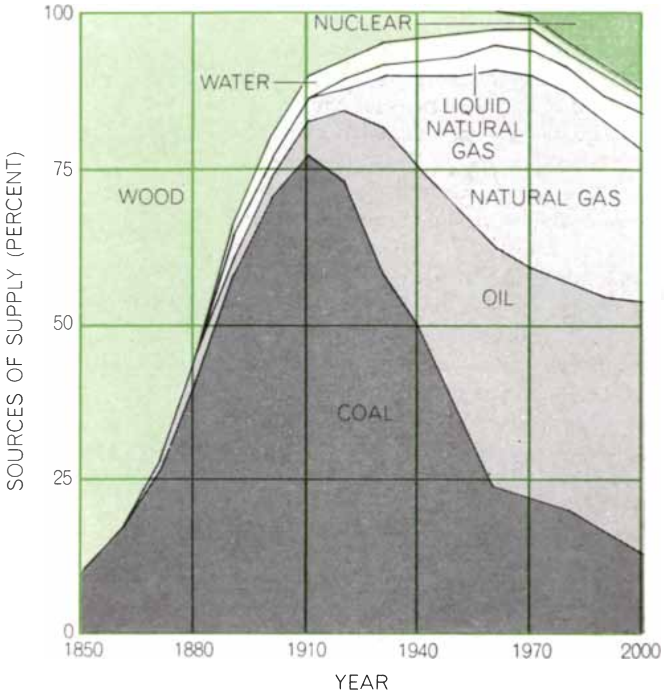
USE OF ENERGY in the U.S. is expressed in terms of thermal kilowatts per capita per day in 1967. All together the consumption averages 10,000 watts per person per day, which is 100 times the food-intake level of 100 watts that is barely exceeded in many nations.

The most widely discussed matter related to these increases is the possibility that they will lead to a worldwide rise in temperature. The molecule of carbon dioxide has strong absorption bands, particularly in the infrared region of the spectrum at wavelengths of from 12 to 18 microns. This is the spectral region where most of the thermal energy radiating from the earth into space is concentrated. By increasing the absorption of this radiation and by reradiating it at a lower temperature corresponding to the temperature of the upper atmosphere the carbon dioxide reduces the amount of heat energy lost by the earth to outer space. The phenomenon has been called the "greenhouse effect," although the analogy is inexact because a real greenhouse achieves its results less from the fact that the glass blocks reradiation in the infrared than from the fact that it cuts down the convective transfer of heat.

The possibility that additional carbon dioxide from the burning of fossil fuels could produce a worldwide increase in temperature seems to have been raised initially by the American geologist P. C. Chamberlain in 1899. In 1956 Gilbert N. Plass calculated that a doubling of the carbon dioxide content of the atmosphere would result in a rise of 6.5 degrees Fahrenheit at the earth's surface. In 1963 Fritz Möller calculated that a 25 percent increase in atmospheric carbon dioxide would increase the average temperature by one to seven degrees F., depending on the effects of water vapor in the atmosphere. The most extensive calculations have been made by Syukuro Manabe and R. T. Wetherald, who estimate that a rise in atmospheric carbon dioxide from 300 to 600 parts per million would increase the average surface temperature by 4.25 degrees, assuming average cloudiness, and by 5.25 degrees, assuming no clouds.

Unfortunately the problem is more complicated than these calculations imply. An increase of temperature at the





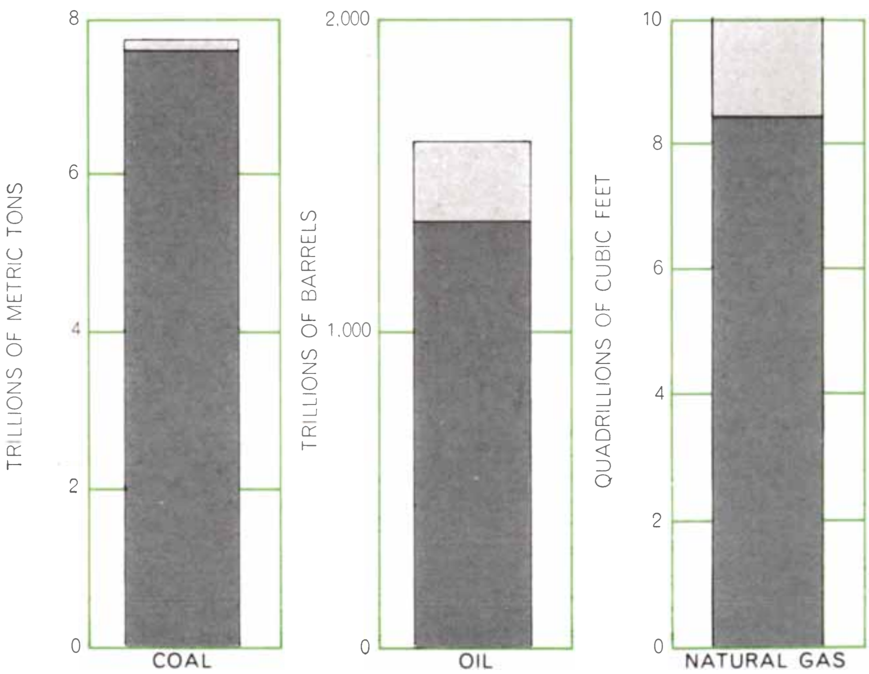
CHANGING SOURCES of energy in the U.S. since 1850 are compared (*right*) with total consumption (*left*) over the same period. At right one can see that in 1850 fuel wood was the source of 90 percent of the energy and coal accounted for 10 percent. By 2000 it is foreseen that coal will be back to almost 10 percent and that other sources will be oil, natural gas, liquid natural gas, hydroelectric power, fuel wood and nuclear energy. The estimates were made by Hans H. Landsberg of Resources for the Future, Inc.

surface of the earth and in the lower levels of the atmosphere not only increases evaporation but also changes cloudiness. Changes of cloudiness alter the albedo, or average reflecting power, of the earth. The normal average albedo is about 30 percent, meaning that 30 percent of the sunlight reaching the earth is immediately reflected back into space. Changes in cloudiness, therefore, can have a pronounced effect on the atmospheric temperature and on climate.

The situation is further complicated by atmospheric turbidity. J. Murray Mitchell, Jr., of the Environmental Science Services Administration has determined that atmospheric temperatures rose generally between 1860 and 1940. Between 1940 and 1960, although warming occurred in northern Europe and North America, there was a slight lowering of temperature for the world as a whole. Mitchell finds that a cooling trend has set in; he believes it is owing partly to the dust of volcanic eruptions and partly to such human activities as agricultural burning in the Tropics. (In the future the condensation trails left by jet airplanes may contribute to this problem.)

In sum, the fact that the carbon dioxide content of the atmosphere has increased is firmly established by reliable measurements. The effect of the increase on climate is uncertain, partly because no good worldwide measurements of radiation are available and partly because of the counteractive effects of changes in cloudiness and in the turbidity of the atmosphere. An exciting technological possibility is the use of a weather satellite to keep track of the energy radiated back into space by the earth. The data would provide a basis for the first reliable and standardized measurement of the "global radiation climate."

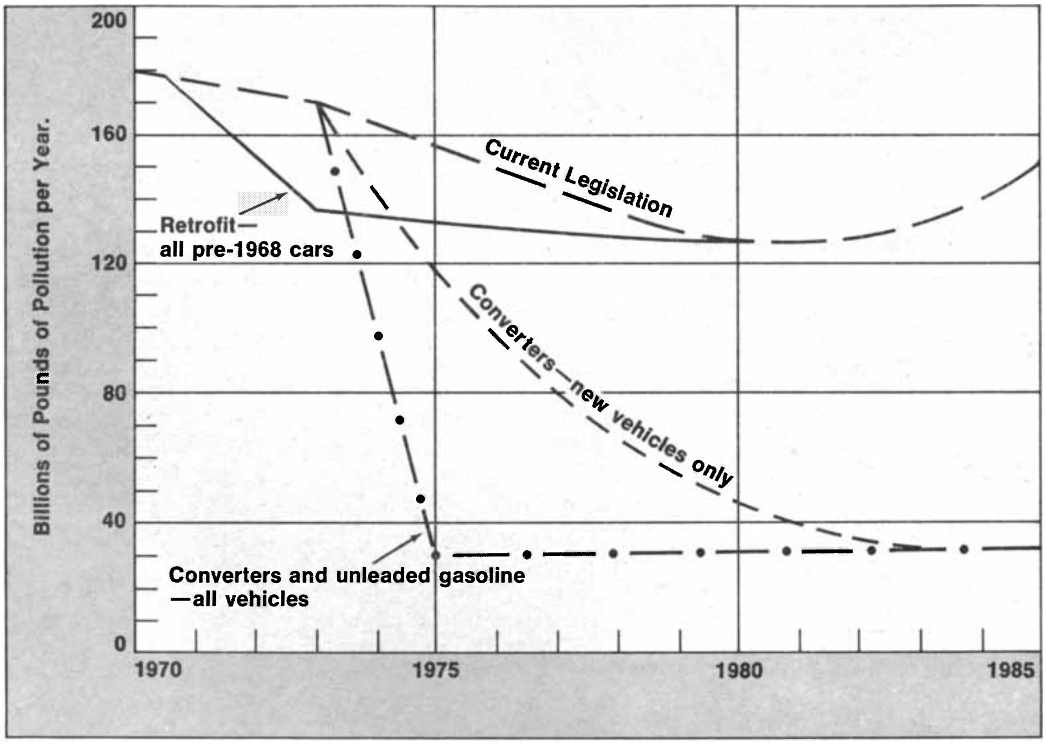
In any event, the higher levels of carbon dioxide may not persist for long. For one thing, the oceans, which contain 60



FOSSIL FUEL SUPPLIES remaining in the world are indicated by a scheme wherein the entire gray bar represents original resources, light gray portion shows how much has been extracted and dark gray area shows what remains. Figures reflect estimates by M. King Hubbert of the U.S. Geological Survey and could be changed by unforeseen discoveries.

"We can't wait 10 or 20 years to end automotive air pollution."

Says John O. Logan, President, UOP



"We as a nation could return the quality of the air we breathe to the level of 15 or 20 years ago *within 2 or 3 years.* This could be done by retro-fitting with pollution control devices all pre-1968 cars now on the highways. (Solid line above.) The technology is available and is now being applied mechanically in new car production.

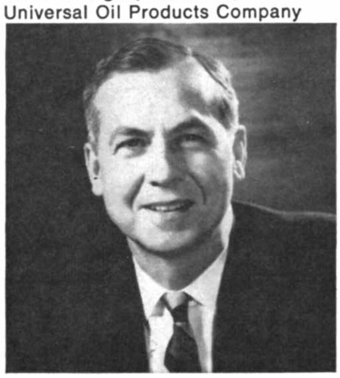
"We can substantially reduce pollution levels even further by using lead-free gasoline in vehicles equipped with catalytic exhaust converters. This will take a little longer because we need ample lead-free gasoline with high enough octane ratings for all cars. This system will not sacrifice engine performance and—in the long run—will be the most economical solution for the consumer.

"Current legislation applies only to new car production and aims to gradually reduce the present level of automotive pollution to 120 billion pounds per year by 1980. This isn't even half the volume we're spewing into the atmosphere right now. Unfortunately, after 1980, the pollution level will again start to climb as the automotive population grows.

"This is a crisis that can only be met by a systems approach involving the oil companies producing a range of lead-free products . . . and Detroit's adoption of the most efficient pollution control devices available from equipment manufacturers.

"In the meantime, we could radically improve our environmental conditions with solutions that are close at hand, if enough responsible people press for early, positive action. Won't you join me in stimulating increased national and local action on this matter of grave concern to all of us?"

John O. Logan, President, Universal Oil Products Company



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UOP is the nation's leading supplier of processes and technology for the petroleum industry to produce automotive fuels and for desulphurizing other petroleum products. In a related area the company manufactures a broad line of industrial air and water pollution control equipment.

times as much carbon dioxide as the atmosphere does, will begin to absorb the excess as the mixing of the intermediate and deeper levels of water proceeds. For another, the increased atmospheric content of carbon dioxide will stimulate a more rapid growth of plants—a phenomenon that has been utilized in greenhouses. It is true that the carbon dioxide thus removed from the atmosphere will be returned when the plants decay. Forests, however, account for about two-thirds of the photosynthesis taking place on land (and therefore for nearly half of the world total), and since forests are long-lived, they tend to spread over a long period of time the return of carbon dioxide to the atmosphere.

The five major air pollutants resulting from the combustion of fossil fuels also interact with the biosphere in various ways, not all of them clearly understood. One tends to think of pollutants as harmful, but the situation is not that simple, as becomes apparent in a consideration of the pollutants and their known effects.

Carbon monoxide appears to be almost entirely a man-made pollutant. The only significant source known is the imperfect combustion of fossil fuels, resulting in incomplete oxidation of the carbon. Although carbon monoxide is emitted in large amounts, it does not seem to accumulate in the atmosphere. The mechanism of removal is not known, but it is probably a biological sink, such as soil bacteria.

Sulfur, which occurs as an impurity in fossil fuels, is among the most troublesome of the air pollutants. Although there are natural sources of sulfur dioxides, such as volcanic gases, more than 80 percent is estimated to come from the combustion of fuels that contain sulfur. The sulfur dioxide may form sulfuric acid, which often becomes associated with atmospheric aerosols, or it may react further to form ammonium sulfate. A typical lifetime in the atmosphere is about a week.

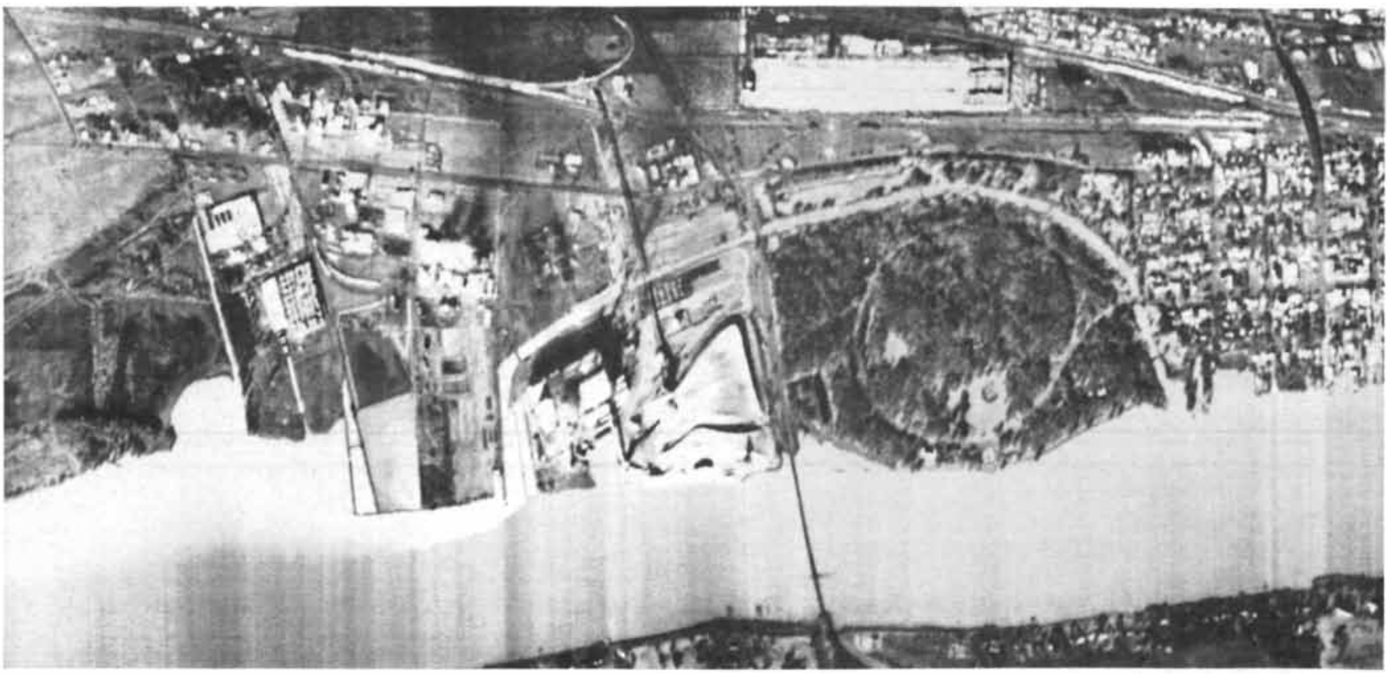
When the sulfur products are removed from the atmosphere by precipitation, they increase the acidity of the rainfall. Values of *p*H of about 4 have been found in the Netherlands and Sweden, probably because of the extensive industrial activity in western Europe. As a result small lakes and rivers have begun to show increased acidity that endangers the stability of their ecosystems. Certain aquatic animals, such as salmon, cannot survive if the *p*H falls below 5.5.

Nothing is known about the global effects of sulfur emission, but they are believed to be small. In any case most of the sulfur ends up in the oceans. It is possible, however, that sulfur compounds are accumulating in a layer of sulfate particles in the stratosphere. The layer's mechanism of formation, its effects and its relation to man-made emissions are not clear. The fine particles of the layer could have an effect on radiation from the upper atmosphere, thereby affecting mean global temperatures.

Hydrocarbons are emitted naturally into the atmosphere from forests and vegetation and in the form of methane from the bacterial decomposition of organic matter. Human activities account for only about 15 percent of the emissions, but these contributions are concentrated in urban areas. The main contributor is the processing and combustion of petroleum, particularly gasoline for the internal-combustion engine.

The reactions of hydrocarbons with nitrogen oxides in the presence of ultraviolet radiation produce the photochemical smog that appears so often over Los Angeles and other cities. The biological effects of several of the products of the reactions, including ozone and complex organic molecules, can be quite severe. Some of the products are thought to be carcinogenic. Ozone has highly detrimental effects on vegetation, but fortunately they are localized. As yet no regional or worldwide effects have been discovered.

Hydrocarbon pollutants in the form of oil spills are well known to have drastic ecological effects. The spill in the Santa Barbara Channel last year, which involved some 10,000 tons, and the *Torrey Canyon* spill in 1967, involving about 100,000 tons, produced intense local concentrations of oil, which is toxic to many marine organisms. Besides these



SOURCES OF WASTE HEAT are evident in a thermal infrared image, made at an altitude of 2,000 feet, of an industrial concentration along the Detroit River in Detroit. The whiter an object is, the hotter it was when the image was made. The complex at left

well-publicized events there is a yearly worldwide spillage from various oil operations that adds up to about a million tons, even though most of the individual spills are small. There are also natural oil seeps of unknown magnitude. Added to all of these is the dumping of waste motor oil; in the U.S. alone about a million tons of such oil is discarded annually. Up to the present time no worldwide effects of these various oil spills are detectable. It can therefore be assumed that bacteria degrade the oil rapidly.

Nitrogen oxides occur naturally in the atmosphere as nitrous oxide (N_2O), nitric oxide (NO) and nitrogen dioxide (NO_2). Nitrous oxide is the most plentiful at .25 part per million and is relatively inert. Nitrogen dioxide is a strong absorber of ultraviolet radiation and triggers photochemical reactions that produce smog. In combination with water it can form nitric acid.

The production of nitrogen oxides in combustion is highly sensitive to temperature. It is particularly likely to result from the explosive combustion taking place in the internal-combustion engine. If this engine is ever replaced by an external-combustion engine that operates at a steady and relatively low temperature rather than at high peaks, the emission of nitrogen oxides will be greatly reduced.

Solid particles are injected into the lower atmosphere from a number of sources, with the combustion of fossil fuels making a major contribution. The technology of pollution control is adequate for limiting such emissions. If it is applied, solid particles will become insignificant pollutants.

Although the fossil fuels still predominate as sources of power, the introduction of nuclear fuels into the generation of power is changing both the scale of energy conversion and the effects of that conversion on the biosphere. Nuclear energy can be considered as a heat source differing from coal or oil, but once the energy has been released in the form of heat it is used in the same way as heat from other sources. Therefore the problem of waste heat is the same. The pollution characteristics of nuclear energy, however, differ from those of the fossil fuels, being radioactive rather than chemical.

Two processes are of concern: the fission of heavy nuclei such as uranium and the fusion of light nuclei such as deuterium. The fission reaction has to start with uranium 235, because that is the only naturally occurring isotope that is fissioned by the capture of slow neutrons. On fissioning the uranium 235 supplies the neutrons needed to carry out other reactions.

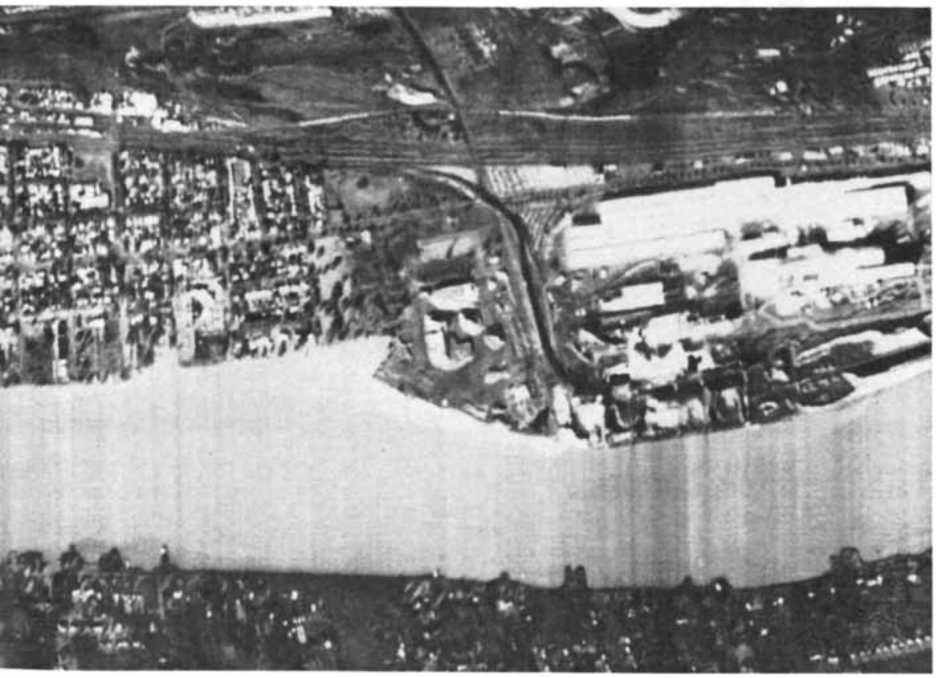
Each fission event of uranium 235 releases some 200 million electron volts of energy. One gram of uranium 235 therefore corresponds to 81,900 million joules, an energy equivalent of 2.7 metric tons of coal or 13.7 barrels of crude oil. A nuclear power plant producing 1,000 electrical megawatts with a thermal efficiency of 33 percent would consume about three kilograms of uranium 235 per day.

A nuclear "burner" uses up large amounts of uranium 235, which is in short supply since it has an abundance of only .7 percent of the uranium in natural ore. If reactor development proceeds as foreseen by the Atomic Energy Commission, inexpensive reserves of uranium (costing less than $10 per pound) would be used up within about 15 years and medium-priced fuel (up to $30 per pound) would be used up by the year 2000. Hence there has been concern that present reactors will deplete these supplies of uranium before converter and breeder reactors are developed to make fissionable plutonium 239 and uranium 233. Either of these isotopes can be used as a catalyst to burn uranium 238 or thorium 232, which are relatively abundant. Thorium and uranium together have an abundance of about 15 parts per million in the earth's crust, representing therefore a source of energy millions of times larger than all known reserves of fossil fuel.

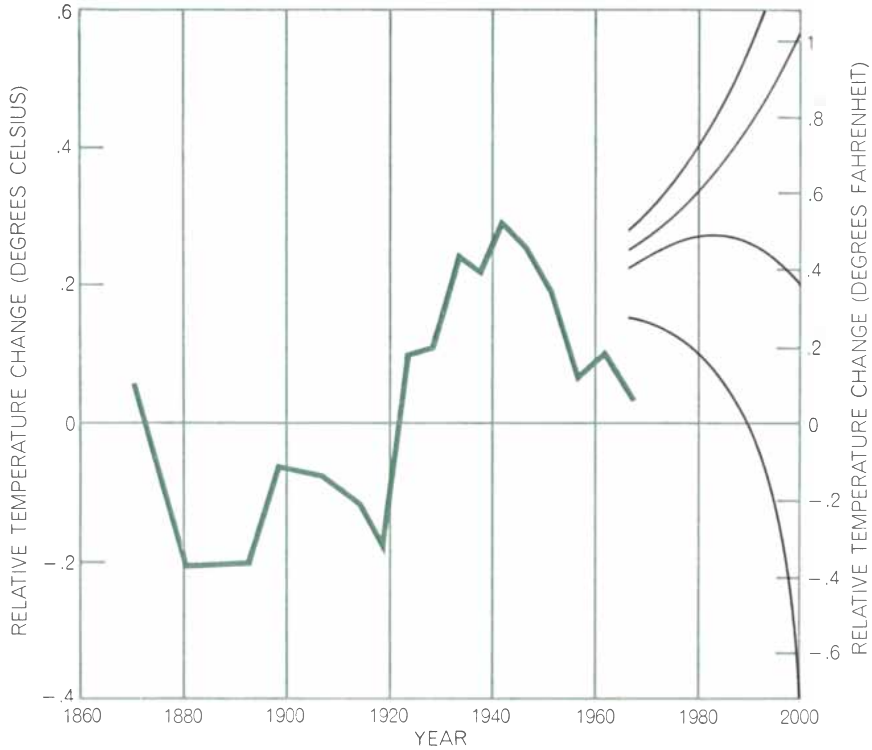
The possibility of generating energy by nuclear fusion is more remote. Of the two processes being considered—the deuterium-deuterium reaction and the deuterium-tritium reaction—the latter is somewhat easier because it proceeds at a lower temperature. In it lithium 6 is the basic fuel, because it is needed to make tritium by nuclear bombardment. The amount of energy available in this way is limited by the abundance of lithium 6 in the earth's crust, namely about two parts per million. The deuterium-deuterium reaction, on the other hand, would represent a practically inexhaustible source of energy, since one part in 5,000 of the hydrogen in the oceans is deuterium.

One must hope, then, that breeder reactors and perhaps fusion reactors will be developed commercially before the supplies of fossil fuel and uranium 235 are exhausted. With inexhaustible (but not cheap) supplies of nuclear energy, automobiles may run on artificially produced ammonia or methane; coal and oil shale will be used as the basis for chemicals, and electricity generated in large breeder or fusion reactors will be used for such purposes as the manufacture of ammonia and methane, the reduction of ores and the production of fertilizers.

It is difficult at this stage to predict



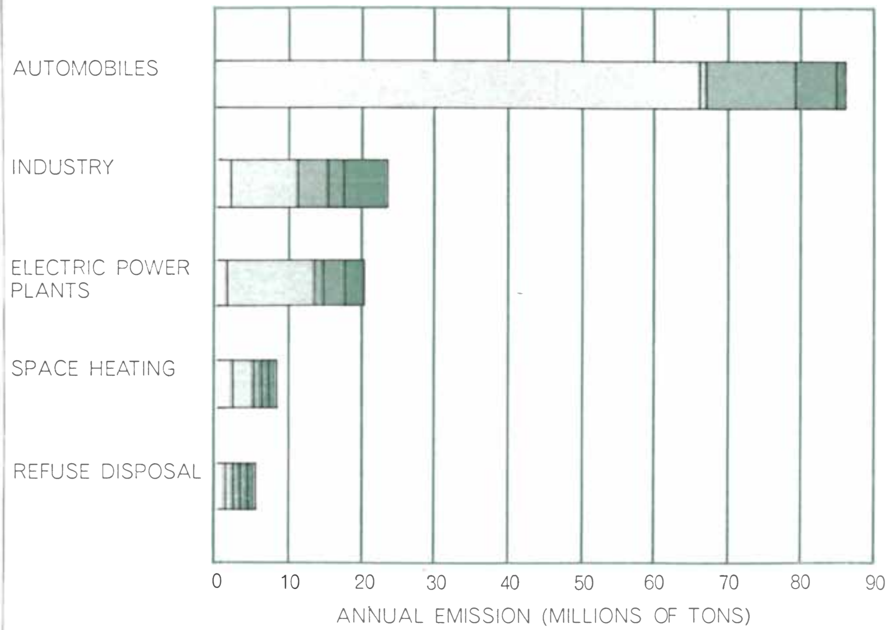
center, identifiable by a distinctly warm effluent entering the river, is a power plant. Group of hot buildings at right is a steel mill. Cool land area at bottom is part of Windsor, Ontario.



TEMPERATURE TREND in Northern Hemisphere is portrayed as observed (*color*) and as predicted under various conditions (*black*). The top black curve assumes an effect from carbon dioxide only; the other black curves also take account of dust. Second and third curves assume doubling of atmospheric dust in 20 and 10 years respectively; bottom curve, doubling in 10 years with twice the thermal effect thought most probable. Chart is based on work of J. Murray Mitchell, Jr., of the Environmental Science Services Administration.

the effects of large-scale use of nuclear energy on the biosphere. One must make certain assumptions about the disposal of radioactive wastes. A reasonable assumption is that they will be rendered harmless by techniques whereby long-lived radioactive isotopes are made into solids and buried. (They are potentially dangerous now because of the technique of storing them as liquids in underground tanks.) Short-lived radioactive wastes can presumably be stored safely until they decay.

For both nuclear energy and for proc-



SOURCES OF EMISSIONS from combustion are ranked. Five parts of each bar represent (*from left*) carbon monoxide, sulfur oxides, hydrocarbons, nitrogen oxides and particles.

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esses involving fossil fuels the major problem and the major impact of human energy production is the dissipation of waste heat. The heat has direct effects on the biosphere and could have indirect effects on climate. It is useful to distinguish between local problems of thermal pollution, meaning the problems that arise in the immediate vicinity of a power plant, and the global problem of thermal balance created by the transformation of steadily rising amounts of energy.

The efficiency of a power plant is determined by the laws of thermodynamics. No matter what the fuel is, one tries to create high-temperature steam for driving the turbines and to condense the steam at the lowest possible temperature. Water is the only practical medium for carrying the heat away. Hence more than 80 percent of the cooling water used by U.S. industry is accounted for by electric power plants. For every kilowatt-hour of energy produced about 6,000 B.T.U. in heat must be dissipated from a fossil fuel plant and about 10,000 B.T.U. from a contemporary nuclear plant.

In the U.S., where the consumption of power has been doubling every eight to 10 years, the increase in the number and size of electric power plants is putting a severe strain on the supply of cooling water. By 1980 about half of the normal runoff of fresh water will be needed for this purpose. Even though some 95 percent of the water thus used is returned to the stream, it is not the same: its increased temperature has a number of harmful effects. Higher temperatures decrease the amount of dissolved oxygen and therefore the capacity of the stream to assimilate organic wastes. Bacterial decomposition is accelerated, further depressing the oxygen level. The reduction of oxygen decreases the viability of aquatic organisms while at the same time the higher temperature raises their metabolic rate and therefore their need for oxygen.

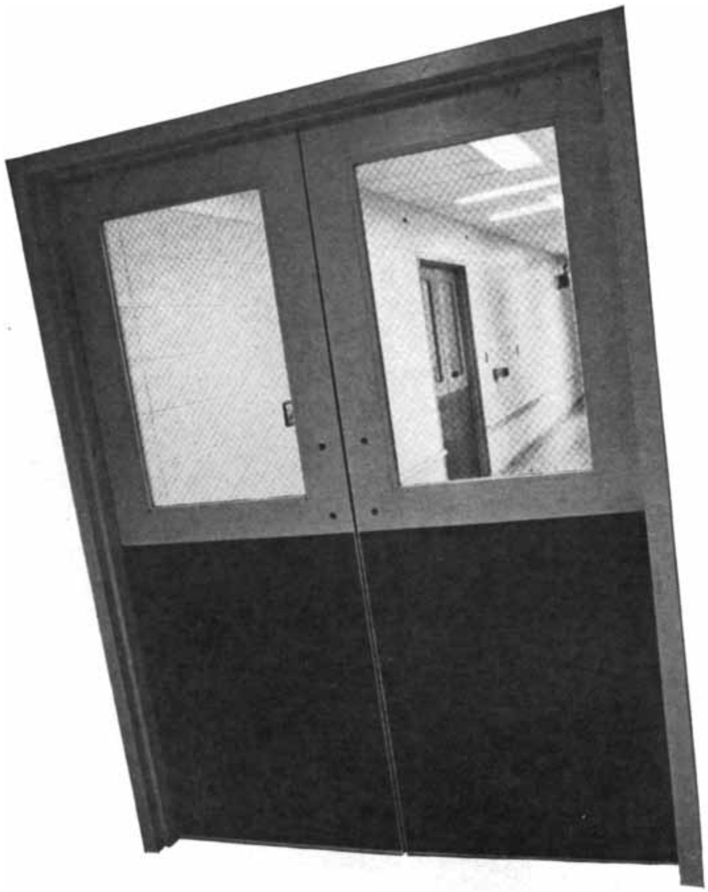
In the face of stringent requirements being laid down by the states and the Department of the Interior, power companies are installing devices that cool water before it is returned to the stream. The devices include cooling ponds, spray ponds and cooling towers. They function by evaporating some of the cooling water, so that the excess heat is dissipated into the atmosphere rather than into the stream.

This strategy of spreading waste heat has to be reexamined as the scale of the problem increases. It is already apparent that the "heat islands" characteristic of metropolitan areas have definite meteorological effects—not necessarily all bad. The fact that a city is warmer than the surrounding countryside affects the ecology and biospheric activity in metropolitan areas in numerous ways. For example, the release of heat in a relatively small local area causes a change in the convective pattern of the atmosphere. The addition of large amounts of particulate matter from industry, space heating and refuse disposal provides nuclei for the condensation of clouds. A study in the state of Washington showed an increase of approximately 30 percent in average precipitation over long periods of time as a result of air pollution from pulp and paper mills.

The worldwide consumption of energy can be estimated from the fact that the U.S. accounts for about a third of this consumption. The U.S. consumption of 685,000 million million B.T.U. per year is equivalent to 2.2 million megawatts. World consumption is therefore some 6.6 million megawatts. Put another way, the present situation is that the per capita consumption of energy in the U.S. of 10,000 watts per day compares with somewhat more than 100 watts (barely above the food-intake level) in most of the rest of the world.

Projections for the future depend on the assumptions made. If one assumes that in 50 years the rest of the world will reach the present U.S. level of energy consumption and that the population will be 10 billion, the total man-made energy would be 110 million megawatts per year. The energy would of course be distributed in a patchy manner reflecting the location of population centers and the distributing effects of the atmosphere and the oceans.

That figure is numerically small compared with the amount of solar energy the earth radiates back into space. Over the entire earth the annual heat loss is about 120,000 million megawatts, or more than 1,000 times the energy that would be dissipated by human activity if the level of energy consumption projected for 2020 were reached. It would be incautious to assume, however, that the heat put into the biosphere as a result of human energy consumption can be neglected because it is so much smaller than the solar input. The atmospheric engine is subtle in its operation and delicate in its adjustments. Extra inputs of energy in particular places can have significant and far-reaching consequences.



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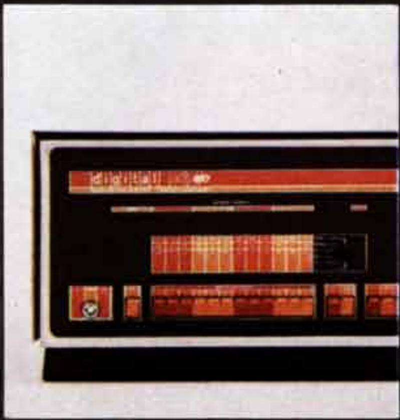

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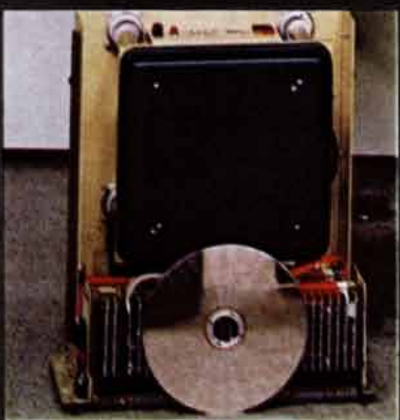

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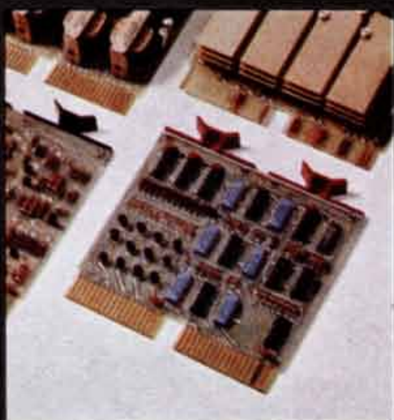

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Human Materials Production as a Process in the Biosphere

Materials such as metals and concrete are not renewable. Man's problem is to devise cycles that will conserve resources of this kind and at the same time prevent their accumulation as solid waste

by Harrison Brown

The materials used by man for tools, shelter and clothing have traditionally been both organic (for example wood and natural fiber) and inorganic (stone, including glass and ceramics, and metals). To this classification we now add synthetic materials, which are mostly made from what are called in another connection fossil fuels. The organic materials are of course products of the biosphere, and assuming appropriate levels of use and sensible management they are self-renewing. The inorganic materials are the product of extremely slow processes in the lithosphere, and are hence not self-renewing in the human scheme of things. Yet the increasing need for such materials—mainly metals, stone and concrete—is one of the outstanding features of advancing societies. Moreover, the fact that inorganic materials are for the most part not recycled creates a pressing need for their disposal. These demands present men with numerous difficult choices, many of which inevitably involve the functioning of the biosphere.

For the greater part of the two million years or so of human existence man's need for materials was modest. With the adoption of each technological innovation that improved the chances of human survival, however, the need for materials increased in both absolute and per capita terms. For example, the controlled use of fire, which increased the variety of things that could be eaten and extended man's environment, created a substantial demand for firewood. Here, of course, a material was being used as fuel, but the development of tools that improved the efficiency of hunting and food gathering and protected men against predators created demands for materials in the strict sense: the right kinds of stone or of plant or animal substance.

With the invention of agriculture the need for materials increased considerably. The new technology made it possible for thousands of people to be supported by the produce of land that formerly could support only one person. Moreover, it was no longer necessary for everyone to be involved in food production. Farmers were able to grow a surplus of food to support nonfarmers. Until relatively recent times this surplus was never large, amounting to perhaps 5 percent, but it meant that some people could devote their energies to occupations other than farming. It was the surplus of food that made possible the emergence of cities and the evolution of the great civilizations of antiquity.

The oldest civilizations came into existence in regions that had ample areas of arable land and adequate supplies of water. Cities could become large only if they could draw on the agricultural surpluses of vast farmlands. Since water transport was by far the easiest way to ship foodstuffs in ancient times, the earliest civilizations and the first large cities came into being in the valleys of the great rivers such as the Tigris and the Euphrates, the Nile, the Indus and the Yellow River. With the emergence of major urban centers increasingly elaborate technologies were developed, and they in turn led to the need for larger per capita quantities of raw materials such as stone, wood, clay, fiber and skin. (The ancient urban centers also confronted a problem that continues today: the disposal of garbage and rubbish. Scavenger birds, such as the kites of modern Calcutta, were probably essential elements in the system of processing garbage, but even so life must have been unsanitary, unsightly and odoriferous, at least for the great masses of the poor. The evidence suggests the prevalence of high mortality rates. Many ancient cities appear to have been literally buried in their own rubbish.)

Until the development of metal technology men appear to have used renewable resources such as wood at rates that were small compared with the rates of renewal. The consumption of nonrenewable resources such as stone was also small, particularly in comparison with the nearly infinite availability of resources with respect to the demand.

Copper was the first metal to come into widespread use on a substantial scale. In actuality copper is not very abundant in the lithosphere, but the metal can be won easily from its ore. The reduction temperature is fairly low, so that smelting can be accomplished in a simple furnace. Once the technology of extracting copper was developed the use of the metal became widespread in the ancient civilizations and the demand for the ore grew rapidly.

COPPER IS MINED at the Twin Buttes mine of the Anaconda Company near Tucson. The conspicuous hole in the photograph on the opposite page was made by removing some 236 million tons of overburden and rock to get at the ore lying between 600 and 800 feet below the surface of the ground. The ore has a copper content of about .5 percent and is considered to be a low-grade ore. Since copper is not highly abundant in the lithosphere but is extensively used, the trend has been toward mining low-grade ores.

In this situation the high-grade deposits of ore close to the ancient urban centers were soon used up. Egypt, for example, quickly depleted her own copper reserves and had to develop an elaborate network of trade routes that enabled her to import copper from as far away as the British Isles and Scandinavia. Even so, high-grade ores of copper were uncommon enough to preclude widespread use of the metal. Copper did make possible a number of new technologies, but farmers, who were by far the greater proportion of society, were almost unaffected. Their implements continued to be made of stone, clay, wood and leather.

Gold is considerably easier to extract from its ore than copper; often the "ore" is metallic gold itself. As one might expect, therefore, the use of gold appears to predate the use of copper by a considerable span of time. Gold, however, is one of the rarest metals in nature, so that its ores are extremely scarce. Its rarity precluded its widespread use, except in small quantities for ornament.

Iron is considerably more abundant in the lithosphere than copper, but it is a much more difficult metal to win from the ore. The reduction temperature is high, and furnaces capable of attaining it were not developed until about 1100 B.C. The new high-temperature technology appeared first in the Middle East and quickly spread westward. The widespread availability of the ore made it possible for metal to be used on an unprecedented scale. New tools of iron helped to transform Europe from a land of dense forests to a fertile cropland.

One of the primary limitations to economic development in the ancient empires was the lack of ability to concentrate large quantities of energy. Insofar as it could be done at all it was usually accomplished by mobilizing gangs of men and to a lesser extent by the use of work animals. Use of the water mill and the windmill spread slowly. Only in sea transport was the wind used even with moderate effectiveness on a large scale as a prime mover. Remarkable as the Roman engineers were, they were limited by the concentration of energy they could mobilize. They went about as far as engineers could in the absence of a steam engine.

The development of a practical steam engine had to await the convergence of a series of developments in England in the late 17th century and the early 18th century. The island entered the Iron Age richly endowed with iron ore. Forests were also abundant, and the trees were used to produce charcoal, which in turn was used to reduce the iron oxide to the metal. These resources enabled England to become a major supplier of metallic iron for the world.

As iron production expanded English trees were consumed faster than they grew. Eventually the depletion of wood for charcoal threatened the entire iron industry. Clearly a substitute for charcoal was needed. The most likely one was coal, which existed abundantly on the island. Unfortunately, although coal can be used to reduce iron ore to the metal, the impurities in it render the metallurgical properties of the iron quite unsatisfactory.

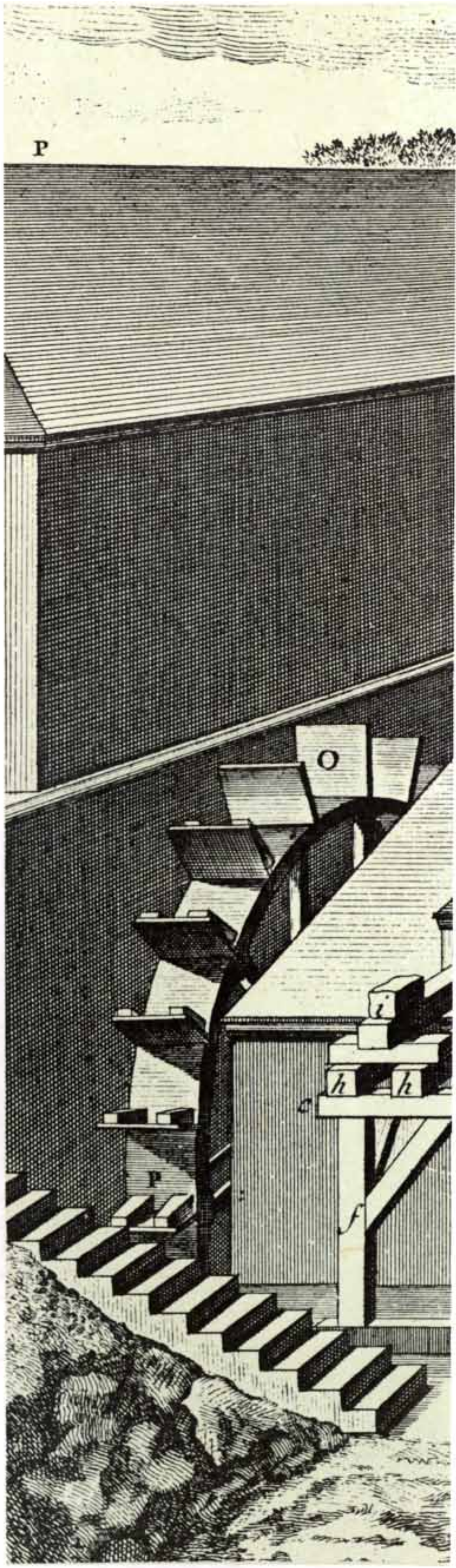
The Darby family, which owned a substantial iron industry, spent many years attempting to transform coal into a substance suitable for the reduction of iron. Eventually a successful process was developed. It was based on the discovery that volatile impurities could be driven off by heating coal under suitable conditions. The resulting product, called coke, yielded metallic iron of satisfactory quality.

Here was a development—the linking of coal to iron—second only to agriculture in its importance to man. The new development led to a rapid expansion of the iron industry. Even more significant, it led directly to the development of the steam engine, which gave man for the first time a means of concentrating enormous quantities of inanimate energy.

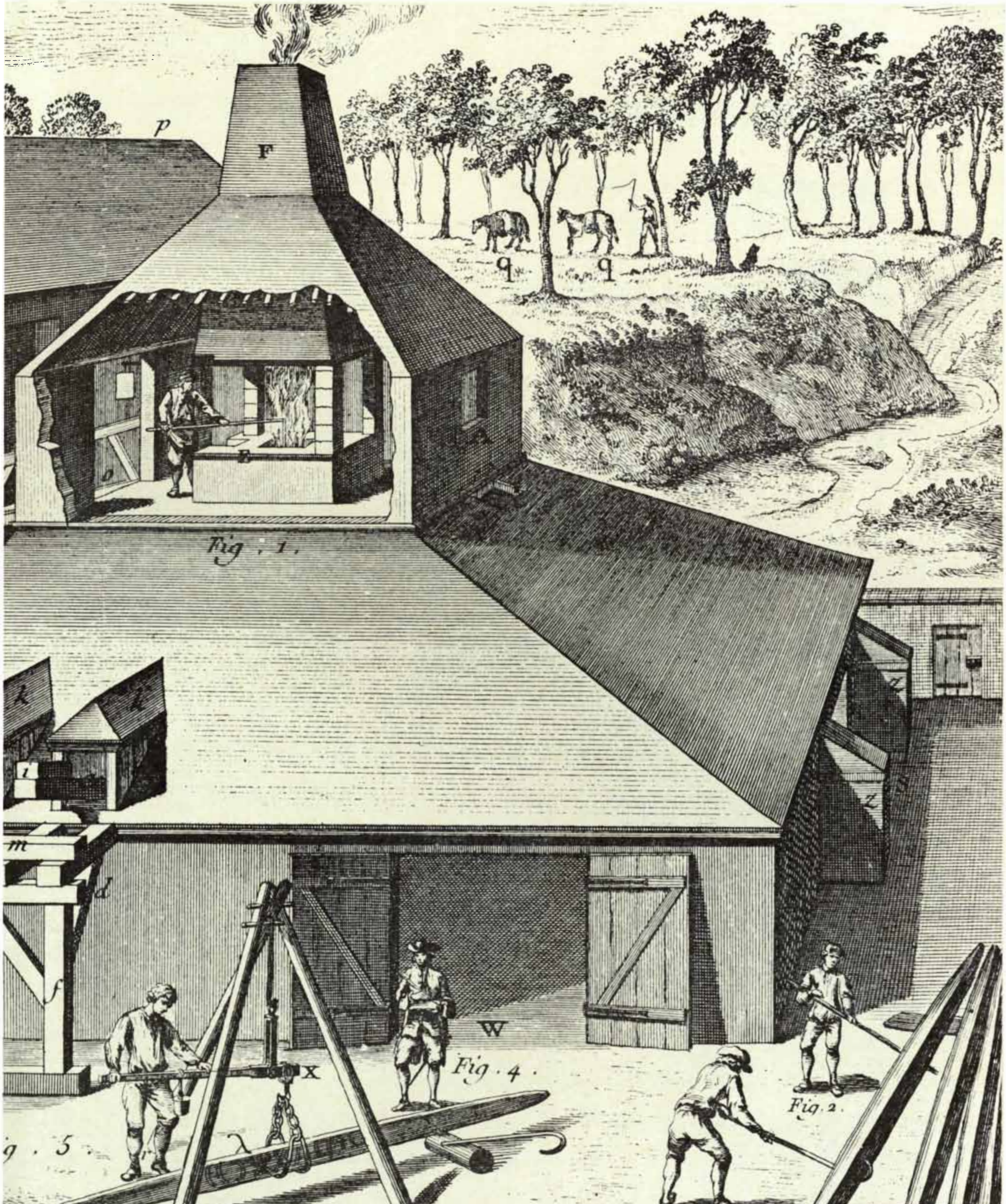
Coal, iron and the steam engine gave rise to the Industrial Revolution, which spread from England to Europe and then to the U.S., the U.S.S.R. and most recently to Japan. Why did it start in the 18th century in England and not several centuries earlier in Rome? The Romans in many ways were the better engineers, and yet the harnessing of steam eluded them.

It is interesting to speculate on the role that random natural processes have played in cultural evolution. What would the course of history have been if copper had been as abundant as iron or if iron could be reduced from its ore as easily as copper? Perhaps the Iron Age would have started in the third millennium B.C. Suppose the Roman iron industry had run out of wood in the second century. Would there have been a linking of coal to iron and would the steam engine have emerged some 1,500 years earlier than it did? Such questions are diverting, but they cannot be answered with anything better than guesses.

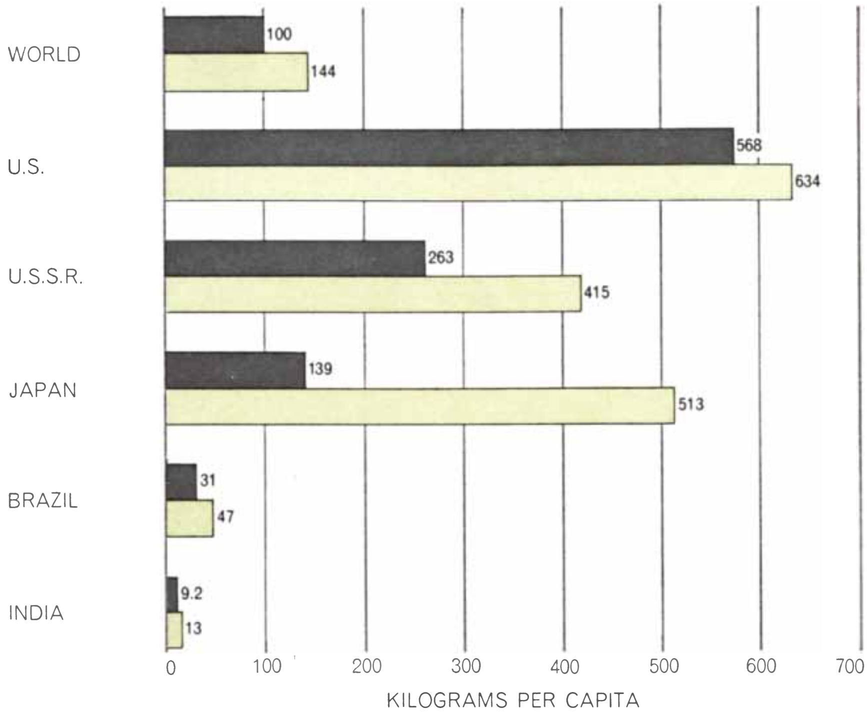
The most important characteristics of



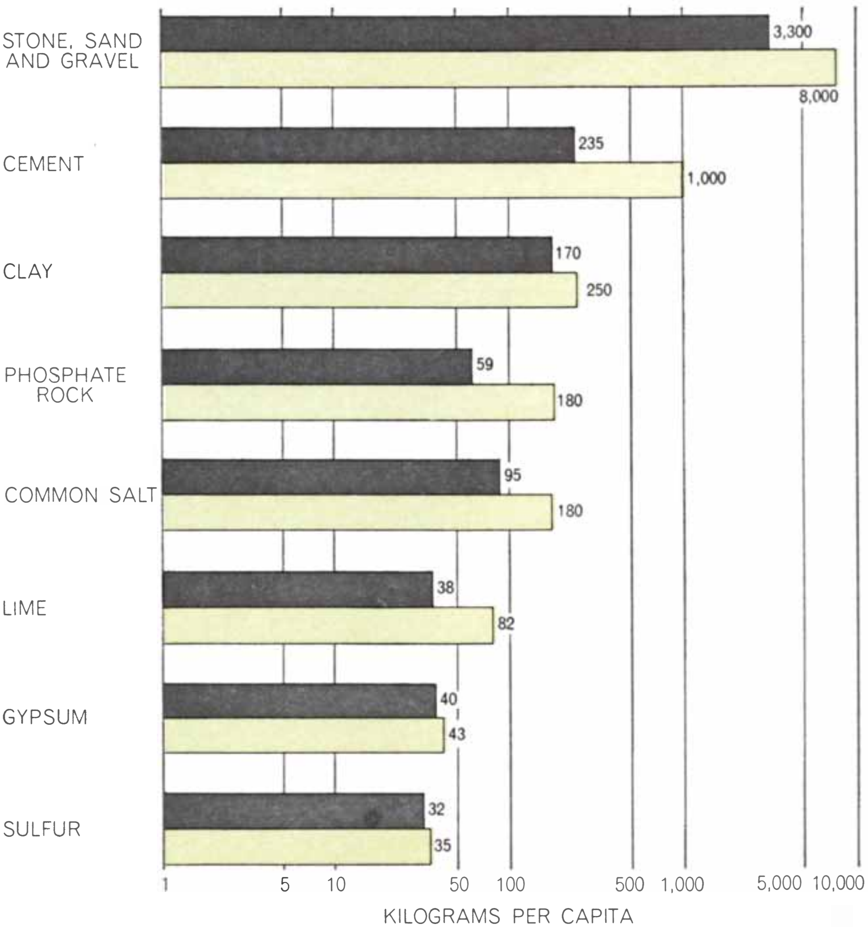
BLAST FURNACE for smelting iron in the 18th century was depicted in Diderot's *Encyclopédie*. The reason for the furnace's lo-



cation near a wooded area was the need for charcoal, which is what the horses in the background are carrying. In England the consumption of charcoal virtually exhausted the supply of trees before the technique of making coke from coal was developed. A furnace of this type might produce some two tons of iron a day. In the foreground a freshly produced pig, No. 289, is being weighed.



STEEL CONSUMPTION rose substantially but unevenly in the world and five major countries between 1957 (*gray*) and 1967 (*color*). The units are kilograms per person per year.



BASIC MATERIALS other than metal were produced in greatly increased amounts in the U.S. in 1967 (*color*) as compared with 1949 (*gray*). Units are kilograms per capita.

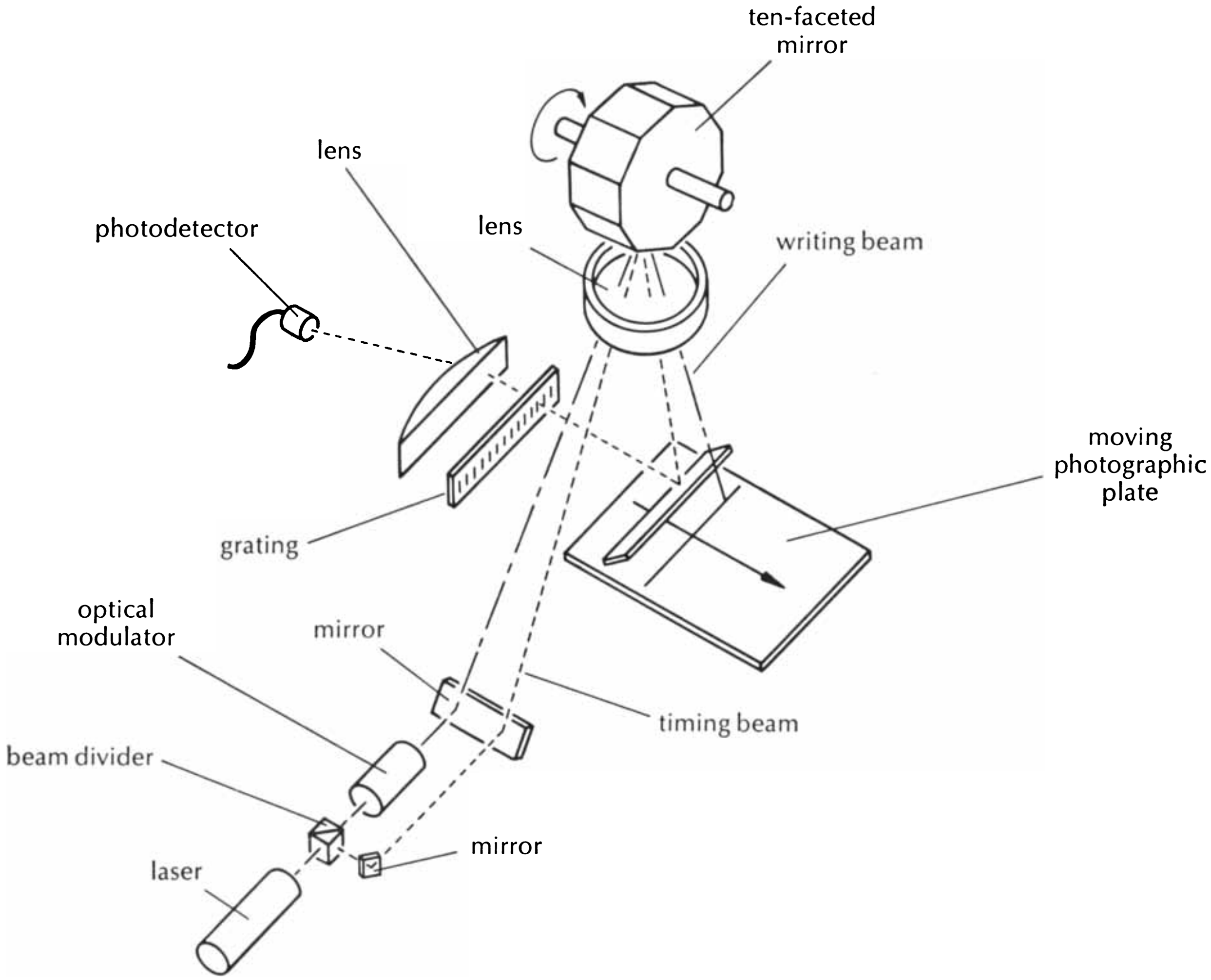
the Industrial Revolution have been rapid change and rapid increases in rates of change. Since the beginnings of the epoch mankind has seen the emergence of almost innumerable technological innovations that have competed with existing ways of doing things and have further released men from physical labor. It is now generally recognized that technological innovation has been a prime contributing factor to economic growth, perhaps equaling the combined effect of the classical factors of land, labor and capital.

Successful innovations have driven many older technologies to extinction and have resulted in higher productivity, greater consumption of energy, increased demand for raw materials, accelerated flow of materials through the economy and increased quantities of metals and other substances in use per capita. The history of industrial development abounds with examples.

In 1870 horses and mules were the prime source of power on U.S. farms. One horse or mule was required to support four human beings—a ratio that remained almost constant for many decades. Had a national commission been asked at that time to forecast the horse and mule population in 1970, its answer probably would have depended on whether its consultants were of an economic or a technological turn of mind. Had they been "economists," they would in all likelihood have estimated the 1970 horse and mule population at more than 50 million. Had they been "technologists," they would have recognized that steam had already been harnessed to industry and to ground and ocean transport. They would have recognized further that it would be only a matter of time before steam would be the prime source of power on the farm. It would have been difficult for them to avoid the conclusion that the horse and mule population would decline rapidly.

In fact, steam power appeared on the farm in about 1875 and spread rapidly. Had it not been for the introduction of the internal-combustion engine shortly after the turn of the century, steam power alone would have driven the horse off the farm. The internal-combustion engine, which was unforeseen in 1875, succeeded in driving off both the horse and the steam combine. Today the horse population is little more than 1.5 million, and most of the horses cannot in any real sense be regarded as work animals.

A second example of technological competition was the introduction of the steam-powered iron ship. In a period of



Better circuit masks exposed

Making integrated semiconductor and thin-film circuits requires a set of photographic masks to outline the application or removal of materials during processing. The demand for these masks has increased as integrated electronics has come of age and it will continue to grow with the technology.

Mask-making has long been automated. The engineer feeds a geometric description into a standard program and a computer generates a tape. The tape controls a machine which moves a light beam or a knife along coordinate axes to draw the mask. This takes many hours.

Now, Bell Labs has developed a machine which can produce complex masks in under 10 minutes. The machine contains an argon-ion laser. The laser beam is scanned across an 8 by 10 inch photographic plate and switched on and off to expose the emulsion on the plate according to the mask pattern. As each scan is completed, the plate is shifted one linewidth. Scanning time—20 milliseconds per line—is independent of the number of times the beam is switched on and off.

Each facet of a ten-faceted rotating mirror (above) sweeps the beam once across the plate. At the same time, each facet sweeps an auxiliary laser beam across a grating, generating 26,000 timing pulses for each scan. A digital computer processes the pulses to determine the position of the scanning beam and to generate control signals for an acousto-optic modulator which switches the beam on and off.

The laser beam can be directed with an accuracy better than 2 arc-seconds, the equivalent of a mile-long straight line with less than 5/8 inch deviation. For such precision, the machine is operated in a special controlled-environment chamber where temperature is maintained within 1/7°C and a cubic meter of air contains fewer than 3500 dust particles larger than one micron.

These high-speed, precise machines will supply the Bell System's mask needs for several years. As integrated circuits gain wider telephone use, this will keep costs down.

From the Research and Development Unit of the Bell System:

Bell Labs

only 30 years (1870 to 1900) the composition of the United Kingdom's merchant marine was transformed from 90 percent wooden sailing ships to 90 percent iron ships powered by steam. This technological transformation resulted in a greatly enhanced ability to transport goods rapidly and inexpensively over long distances. It also resulted in a greatly increased demand for iron and coal.

In the modes of intercity transportation in the U.S. one can see a dramatic sequence of competitions. In the first years of this century nearly all passenger traffic between cities was carried by the railroads. By 1910 the private car was competing seriously, and by 1920 the automobile was accounting for more passenger-miles between cities than the railroads were. Since World War II the airplane has competed with both the railroad and the automobile for intercity traffic. The combined impact of the automobile and the airplane has come close to putting railroads out of the passenger business. In the decade of the 1970's the airplane will probably make serious inroads on intercity automobile traffic as well. The net result of these changes, as with others, has been increased expenditure of energy and increased demand for materials in both absolute and per capita terms.

Levels of steel production and consumption are among the most useful indicators of worldwide technological and economic change. In the 19th century England became the dominant producer and consumer of steel, later being replaced by Germany. After World War I the U.S. became the largest industrial power, and steel production rose rapidly. In 1900 per capita steel production in the U.S. reached 140 kilograms, and by 1910 it was up to 300 kilograms. The level exceeded 400 kilograms during World War I, and during World War II it rose to 600 kilograms. Since World War II the picture has changed: although total steel production has continued to rise, the annual per capita level has changed little, averaging about 550 kilograms.

Per capita steel consumption has risen since World War II, but the rise has been slow. The difference between production and consumption has been made up by an increase in imports. In 1967 U.S. steel consumption was 634 kilograms per capita.

Although this is at present the highest per capita level of steel consumption in the world, the U.S. is being overtaken rapidly by other countries. Levels of consumption in much of western Europe and in Japan, Czechoslovakia, East Germany, the U.S.S.R. and Australia are now close to the U.S. level, and the rates of growth are such that Japan will overtake the U.S. quite soon. The per capita level of steel consumption in the U.S.S.R. will probably equal that of the U.S. within another decade. The worldwide rate of increase in per capita steel consumption from 1957 to 1967 was 44 percent, compared with the U.S. rate of 12 percent and the Japanese rate of 270 percent [*see top illustration on page 198*]. In view of the fact that virtually all elements of economic growth correlate reasonably well with per capita steel consumption, it is useful to inquire into the future levels of consumption in the U.S. and the rest of the world.

Consumption of metals other than iron can conveniently be stated in terms of steel consumption. When this is done, it becomes apparent that the consumption levels of certain metals, such as copper, zinc and lead, have remained remarkably constant over the past 50 years in spite of rapidly changing technologies. Consumption of certain other metals, such as tin, has been decreasing with respect to steel as a result of decreasing availability of ore and the development of substitutes. Consumption levels of the light metals, such as aluminum, are rising. Although these metals are still much less used than steel is, they will increasingly supplant steel for certain purposes.

If all the metallic iron that has been produced in the U.S. were still in ex-

TREND IN CONSUMPTION of key materials is traced. The production of timber is usually reckoned in terms of board feet or cubic feet. For purposes of comparability it has been stated here in pounds, assuming an average density of 35 pounds per cubic foot.

There is no electronic calculator in the world to match the new Marchant electronic.

It's the only one to use a remarkable new technology: Super MOS.

When you buy an electronic calculator, there are dozens to choose from. How do you know which one's best? We think the answer is, simply pick the most advanced one you can find.

And that happens to be the Marchant® Model 414. It may look like other electronic calculators, but the resemblance ends right there. Because the 414 uses a totally new kind of technology in both its memory and logic functions.

It has a space age brain.

Our technology utilizes sub-miniaturization akin to the space age. Hundreds of transistors (which by themselves are marvels of electronic wizardry) are microscopically incorporated on a single chip so small 8 of them can sit comfortably on the face of a dime.

This tiny speck of material is the very brain of our calculator. It is a custom designed Metallic Oxide Semi-Conductor (we call it Super MOS for short). And, just to put it in perspective for you, it helps to know that each Super MOS chip contains 40 square feet of complex electrical diagrams.

Think of it! A blueprint 5 by 8 feet is reduced to something you can hardly see. And it works!

8 Super MOS chips.

Our 414 has 8 Super MOS chips. Each chip handles the work load previously assigned to 20 integrated circuits. We are the first manufacturer of calculators to use Super MOS chips. And to date, no other maker has achieved this extraordinary sophistication in design.

With Super MOS to do the work, the 414 can add, subtract, multiply, divide, place decimals automatically, and recall the last number displayed just as if you had entered it. And with fewer components and electrical connections, our 414 has fewer parts to wear out, fewer things to go wrong.

What does it all mean?

When all is said and done, it really comes down to just what we said up at the top. If you're going to buy a brand-new electronic calculator, you really ought to get the most singularly advanced one you can find.

The American made Marchant Model 414.

It may look like other calculators, but its brain thinks just a little bit ahead of all the rest.

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Marchant. The First.

A hurricane.

Six hundred people were killed by one in New England in 1938.

Four years later, eleven thousand were killed by one in India.

The winds of a hurricane are over 75 miles an hour.

It takes the form of a circle or an oval, sometimes as much as 500 miles in diameter.

There is no prevention.

But if we reduce the element of surprise, we can reduce its deadly potential.

And we've taken steps so that it will never surprise us again.

RCA has designed, developed and produced the world's most advanced family of weather satellites. It's called the ITOS program.

It's the most sophisticated weather detector yet devised by man, and perhaps one of the most beneficial facilities man has created since he broke the bonds of earth.

From the detailed photographs transmitted back to earth, we can see the formation and plot the course of hurricanes, typhoons, storm centers. We can spot sea ice and snow cover. Calculate wind speeds.

Anywhere on earth.

This program exemplifies the importance of interdisciplinary engineering, the engineering concept of the future.

It is becoming increasingly more apparent that in the future, the engineer will touch virtually every aspect of our lives. From medicine to the arts to education to leisure products.

And he will do this in conjunction with other disciplines to complement, overlay, and unite his output for an end result that is both balanced and complete.

Think for a moment about an endeavor which, like meteorology, is seemingly unrelated to classical engineering: the graphic arts industry.

Recently, RCA engineers, working in conjunction with that industry, developed the world's most advanced electronic typesetting machine. It's called the VideoComp.

It can set type as fast as 900 lines per minute. Compare this with the 15/minute of mechanical typesetting, or the 300/minute of photosetters.

A strong effort is also being made to improve color separations. The RCA Graphic 70/8800 Color Scanner family of equipment is the initial result of this effort.

It is our goal ultimately to produce an RCA electronic printing system that will accept a manuscript as input and deliver printed copy — packaged, addressed and sorted — to the shipping dock.

Now consider another field which had previously been outside the realm of the engineer: medicine and health services.

We've been involved in the development of a mobile laboratory to provide comprehensive physical examinations in on-the-spot locations to people otherwise out of the mainstream of our health services.

And we've researched a high-speed turbine drill to increase the efficiency and decrease the pain in dental work.

And we've done extensive work in developing facilities for teaching speech to the retarded.

Communications? Computer education? Oceanography? We're involved with them. And with so much more.

We like to think that at RCA, the future of the engineer is everywhere.

Because everywhere is needed the forward look of creative technology.

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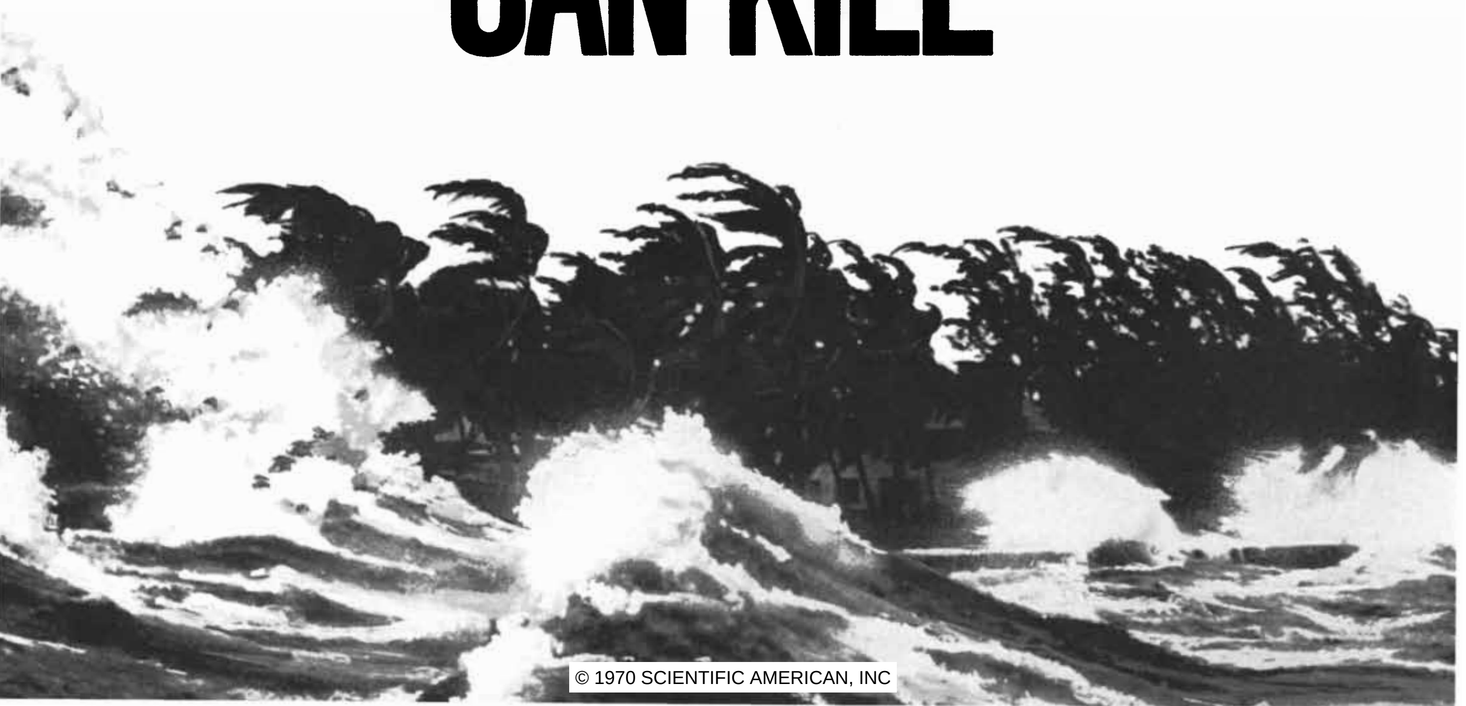
RCA

A SURPRISE CAN KILL



istence, there would now be in use some 15 tons of steel per capita. In actuality a great deal of the steel produced has disappeared as a result of junking, production losses, corrosion and other causes. Analysis of production figures and losses suggests that the amount of steel now in use is some 9.4 metric tons of steel per capita. The greater part of it is in the form of structural materials such as heavy structural shapes and pilings, nails and staples, galvanized sheet metal and wire fence. About 8 percent of the steel, or 750 kilograms per person, is in the form of private automobiles, trucks and buses.

Of the roughly 600 kilograms of new steel consumed annually per capita in the U.S. about a third is returned to the furnaces as plant scrap, which is created as a result of the production of standard shapes and forms such as beams, sheet, pipe and wire. Therefore about 410 kilograms of the new steel enters the inventory of steel in use. At the same time about 350 kilograms of steel becomes obsolete or is lost as a result of corrosion and other processes. Of this some 140 kilograms (about 40 percent) is recovered and returned to the steel furnaces in the form of junked automobiles and other worn-out iron and steel products. The balance, corresponding to some 210 kilograms, is lost, probably never to be recovered. Some of it is dissipated widely; much of it is buried in dumps. During the course of the year the steel inventory increases by about 80 kilograms per capita, or somewhat less than 1 percent.

The mean lifetime of steel products varies enormously. Whereas an item such as a can may be in use for only a few weeks or months, steel in motor vehicles is in use on the average for about 10 years. Steel in ships may be in use for about 25 years. Steel structural shapes such as girders and concrete reinforcement may be in use for 50 years or more. The mean lifetime of all steel in use appears to be some 25 to 30 years.

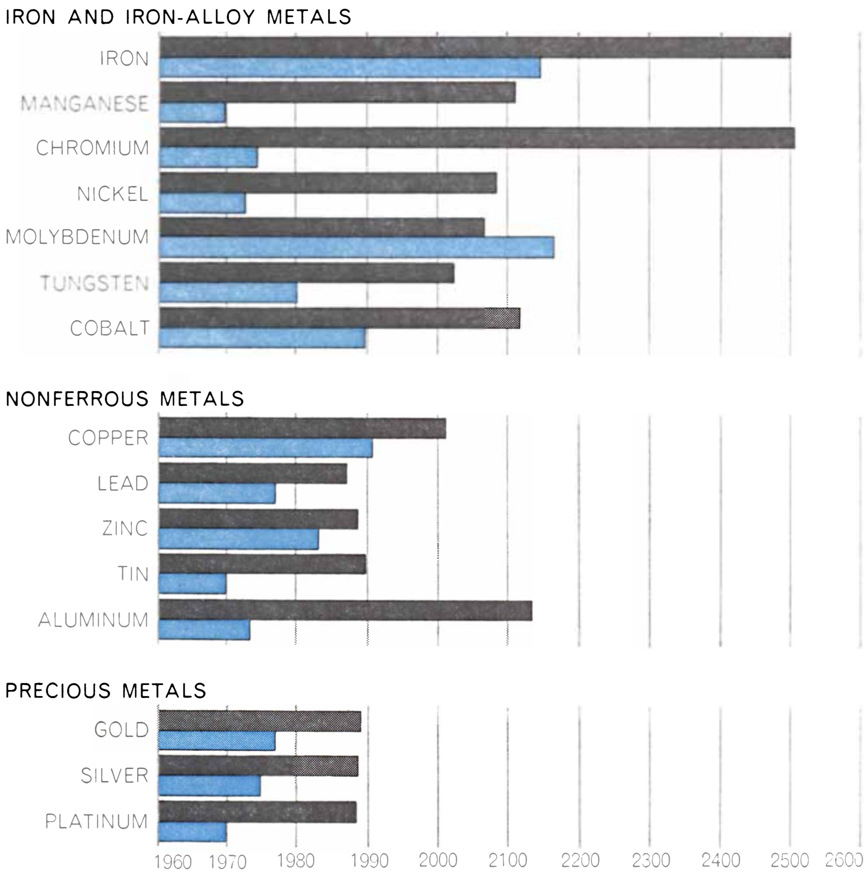
Similar considerations apply to other metals. They are extracted, introduced into the national inventory and eventually lost or recycled as scrap. The mean lifetime of most of them appears to be shorter than that of steel.

Although the quantities of metal in use and the volumes of metalliferous ore that must be dug up and processed to support a human being in our society are large, the quantities of nonmetals consumed each year loom even larger and are increasing extremely rapidly [*see bottom illustration on page 198*]. Between 1949 and 1967 the per capita consumption of stone, sand and gravel in the U.S. rose some 2.5 times to about eight tons per capita. For cement the rise was by a factor of four to one ton per capita. In the same period the per capita consumption of phosphate rock rose by a factor of three and that of ordinary salt by a factor of two. All together, in order to support one individual in our society, something like 25 tons of materials of all kinds must be extracted from the earth and processed each year. This quantity seems certain to increase considerably in the years ahead.

The use of synthetic plastics is now increasing with impressive speed. Total world production of these materials now exceeds in both volume and weight the production of copper and aluminum combined. The production of synthetic fibers is now about half the combined production of cotton and wool. The relative rates of growth suggest that the output of such fibers will exceed that of cotton and wool within a short time.

Between 1945 and 1965 the price of polyethylene dropped by about 75 percent while the price of steel tripled. Already polyethylene is less expensive than steel on a volume basis, although per unit of strength it remains some 15 times more expensive than steel. It is quite possible, however, that before long fiber-glass laminates will compete seriously with steel for structural purposes.

The overall figures suggest that the U.S. now has in use for every person about 150 kilograms each of copper and lead, well over 100 kilograms of aluminum, some 100 kilograms of zinc and perhaps 20 kilograms of tin. To meet the need for raw materials and the products derived from them the nation transports almost 15,000 ton-kilometers of freight per capita per year. Each person travels on the average each year some 8,500 kilometers between cities, makes more than 700 telephone calls and receives nearly 400 pieces of mail. There is now a ratio of almost one private automobile for every two people. In order to accomplish all the mining, production and distribution the American people spend energy at a rate equivalent to the burning



LIFETIMES OF METAL RESERVES are indicated for the world (*gray*) and the U.S. (*color*). These rough estimates are based on the assumption that the utilization of metals will continue to increase with population growth and rising per capita demand. They take into account, however, that new reserves will be discovered by exploration or created by innovation. It is estimated U.S. demands will increase four and a half times by the year 2000.

of about 10 tons of coal annually per person or about 16 tons of coal per ton of steel consumed or about one ton of coal per ton of steel in use. A convenient rule of thumb is that we must burn about one ton of coal each year, or its equivalent in some other source of energy, to keep one ton of steel in use.

Clearly man has become a major geologic force. The amount of rock and earth he moves each year in the present industrialized regions of the world is already prodigious and will continue to grow because of rising population levels, increasing demand from the industrialized nations and the gradual decline in grades of raw materials. If one adds to these requirements the fantastically high demand that would arise if the development process were to be accelerated in the poor countries, the total potential demand staggers the imagination. If the entire human population were to possess the average per capita level of metal characteristic of the 10 richest nations, all the present mines and factories in the world would have to be operated for more than 60 years just to produce the capital, assuming no losses.

Given an eventual world population of 10 billion, which is probably a conservative estimate, and a per capita steel inventory of 20 tons, some 200 billion tons of iron would have to be extracted from the earth. The task would require 400 years at current rates of extraction. Anything approaching such a demand would clearly place enormous strains on the earth's resources and would greatly accentuate rivalries between nations for the earth's remaining deposits of relatively high-grade ores. Most of the industrialized nations already import a substantial fraction of their raw materials. Japan is almost completely dependent on imports. Whereas the U.S. imported in 1950 only 8 percent of the iron ore that it consumed, the figure today is more than 35 percent.

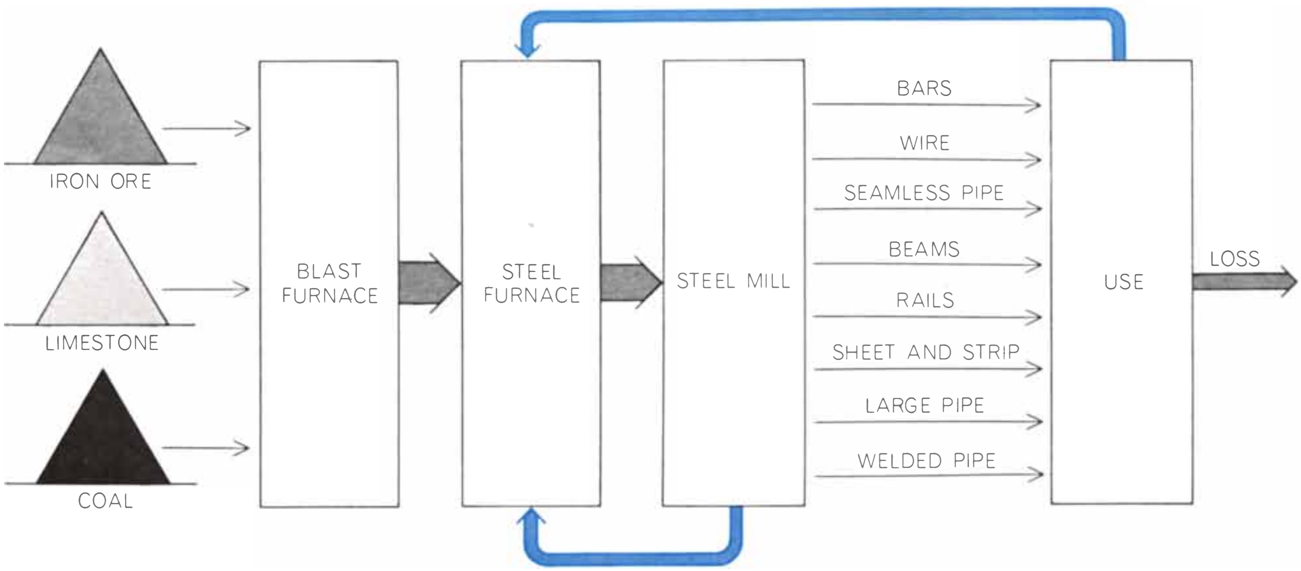
At present the world can be divided into two major groups of steel consumers. The first group consists of about 680 million people, living in 18 nations, who consume steel at rates varying between 300 and 700 kilograms annually per capita. The total consumption of this group comes to about 420 million tons of steel per year. The second group consists of 1,400 million people, living in 13 nations, who consume steel at rates varying between 10 and 25 kilograms annually per capita. The total consumption of this group comes to 27 million tons of steel per year. An additional 400 million people live under circumstances that are still poorer, and 440 million more live under circumstances intermediate between those of the rich and the poor. The distribution of per capita energy consumption follows a similar pattern, as does the distribution of per capita income.

The slowness of the development process and the magnitude of the task the poor countries face can be gauged by the fact that with existing production facilities the poorer group (not the poorest one) would need about 500 years to produce the per capita quantity of steel in use now characteristic of the U.S. Although production levels in the poorer group are increasing fairly rapidly (close to 50 percent per decade on a per capita basis), many decades will be required, even in the absence of any major upheaval, before the amounts of steel in use can enable those nations to feed, clothe and house their populations adequately.

What goes into a system must eventually come out. As I have noted, somewhat less than 4 percent of the steel inventory in the U.S. is exuded annually into the environment, and only about 40 percent of this amount is recovered. As the grades of resources dwindle and locations for dumping solid wastes become more difficult to find, the economic and social pressure for more substitution, more attention to priorities of use of scarce materials and more efficient cycling will increase.

It is clear that various metals can substitute for one another, and that plastics can substitute for a number of metals. Aluminum already substitutes for copper in many roles, as copper and nickel now replace silver in coinage. Synthetic crystals come increasingly into use. All these techniques can be pushed a good deal farther than they have been up to now.

Improved efficiency of cycling is desirable for all solid wastes not only to lower the rate of depletion of high-grade resources but also to reduce the injurious effects of such wastes on the biosphere. The quantities of wastes are becoming substantial. They now amount to nearly one ton per year per person, of which



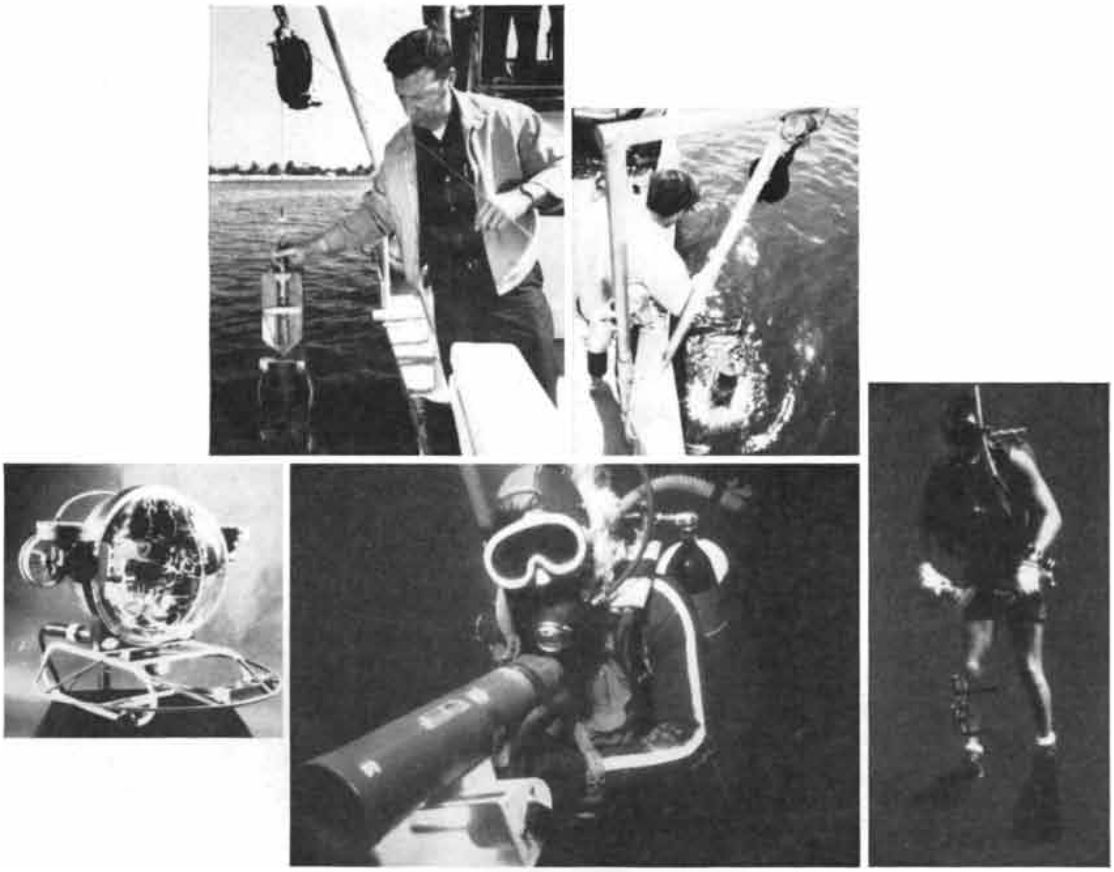
FLOW OF MATERIALS through the biosphere is depicted using steel as an example. Of the steel produced from iron ore, about a third is recycled immediately in the form of scrap left over from the production of beams, wire and other shapes. Two-thirds enters the national inventory. During each year, however, a somewhat smaller amount of steel becomes obsolete. About 40 percent of it is recycled in the form of scrap. The remainder is lost as a result of such factors as wear, corrosion and disposal through junking.

about a third consists of packaging materials. In 1968, for example, the average American threw away almost 300 cans, 150 bottles and about 140 kilograms of paper. The quantities are increasing rapidly on both an absolute and a per capita basis. Properly cycled, they could provide raw materials for the glass, steel, aluminum and plastics industries.

From a purely technological point of view man could in principle live comfortably on a combination of his own trash and the leanest of earth substances. Already, for example, copper ore containing only .4 percent copper is being processed. If the need arose, copper could be extracted from ore that is considerably leaner than .4 percent. Eventually man could, if need be, extract his metals from ordinary rock. A ton of granite contains easily extractable uranium and thorium equivalent to about 15 tons of coal, plus all the elements necessary to perpetuate a highly technological civilization. Such a way of life would create new problems, because under those circumstances man would become a geologic force transcending by orders of magnitude his present effect on the earth. Per capita energy consumption would come to the equivalent of perhaps 100 tons of coal per year, and there might be some 100 tons of steel in use per person. The world would be quite different from the present one, but there is no reason a priori why it would necessarily be unpleasant.

Man has it in his power technologically to maintain a high level of industrial civilization, to eliminate deprivation and hunger and to control his environment for many millenniums. His main danger is that he will not learn enough quickly enough and that he will not take adequate measures in time to forestall situations that will be very unpleasant indeed.

SHREDDING TECHNIQUE was recently developed for turning worn-out or wrecked automobiles into scrap that can be recycled to steel furnaces. At top stripped automobile bodies are being fed into the shredder; the product that emerges is shown at bottom.



MATHEMATICAL GAMES

On the cyclical curves generated by wheels that roll along wheels

by Martin Gardner

The miraculous paradox of smooth round objects conquering space by simply tumbling over and over, instead of laboriously lifting heavy limbs in order to progress, must have given young mankind a most salutary shock.

—VLADIMIR NABOKOV, *Speak, Memory*

Things would be very different without the wheel. Transportation aside, if we consider wheels as simple machines—pulleys, gears, gyroscopes and so on—it is hard to imagine any advanced society without them. H. G. Wells, in *The War of the Worlds,* describes a Martian civilization far ahead of ours but using no wheels in its intricate machinery. Wells may have intended this to be a put-on; one can easily understand how the American Indian could have missed discovering the wheel, but not a society capable of sending spaceships from Mars to the earth.

Until recently the wheel was believed to have originated in Mesopotamia. Pictures of wheeled Mesopotamian carts date back to 3000 B.C. and actual remains of massive disk wheels have been unearthed that date back to 2700 B.C. Since World War II, however, Russian archaeologists have found pottery models of wheeled carts in the Caucasus that suggest the wheel may have originated in southern Russia even earlier than it did in Mesopotamia [see "The Beginnings of Wheeled Transport," by Stuart Piggott; SCIENTIFIC AMERICAN, July, 1968]. There could have been two or more independent inventions of the wheel, or it may have spread around the world by word of mouth.

It seems surprising that evolution never hit on the wheel as a means for making animals go, but on second thought one realizes how difficult it would be for biological mechanisms to make wheeled feet rotate. Perhaps the tumbleweed is the closest nature ever came to wheeled transport. (On the other hand, the Dutch artist Maurits C. Escher designed a creature capable of curling itself into a wheel and rolling along at high speeds. Who can be sure such creatures have not evolved on other planets?) There may also be submicroscopic swivel devices inside the cells of living bodies on the earth, designed to unwind and rewind double-helix strands of DNA, but their existence is still conjectural.

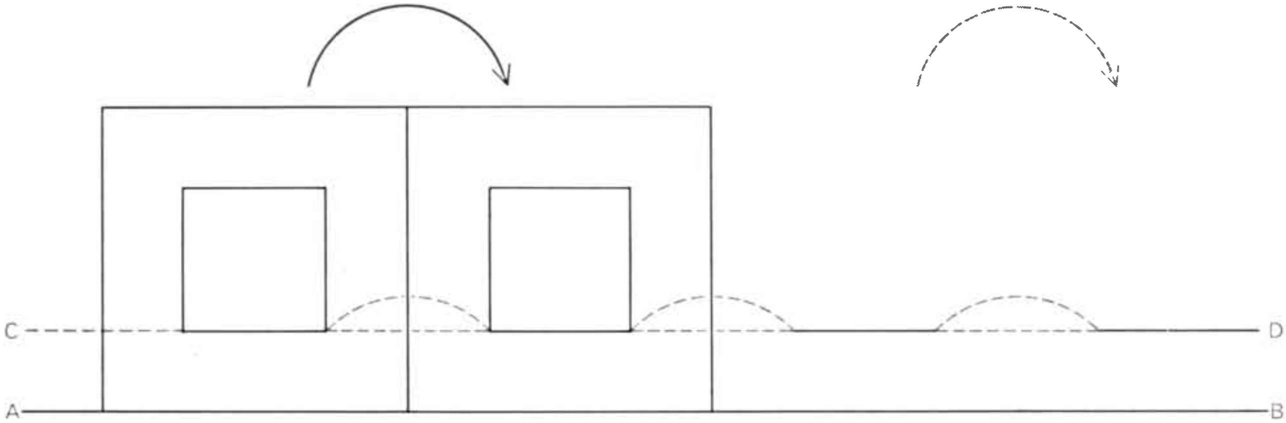
A rolling wheel has many paradoxical properties. It is easy to see that points near its top have a much faster ground speed than points near its bottom. Maximum speed is reached by a point on the rim when it is exactly at the top, minimum speed (zero) when the point touches the ground. On flanged train wheels whose rims extend slightly below a track, there is even a short segment in which a point on the rim moves backward. G. K. Chesterton, in an essay on wheels in his book *Alarms and Discursions,* likens the wheel to a healthy society in having "a part that perpetually leaps helplessly at the sky; and a part that perpetually bows down its head into the dust." He reminds his readers, in a characteristically Chestertonian remark, that "one cannot have a Revolution without revolving."

Aristotle's wheel paradox

The most subtle of all wheel paradoxes is surprisingly little known, considering that it was first mentioned in the *Mechanica*, a Greek work attributed to Aristotle but more likely written by a later disciple. "Aristotle's wheel," as the paradox is called, is the subject of a large literature to which such eminent mathematicians as Galileo, Descartes, Fermat and many others contributed. As the large wheel in the illustration on this page rolls from A to B, the rim of the small wheel rolls along a parallel line from C to D. (If the two lines are actual tracks, the double wheel obviously cannot roll smoothly along both. It either rolls on the upper track while the large wheel continuously slides backward on the lower track, or it rolls on the lower track while the small wheel slips forward on the upper track. This is not, however, the heart of the paradox.) Assume that the bottom wheel rolls without slipping from A to B. At every instant that a unique point on the rim of the large wheel touches line AB, a unique point on the small wheel is in contact with line CD. In other words, all points on the small circle can be put into one-to-one correspondence with all points on the large circle. No points on either circle are left out. This seems to prove that the two circumferences have equal lengths.

Aristotle's wheel is closely related to Zeno's well-known paradoxes of motion, and it is no less deep. Modern mathematicians are not puzzled by it because they know that the number of points on any segment of a curve is what Georg Cantor called aleph-one, the second of his transfinite numbers. It represents the "power of the continuum" [see "Mathematical Games," March, 1966]. All points on a one-inch segment can be put in one-to-one correspondence with all points on a line a million miles long as well as on a line of infinite length. Moreover, it is not hard to prove that there are aleph-one points within a square or cube of any size, or within an infinite Euclidian space having any finite number of dimensions. Of course, mathematicians before Cantor were not familiar with the peculiar properties of transfinite numbers, and it is amusing to read their fumbling attempts to resolve the wheel paradox.

Galileo's approach was to consider what happens when the two wheels are



Galileo's approach to the wheel paradox

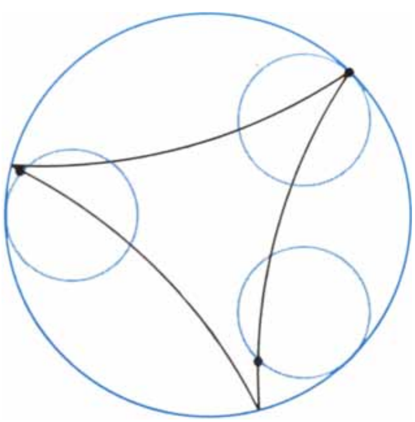
replaced by regular polygons such as squares [*see illustration above*]. After the large square has made a complete turn along *AB*, the sides of the small square have coincided with *CD* in four segments separated by three jumped spaces. If the wheels are pentagons, the small pentagon will jump four spaces on each rotation, and so on for higher-order polygons. As the number of sides increases, the gaps also increase in number but decrease in length. When the limit is reached—the circle with an infinite number of sides—the gaps will be infinite in number but each will be infinitely short. These Galilean gaps are none other than the mystifying "infinitesimals" that later so muddied the early development of calculus.

And now we are in a quagmire. If the gaps made by the small wheel are infinitely short, why should their sum cause the wheel to slide a finite distance as the large wheel rolls smoothly along its track? Readers interested in how later mathematicians replied to Galileo, and argued with one another, will find the details in "Aristotle's Wheel: Notes on the History of the Paradox," by Israel E. Drabkin (*Osiris*, Vol. 9, pages 162–198, 1950), and "The Wheel of Aristotle and French Consideration of Galileo's Arguments," by Pierre Costabel (*The Mathematics Teacher*, Vol. 61, pages 527–534, 1968).

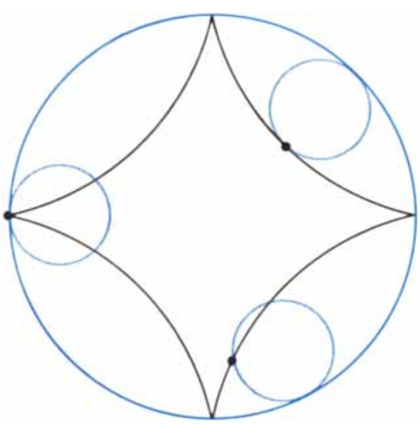
As a wheel travels a straight line, any point on its circumference generates the familiar cycloid curve. (The cycloid will not be discussed here because it was the topic of this department for July, 1964.) When a wheel rolls on the inside of a circle, points on its circumference generate curves called hypocycloids. When it rolls on the outside of a circle, points on the circumference generate epicycloids. Let R/r be the ratio of the radii, R for the large circle, r for the small. If R/r is irrational, a point a on the rolling circle, once in contact with point b on the fixed circle, will never touch b again even though the wheel rolls forever. The curve generated by a will have an aleph-null infinity of cusps. If R/r is rational, a and b will touch again after a finite number of revolutions. If R/r is integral, a returns to b after exactly one revolution.

Consider hypocycloids traced by a circle of radius r as it rolls inside a larger circle of radius R. When R/r is 2, 3, 4, . . . , points a and b touch again after one revolution and the curve will have R/r cusps. For example, a three-cusped deltoid results when R/r equals 3 [*see illustration at left below*]. The same deltoid is produced when R/r is 3/2; that is, when the rolling circle's radius is two-thirds that of the fixed circle. All line segments tangent to the deltoid, with ends on the curve, have the same length. A four-cusped astroid is generated when R/r equals 4 or 4/3 [*see middle illustration below*]. The two ratios apply to all higher-order hypocycloids of this type: when R/r is either n or $n/(n-1)$, the rolling circle produces an n-cusped curve.

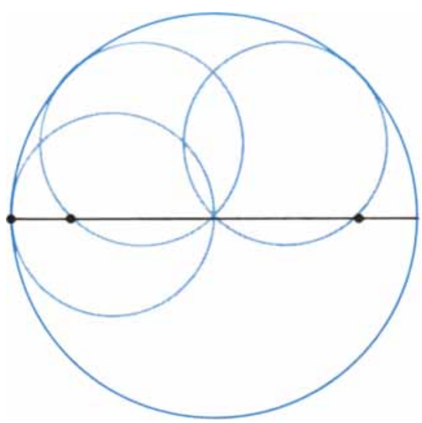
There is a surprising result when R/r equals 2 [*see illustration at right below*]. The hypocycloid degenerates into a straight line coinciding with a diameter



The deltoid



The astroid

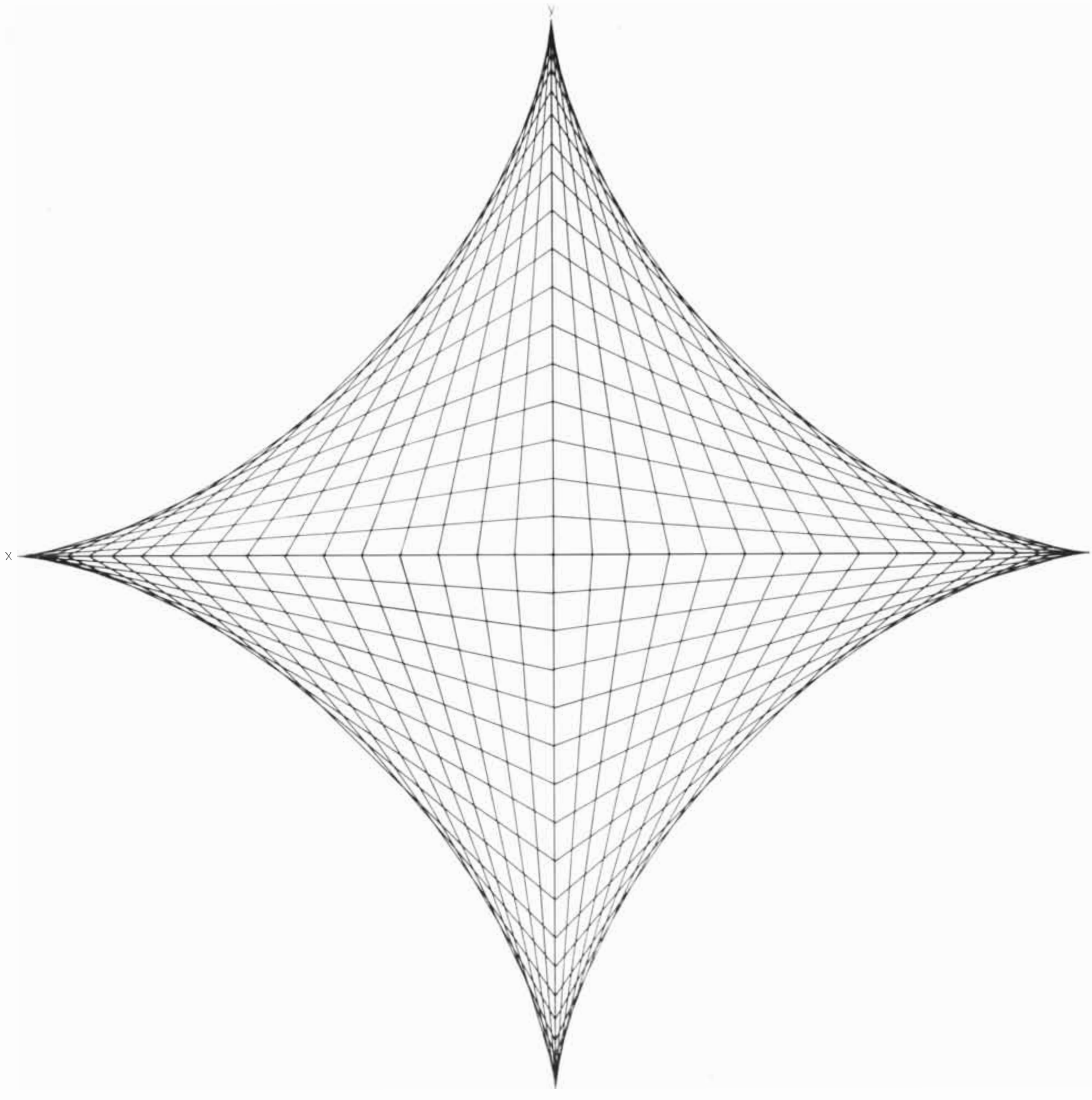


"Two-cusped" hypocycloid

of the larger circle. Its two ends may be regarded as degenerate cusps. Can you guess the shape of the region swept over by a given diameter of the smaller circle? It is a region bounded by an astroid. This is the same as saying that the astroid is the envelope of a line segment that rotates while it keeps its ends on two perpendicular axes, as shown in the illustration below.

The simplest case of an epicycloid traced by a point on the rim of a wheel rolling outside another circle is seen when the two circles are equal. The result is a heart-shaped curve called the cardioid [*see top illustration on page 216*]. All chords drawn through its cusp have the same length. The cardioid in the illustration was drawn by dividing the fixed circle [*solid color*] into 32 equal arcs and then drawing a set of circles whose centers are on this fixed circle and that pass through other points on the same circle. The figure can be colored to produce a dazzling Op-art pattern [*see bottom illustration on page 216*]. (Both pictures are from Hermann von Baravalle, *Geometrie als Sprache der Formen*, Stuttgart, 1963.)

The cardioid is also generated by a point on the circumference of a circle that rolls twice around a fixed circle inside it that is half as large in diameter. This fact underlies a problem that was incorrectly answered in *The American Mathematical Monthly* for December, 1959 (Problem E 1362) but correctly answered in the March 1960 issue of the same journal. Imagine a girl whose bare waist is a perfect circle. Rolling around her waist, while she remains motionless, is a hula hoop with a diameter twice that of her waist. When a point on the hoop, touching the girl's navel, first returns to her navel, how far has that point trav-



Astroid drawn as the envelope of a moving line segment

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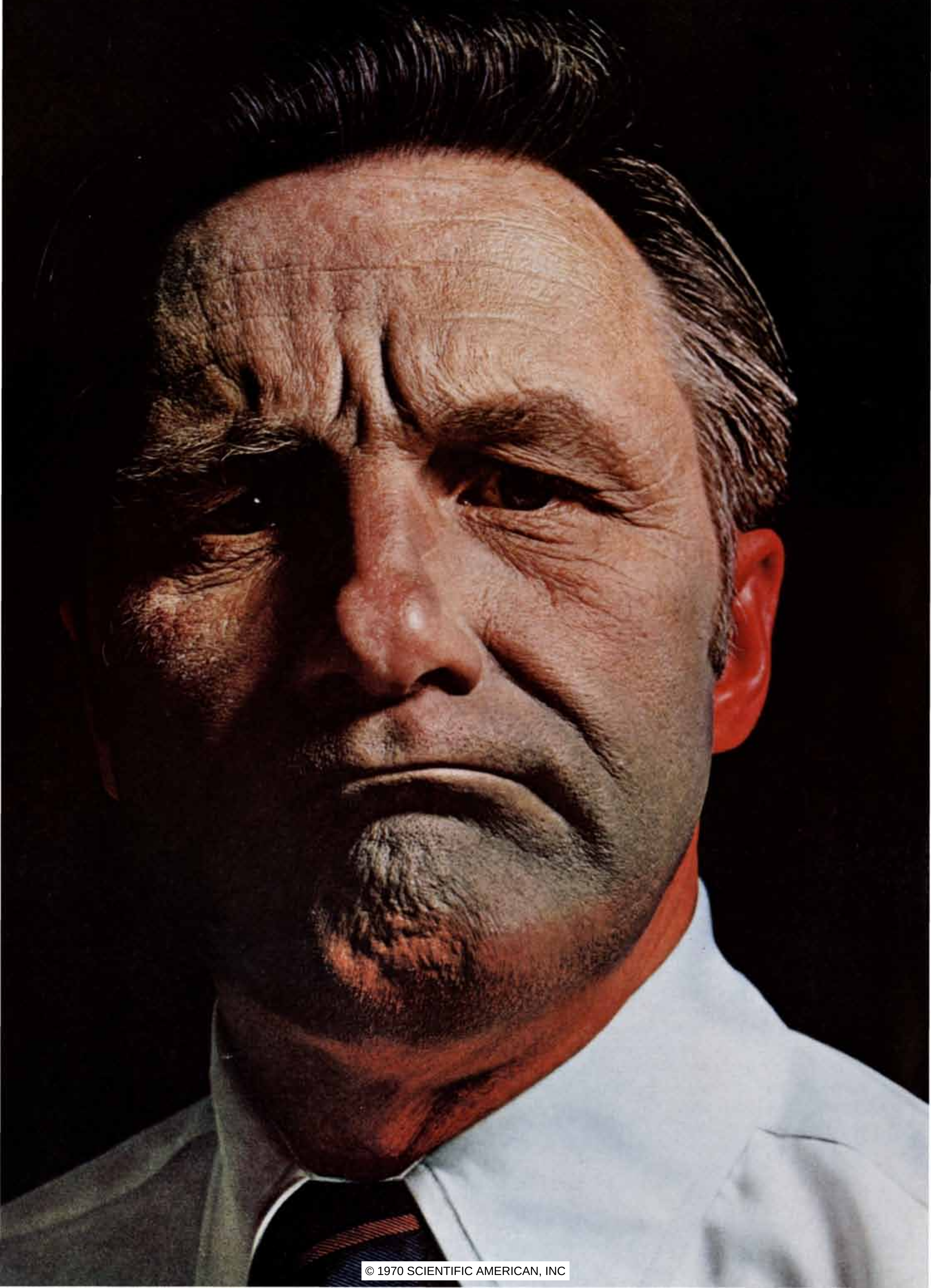
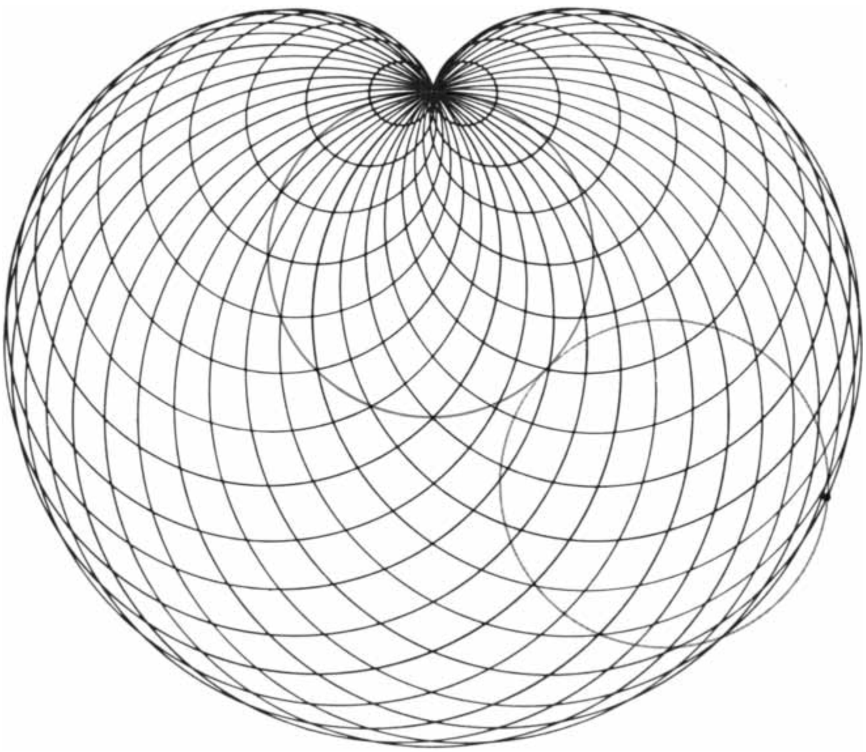




The cardioid

Op-art cardioid

eled? Since the point traces a cardioid, this is equivalent to asking for the cardioid's length. It is not hard to show that it is four times the diameter of the hoop or eight times the diameter of the girl's waist.

When a rolling circle is half the diameter of a fixed circle that it touches externally, the epicycloid is the two-cusped nephroid (meaning kidney-shaped) that is shown in the illustration on page 218. The drawing both shows the rolling circle and demonstrates a method of constructing the nephroid as the envelope of circles whose centers are on the fixed circle [*solid color*] and that are tangent to the vertical central axis. As before, the curve can also be generated by rolling a circle around a smaller circle inside it; in this case, when R/r is $3/2$. This is the same ratio as that which produces a deltoid, but now it is the larger circle that does the rolling.

The cardioid and the nephroid are both caustics, curves enveloped by reflected light rays. The cardioid appears when the rays originate at a point on the circumference and are reflected by the circumference. The nephroid is produced by parallel rays crossing the circle, or from rays originating at the cusp of a cardioid and reflected by the cardioid. The cusped curve that one often sees on the surface of tea or coffee in a cup, when slanting light falls across the liquid from a window or other light source far to one side, is a good approximation of a nephroid cusp.

There are varied and perplexing problems that involve noncircular "wheels." For example, suppose a square wheel rolls without slipping on a track that is a series of equal arcs, convex sides up. What kind of curve must each arc be to prevent the center of the wheel from moving up and down? (In other words, the wheel's center must travel a straight horizontal path.) The curve is a familiar one and, amazingly, the same curve applies to similar tracks for wheels that are regular polygons with any number of sides. The answer will be disclosed next month.

And can any reader solve this new riddle from Stephen Barr: What type of conveyance has eight wheels, carries only one person and never pollutes the atmosphere?

Readers were asked last month to prove that no prime except 11 can be a palindrome if it has an even number of digits. The proof exploits a well-known test of divisibility by 11 (which will not be proved here): If the difference be-

tween the sum of all digits in even positions and the sum of all digits in odd positions is zero or a multiple of 11, the number is a multiple of 11. When a palindrome has an even number of digits, the digits in odd positions necessarily duplicate the digits in even positions; therefore the difference between the sums of the two sets must be zero. The palindrome, because it has 11 as a factor, cannot be prime.

The same divisibility test applies in all number systems when the factor to be tested is the system's base plus one. This proves that no palindrome with an even number of digits, in any number system, can be prime, with the possible exception of 11. The number 11 is prime if the system's base is one less than a prime, as it is in the decimal system.

A large number of readers agreed that the best explanation for the sliding-penny illusion explained in May is that, as the index fingertips move back and forth, the positions of the coins overlap at the lower end but not at the upper end, producing the ghost penny only where the overlap occurs. It is probably a correct explanation because, as many letters pointed out, when the pennies are manipulated in ways that prevent overlap, no ghosts appear.

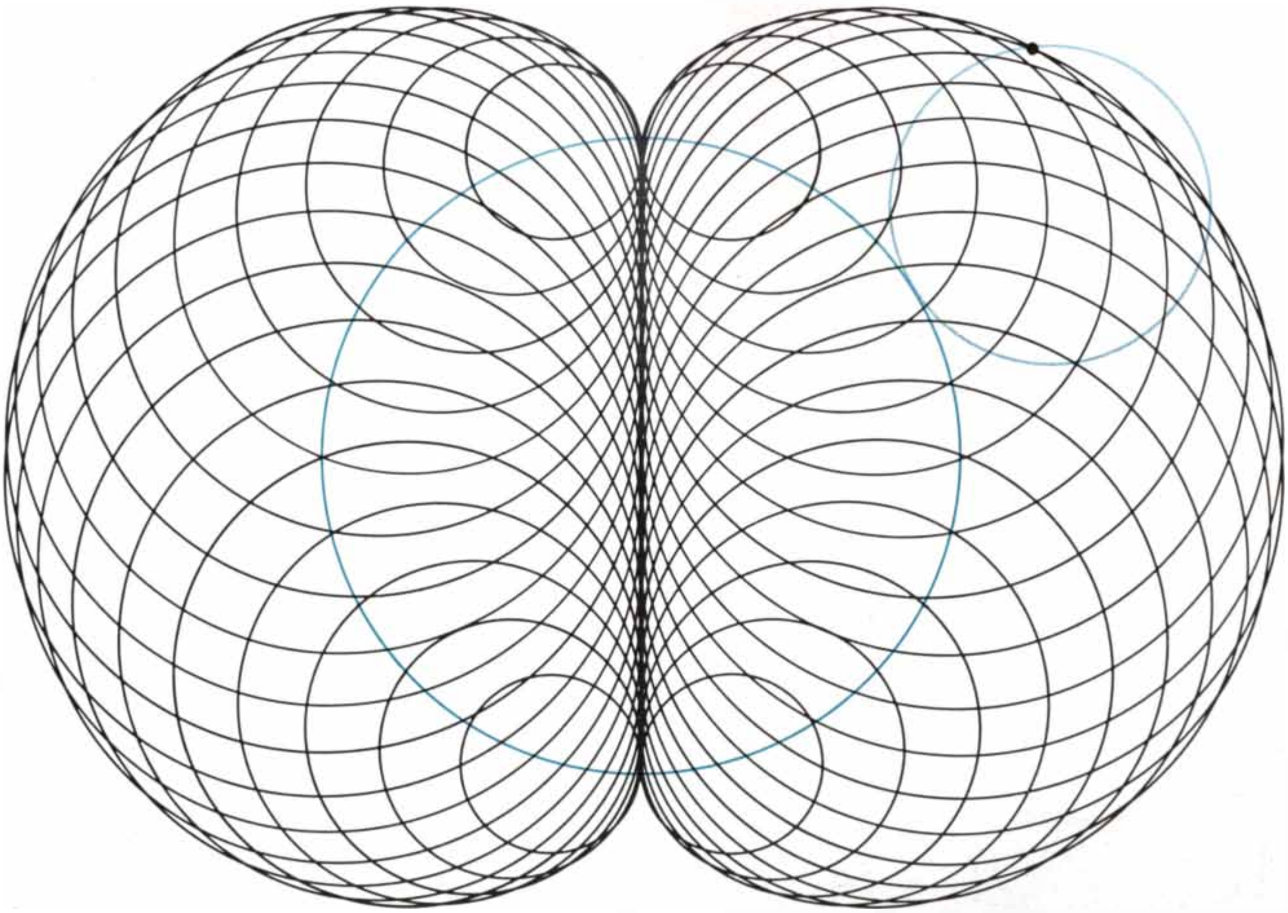
A beautifully symmetrical equation for finding the side of an equilateral triangle, given the distances of a point from its three corners (a problem posed in June), is given in L. A. Graham's *Ingenious Mathematical Problems and Methods* (Dover, 1959), page 190:

$$a^4 + b^4 + c^4 + d^4 = a^2b^2 + a^2c^2 + a^2d^2 + b^2c^2 + b^2d^2 + c^2d^2 .$$

Any three variables can be the three distances. Solving for the fourth gives the triangle's side. John Anderson and Frederick Hartmann each pointed out the simplest integral solution: 3, 5, 7, 8. The point is outside the triangle except when the side is 8, when it lies on a side of the triangle. Jörg Waldvogel of the University of Texas wrote a computer program that found 58 solutions with the point inside. The smallest solution has distances of 57, 65 and 73 and a triangle side of 112.

The integral values I gave in June for the crossed-ladders problem are minimal only when it is required that all line segments in the diagram be integral. John W. Harris of Santa Barbara, Calif., wrote to say that the segments of the base line can be nonintegral while the ladders, the width between buildings and the height of crossing remain integral. The solution I gave may minimize the width if only these four values must be integers. Harris believes the height of the crossing is minimized if the ladders are 238 and 113, the width is 112 and the crossing height is 14 (the two parts of the base and the four segments of the ladders are nonintegral).

In discussing the "integral brick" in July I erred in giving the figures for the brick, discovered by John Leech, on which one edge only is irrational. I gave the edges as 3, 4 and the square root of 136,990,339,200. The first two values should have been multiplied by a constant to give edges of 385,917 and 514,556. I hope no readers who caught the mistake thought Leech could have made it. He has since found a smaller brick of the same type, with edges of 7,800, 18,720 and the square root of 211,773,121.



The nephroid

THE AMATEUR SCIENTIST

Curious oscillators that involve salt water, flame and hot wire

Conducted by C. L. Stong

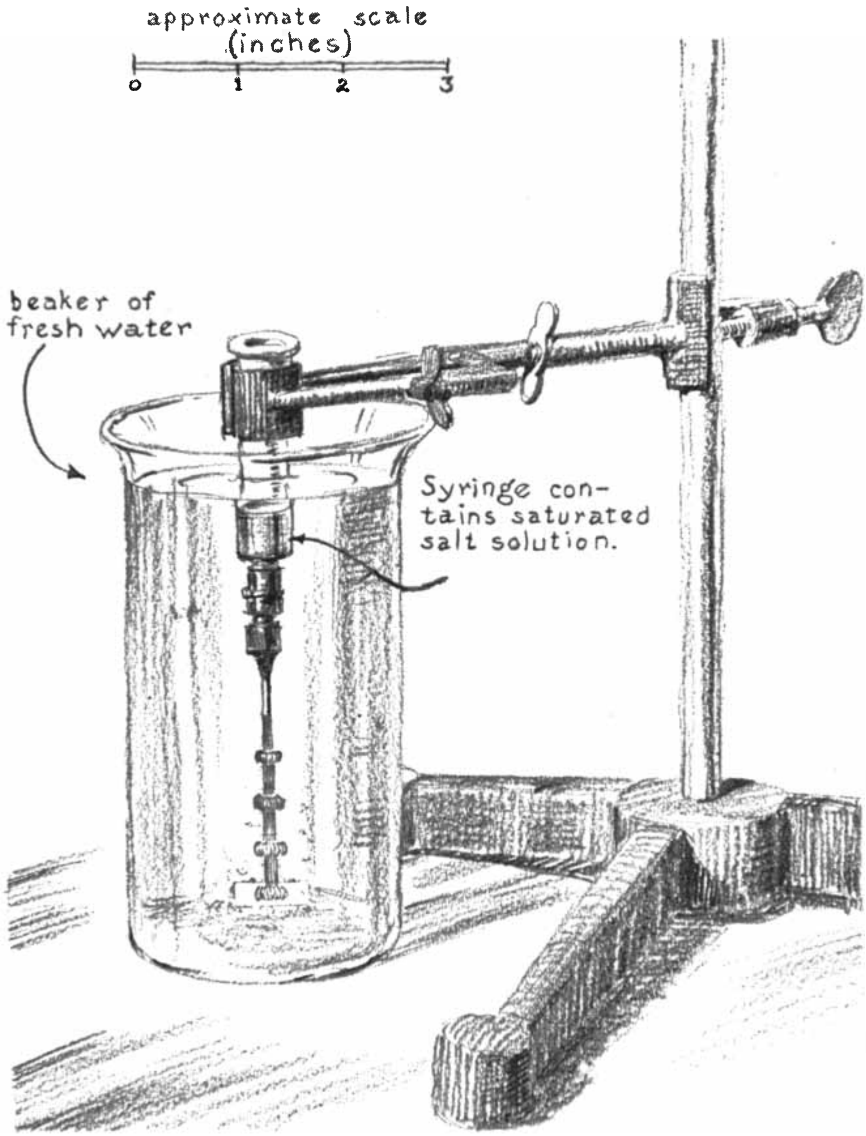
Some of the world's most useful work is performed by oscillators, which are devices that cause a flow of energy to alternate between two directions. An oscillator is an essential element of apparatus as diverse as pendulum clocks, jackhammers, radios, lasers, hydraulic rams and electronic heart pacemakers. For every kind of oscillator that has been put to work at least a dozen other kinds repose on laboratory shelves as interesting but useless gadgets. Three new examples of such gadgetry recently came to the attention of this department. The first of the three, which is known as a salt oscillator, is the creation of Seelye Martin of the University of Washington. Martin writes:

"I discovered this fascinating device while setting up a demonstration of a buoyant jet for a class in meteorology. The apparatus consisted of a hypodermic syringe, with the plunger removed, and a beaker of fresh water. The syringe was partly immersed in the water and held in position by an apparatus stand [*see illustration at right*]. Into the syringe I poured a saturated solution of table salt. (I made the solution by stirring salt into fresh water until no more would dissolve.) The level of the brine in the syringe was well above the level of the fresh water in the beaker.

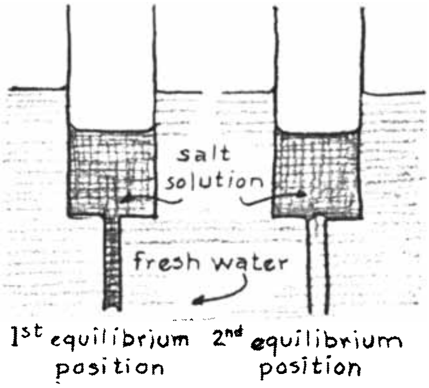
"As I expected, the dense brine streamed out of the hypodermic needle in the form of a turbulent jet and sank to the bottom of the beaker. Although both fluids were clear, the stream of brine could be seen almost as easily as an icicle in air, because the difference in density of brine and fresh water refracts light. As the surface level of the salt water fell substantially below that of the fresh water the velocity of the jet decreased and the flow eventually stopped.

"At this point an astonishing effect was observed. The flow reversed! A jet of fresh water spurted into the syringe from the top of the needle and rose to the surface of the brine. The upward flow continued for a time and then reversed. Saltwater again flowed out of the needle and sank to the bottom. The sequence of alternating jets continued for many cycles.

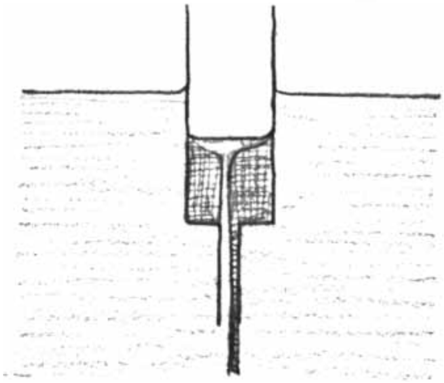
"To explain the cause of these oscillations one must examine the dynamics of the system. The fluid level inside the syringe oscillates back and forth between two equilibrium positions where the forces that generate flow in each direction are exactly balanced. The first position is reached when salt water fills the needle. In this position the system is in equilibrium because the weight of the



Seelye Martin's salt-water oscillator



Two states of the salt oscillator


Stable flow in a capillary

column of salt water that extends from the tip of the needle to the surface of the salt water just equals the weight of an equivalent column of fresh water of the same cross section that extends from the tip of the needle to the relatively higher surface of fresh water outside the syringe. The column of salt water is shorter than the equivalent column of fresh water, but the salt water is proportionately denser; hence the weights of the two columns are equal.

"The second position of equilibrium occurs when fresh water fills the needle. This column now consists of two parts: fresh water in the needle and, adjoining it above, a column of salt water of equal cross section. Accordingly the compound column is less dense than the column of pure brine, but the surface of the brine in the barrel of the syringe is now proportionately higher than it was when brine filled the needle—precisely enough higher to restore the balance of the system.

"Both positions of equilibrium are extremely sensitive to disturbances because heavy brine overlies light fresh water. Equilibrium can exist only if the interface between the brine and the fresh water is parallel to the free surface of the solutions and is motionless. Just as water flows out of an inverted vessel and air flows in, so does the interface overturn between brine and fresh water. Salt water tends to flow down one side of the needle and fresh water to flow up the other side.

"In the case of the salt oscillator, however, flow in one direction tends to choke off flow in the other direction if the difference in density and velocity of the two fluids is sufficient. To visualize the action, assume that salt water fills the needle. Any disturbance of the interface between salt water and fresh water at the bottom of the needle causes fresh water, however little in amount, to enter the needle and displace an equal amount of salt water. The column now consists of both salt water and fresh water. Accordingly it is lighter than the equivalent column of fresh water outside the syringe. The columns are unbalanced. The resulting force causes additional fresh water to enter the needle, further increasing the imbalance.

"Because the volume of the needle is much smaller than the volume of the barrel, this intrusion of fresh water into the needle barely affects the surface level of the brine in the syringe. As a result the higher fresh water rises in the needle, the larger becomes the force that accelerates its upward flow. Eventually the forces that accompany the upward acceleration of fresh water become large enough to choke off the downward flow of brine. One-way flow is established in the needle. Immediately thereafter a jet of fresh water erupts in the barrel of the syringe. The level of the diluted brine rises [*see illustration below*].

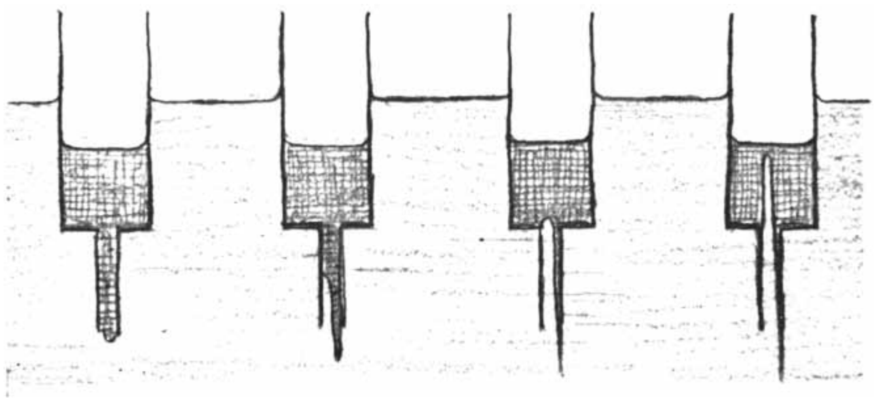
"Upward flow continues until the free surface of salt water in the syringe approaches the level of the second point of equilibrium. There the flow stops. The system is again in equilibrium, with the needle full of fresh water. Instability then initiates a local overturning of the interface and starts salt water down the needle. Thereafter the flow of brine continues until the first equilibrium point is reached once again and a new cycle begins.

"The salt oscillator runs for many cycles. The flow of fresh water into the syringe during each cycle increases the dilution of the salt water and thereby reduces after each cycle the pressure caused by the infusion of brine or fresh water into the needle at the beginning of the downward or upward flow. After many cycles this force becomes so small that it can no longer choke off the downward-upward motion induced by the instability. At this point steady, two-directional flow forms in the needle: fresh water streams up one side and salt water moves down the other [*see illustration above*]. Finally the salt solution in the syringe becomes so dilute that it cannot maintain convective mixing. All visible motion ceases.

"The period of oscillation depends primarily on the geometry of the syringe. It varies roughly in proportion to the length of the needle. Doubling the length of the needle approximately doubles the period. An increase in the radius of the barrel or a decrease in the radius of the needle also increases the period.

"In oscillators with periods of more than 10 seconds the frequency of oscillation is independent of differences in the density of the fluids and appears from experiments to be influenced only slightly by their viscosity. The viscosity of the fresh water is constant, of course, so that the duration of the upward flow is almost constant throughout the period of operation. On the other hand, the salt concentration decreases with each successive cycle, and so therefore does the viscosity of the brine. The duration of the downward flow is initially from 5 to 10 percent greater than that of the upward flow, but the two intervals approach equality as the cycles continue.

"I was particularly fascinated by an


Development of stable, one-way flow

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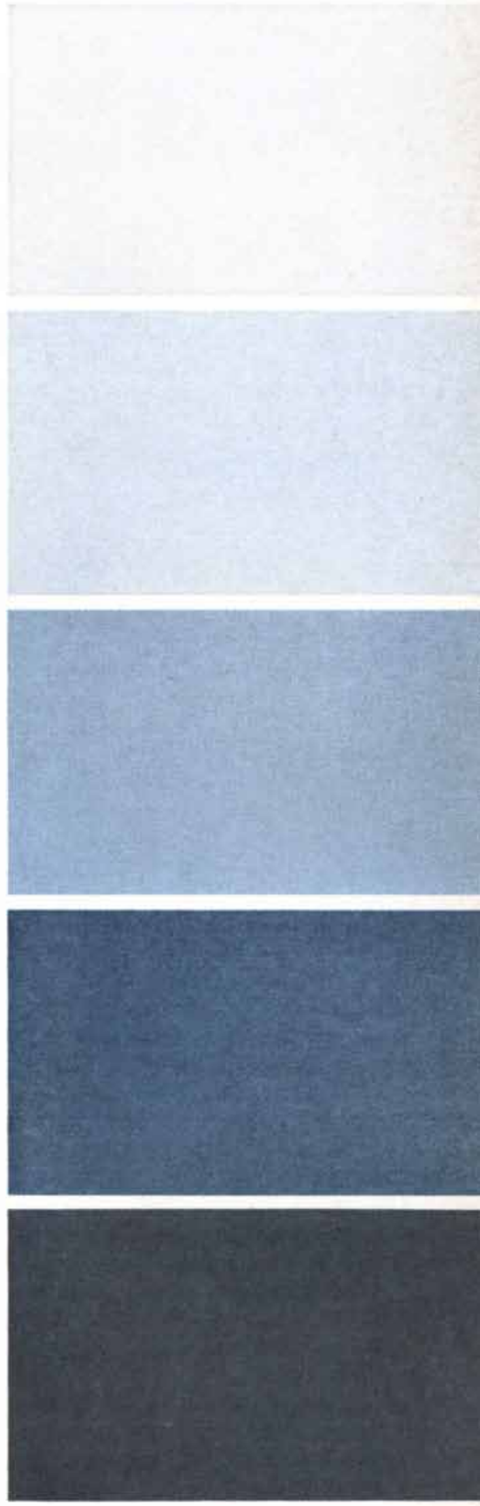

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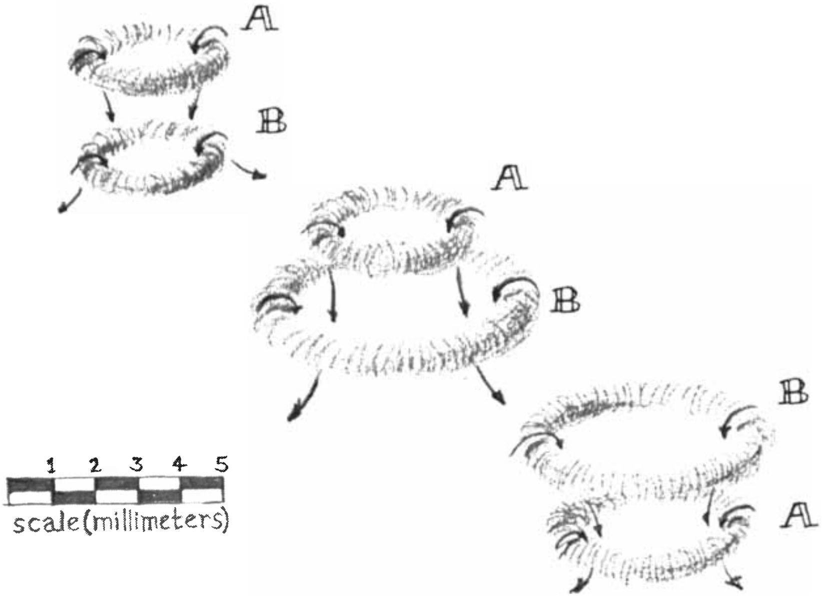


Interaction of a vortex pair

incidental feature of the oscillator. It can be made to generate sequences of small vortex rings by mounting the syringe in a container of deep water such as a 1,000-milliliter graduated cylinder or an equivalent transparent vessel with a depth of at least 20 centimeters. If the period of oscillation is three seconds or more, the downward flow of salt water will usually break up into a chain of vortex rings that are between five and 20 millimeters apart on a common vertical axis.

"The vortex rings interact by overtaking and passing through one another, a phenomenon that has been described as follows by the British physicist George K. Batchelor: 'The velocity field associated with the rear vortex ring has a radially outward component at the position of the front ring, and so the radius of the front ring gradually increases. This leads to a decrease in its speed of travel, and there is a corresponding increase in the speed of travel of the rear vortex, which ultimately passes through the larger vortex and in turn becomes the front vortex. This maneuver is then repeated. It is possible to demonstrate in the laboratory one or two such passages of one vortex through another before they decay [*see illustration above*].'

"Both the jets and the vortexes can be made strikingly colorful by adding a few grains of fluorescein dye to the salt solution. I use the water-soluble form of fluorescein sodium salt known as uranine. Very small concentrations of this nontoxic dye turn a bright fluorescent green when the fluid is illuminated by a strong lamp. Uranine is available from dealers in chemical supplies. One can also stain the fresh water lightly with a dye. A drop or two of eosin will turn the water pink. (Most red inks are eosin solutions.)

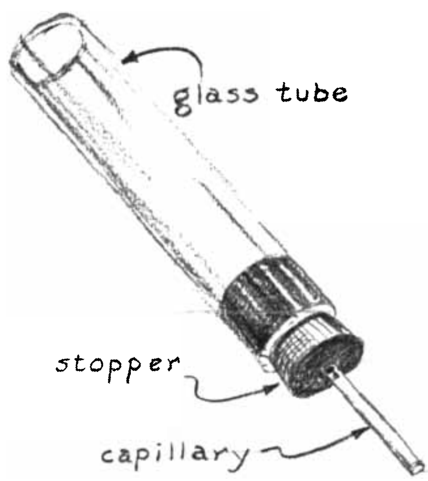
"The salt oscillator can be improvised from various materials and in a number of different arrangements. I used Yale Luer-lok hypodermic syringes and needles primarily because needles of uniform bore and accurately known radius could be easily interchanged. This feature enabled me conveniently to make a variety of oscillators for investigating the influence of the geometry of the needle on the period of oscillation.

"The sale of hypodermic syringes to laymen is restricted in some communities. A simple substitute can be improvised by softening a glass pipette in the flame of a gas burner and drawing the end to a length of from three to 25 millimeters and a bore of from one to three millimeters. The period of oscillators made from pipettes tends to vary because the radius of the 'needle' is not constant. A glass capillary tube of reasonably constant radius can be made by softening the center of a length of 10-millimeter tubing and quickly stretching the glass until it shrinks to a diameter of about two millimeters. Scratch the glass lightly with a file at two points about a centimeter apart near the center of the stretched portion. The one-centimeter length can be removed by grasping the ends of the capillary and pulling them to crack the glass.

"To generate oscillations of uniform period the ends of the capillary must be cut at right angles with respect to the axis of the tube. Glass tubing will usually break at a right angle if one pulls the capillary apart without exerting a lateral, or bending, force. The broken end can be ground true on fine emery cloth. (An experimenter using a hypodermic needle must also square off the pointed end.) The syringe-like structure can be completed by fitting a stopper into a length of large-diameter tubing and pushing the capillary into a hole made in the center of the stopper [*see illustration below*].

"Thin stoppers can be made by fitting a conventional stopper into the large-diameter tubing. Mark the protruding portion at the end of the glass with a sharp pencil. Remove the stopper and make transverse cuts on both sides of the mark with a razor blade. For use in the salt oscillator the capillary must be vertical, that is, parallel to the gravitational field. An oscillator equipped with a capillary of one-millimeter bore and a length of four millimeters will have a period of about eight seconds. An extremely simple oscillator of the salt type can be built by making a pinhole in the center of the bottom of a soup can. One that I built this way operated for four days."

Another recently developed oscillator of more than passing interest has been made by Patrick Peebles of London. The active element is a flame of burning gas. In some respects the device is similar to the "sensitive flames" that were objects of popular experimentation during the 19th century. The burner used in that era consisted of a simple nozzle about a millimeter in diameter. When the nozzle was supplied with methane or a similar gas at a pressure of one ounce per square inch, the resulting jet was characterized by laminar flow: the ignited gas burned as a steady, quiet flame. The length of the flame could be



Salt oscillator made of glass tubes

Basic Research at Honeywell
Research Center
Hopkins, Minnesota

The Effect of Insecticides on Enzymes

The study of the effect of pollutants on the olfactory system has led to a possible explanation of how common chlorinated hydrocarbon insecticides kill.

Although developed to control unwanted insects, chlorinated hydrocarbon insecticides (DDT, Chlordane, Lindane and others) are now regarded under certain conditions as pollutants which can endanger other desirable forms of life. Like all pollutants, the first step in controlling usage is to set permissible standards of concentration of the insecticide in the environment. However, unlike most pollutants, these insecticides become stored in the body tissues of the humans and other animals who acquire them from water and food. For example, fish kills have been noted where the concentration of DDT in the fish was far greater than the concentration in the water. To further complicate the problem, the mechanism by which these insecticides operate is unknown so that toxic limits cannot be set.

Honeywell scientists have been working on means of detecting, identifying and measuring pollutants in the water and atmosphere for a long time. One promising avenue of research in detecting pollutants has been the study of the olfactory mechanism.

Previous studies in olfaction suggested that the absorbance spectra of water soluble extracts from olfactory mucosa were altered after they were exposed to certain odorants. Because the first odor-sensing action is believed to take place on the plasma membrane where enzymes could play a major role in olfaction, the odorant effects on membrane-bound enzymes are under investigation.

The ATP (adenosine triphosphatase) enzymes, are extremely important in metabolic processes such as cation transport through plasma membranes and oxidative phosphorylation, a process by which food energy is converted and stored as usable chemical energy in the form of ATP. Inhibition of these enzymes could have a profound effect on metabolic processes.

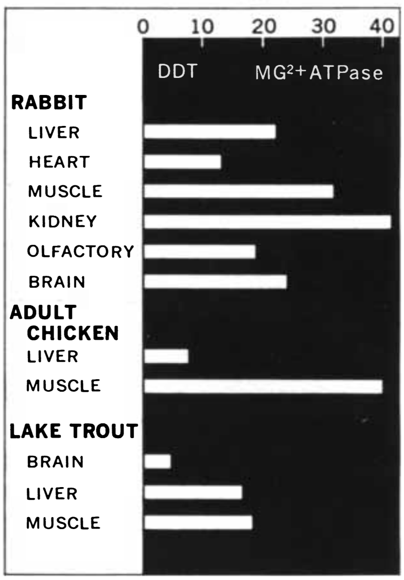
Sodium-potassium ATPase is found exclusively in plasma membranes and plays an important role in maintaining the electrical potential across nerve-cell membranes by cationic transport. This enzyme is able to transport sodium out of the cell and potassium into the cell, both against high concentration gradients of the ions. To carry on this process, ATP is required as an energy source and is produced within the cell itself in a subcellular organelle called the mitochondrion.

The inhibition of the ATPases by chlorinated hydrocarbon insecticides may therefore seriously change cellular energy production and nerve action.

Honeywell scientists succeeded in isolating the plasma membranes from olfactory tissue by differential centrifugation and were able to concentrate the enzymes. Experimentation confirmed the toxicity of chlorinated hydrocarbon insecticides. DDT, chlordane, lindane, aldrin, dieldrin and dicofol were all shown to have an inhibitory effect on the ATPase enzymes.

The lethal hyperactivity commonly observed in cockroaches exposed to DDT concentrates may be associated with the inhibition of the magnesium ATPase. The response was similar to asphyxiation, but it appeared that the agent was interfering not with oxygen intake but with the primary energy production (ATP). In chlordane exposure, the opposite effect has been observed; there was a strong inhibitory effect on the sodium-potassium ATPase and the cockroach seemed to be paralyzed, as if a nerve had been shorted.

INHIBITION OF ENZYME ACTIVITY (PER CENT)



The inhibitory effects of the chlorinated hydrocarbon insecticides on the ATPase systems could account for the observed toxic effects. However, results of fairly extensive studies indicate that although these insecticides inhibit the ATPase system in general, there may be particular tissues which are more sensitive to specific insecticides (see figure).

Scientists at Honeywell are now working with entomologists at the University of Minnesota to find out the specific reactions of various animals exposed to insecticides, since a wide variety of effects have been seen. Studies have shown that animals concentrate DDT and other insecticides in their tissues. The amount of DDT present in some lake trout has been reported to be more than 13,000 times greater than the solubility of DDT in water. This concentration will, of course, affect any limits which must be set to protect the fish. Also detoxification of insecticides occurs slowly and knowledge of the extent and speed of this process is essential for determining threshold limits. In addition, the site that the insecticide affects may have a bearing on its toxicity. For instance, Honeywell and University scientists have found that in bluegills DDT affects muscle, primarily, and brain ATPase activities to a lesser extent.

After extensive study of these and other variables, they hope to be able to determine whether or not the ATPase enzymes can be used as a measure of the toxicity of chlorinated hydrocarbon insecticides. If they can, studies on animals will be extended to determine which tissues are most affected by which insecticides.

The goal is to set threshold limits for the use of these insecticides but the problem is extremely complex because of the variety of mechanisms which must be understood before the toxicity can be measured on the one hand and the obvious beneficial effects of these insecticides on the other.

If you are working in the area of olfactory sensing or the effects of chlorinated hydrocarbons on ATPase inhibition and wish to know more of Honeywell's work, please contact Dr. Robert Koch, Honeywell Corporate Research Center, 500 Washington Ave. S., Hopkins, Mn. 55343. If you have an advanced degree and are interested in a career in research at Honeywell write to Dr. John Dempsey, Vice President, Science and Engineering, Honeywell, 2701 Fourth Ave. S., Mpls. Mn. 55408.

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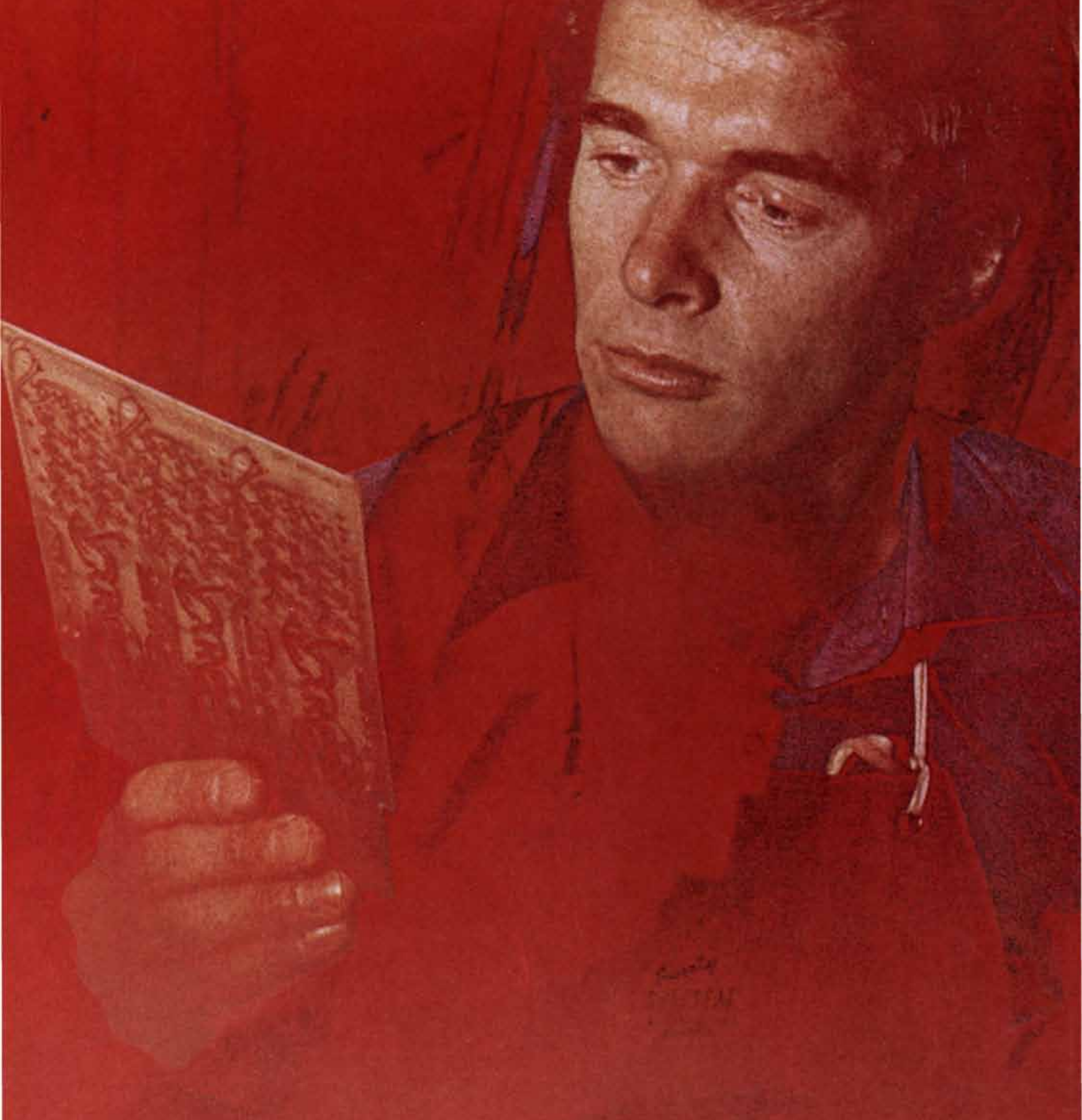

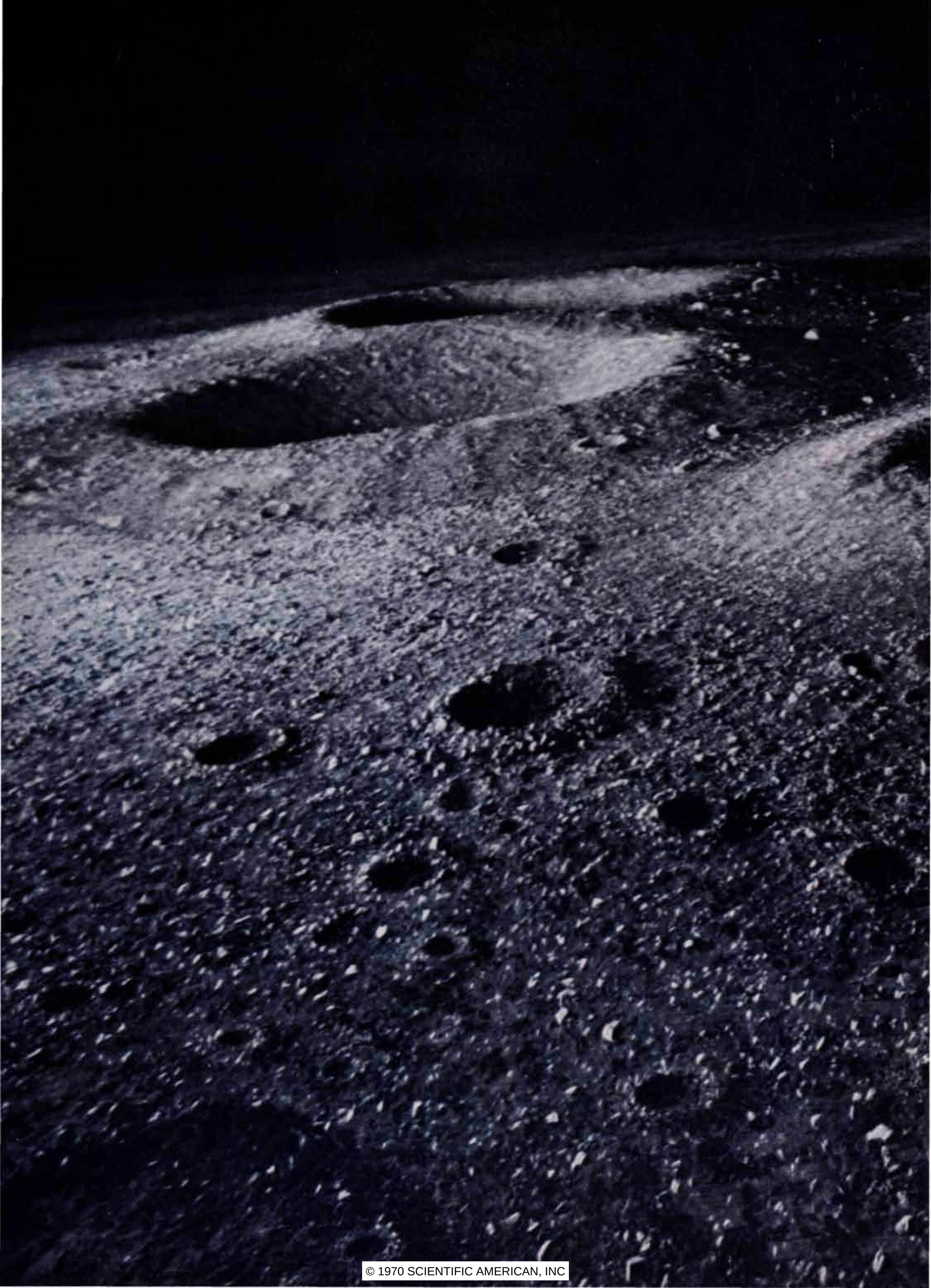


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increased by raising the pressure of the gas.

At a certain critical pressure that depended in part on the diameter of the nozzle the jet abruptly became turbulent: the flame danced and emitted a low roar that could be heard at a distance of several meters. When the pressure was adjusted almost to the point of turbulent flow, the flame became remarkably sensitive to external sounds. For example, at the critical adjustment the flame could be momentarily shortened to half its length by a finger snap at distances of up to 10 meters from the apparatus.

The sensitive flame would also oscillate if it was put inside a resonant cavity. A typical cavity consisted of a vertical tube open at both ends. When the burner was placed inside the tube at a position where the pressure of the standing sound wave was maximum, the sensitive flame would flicker at the resonant frequency of the tube and would emit sound waves continuously. So, at least, one can read in accounts published at the time. The editor of this department has never succeeded in making the arrangement work as an oscillator. Convection currents in the vertical tube blow out the flame.

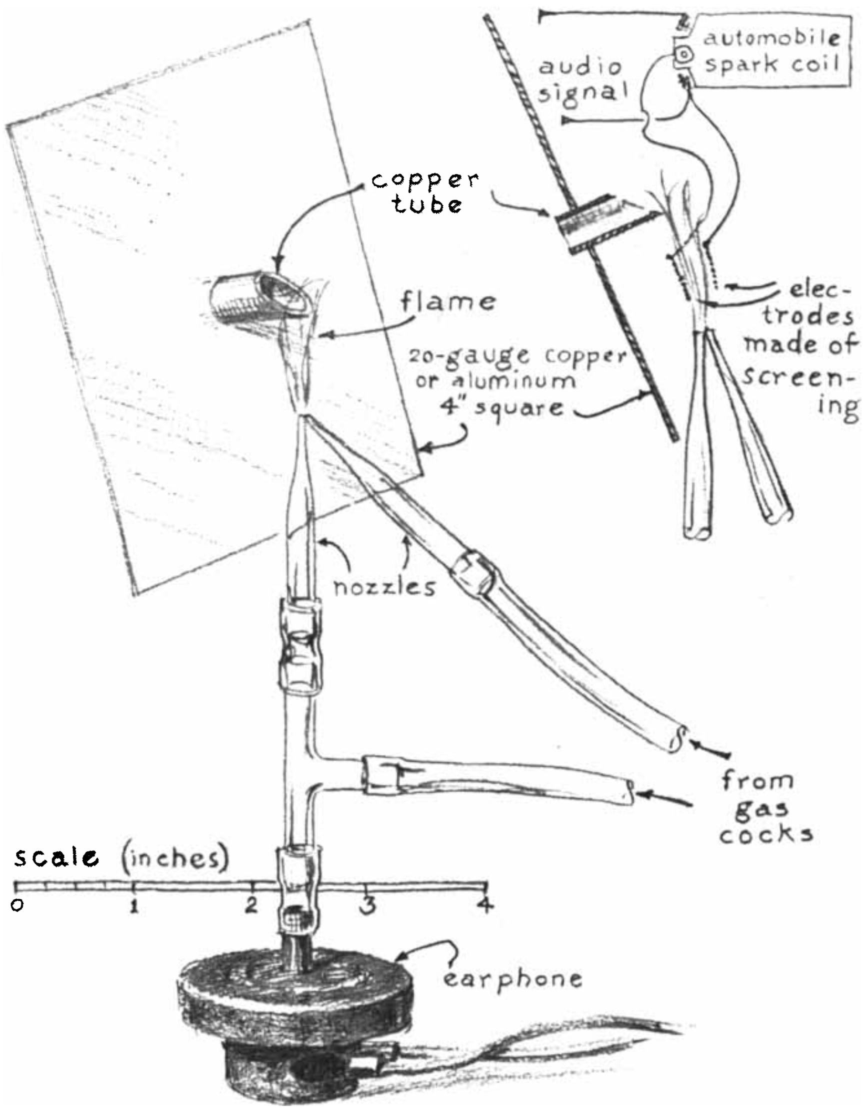
Peebles' oscillator, however, works nicely. It consists essentially of two nozzles of one-millimeter bore mounted at an acute angle of approximately 30 degrees. One nozzle makes a vertical jet and the other deflects the jet from the perpendicular [*see illustration at right*]. The resulting fan-shaped flame is made sensitive both by adjusting the pressure of the gas almost to the point of instability and by inserting the tip of an open copper tube into the flame about a centimeter from the top. The copper tube is two centimeters long and about eight millimeters in diameter. The end that penetrates the flame to a depth of about three millimeters is cut at an angle of 45 degrees. The edges of the cut should be smooth and sharp.

The opposite end of the tube makes a tight fit with a hole in the center of a copper plate that is some 10 centimeters square. The plate functions as a heat sink for cooling the copper tube. When one end of a second copper tube of similar diameter and a length of three centimeters or more is placed close to the base of the flame, the system goes into oscillation, emitting continuous sound at a pitch determined by the geometry of the second tube.

Essentially the oscillator functions by amplifying a small initial disturbance. A portion of the amplified output serves as a succeeding disturbance that initiates the next cycle, and so on. When the system is properly arranged, it can also be made to function as a conventional amplifier. Indeed, Peebles modified the device in two ways for use as both an amplifier and a loudspeaker.

In one scheme he coupled the acoustic output of an earphone into the tubing that supplies gas to the vertical jet. Sound waves from the earphone alter the pressure of the vertical jet and reappear as amplified sound that is emitted by the flame. He estimates that the output is amplified about 2,500 times. Speech sounds can be understood five meters from the flame although the quality of the reproduction is not good. Peebles operates the earphone with a small transistor radio. The amplifier can also be driven electrically.

In Peebles' second scheme the output of a radio that develops about 10 watts is coupled through a step-up transformer to a pair of electrodes placed on opposite sides of the flame near the base. The electrodes are two squares of copper screening about 15 millimeters wide spaced 10 millimeters apart. An automobile ignition coil can be used for the transformer, although the quality of the amplified sound will be higher if the experimenter uses a grid transformer of the kind designed for coupling low-impedance input circuits to vacuum-tube amplifiers. Peebles makes nozzles for the system by softening the middle of a six-millimeter length of glass tubing in a gas flame and drawing the softened portion down to a bore of about a millimeter. If the device refuses to work, try adjusting the depth to which the upper copper tube is immersed in the upper part of



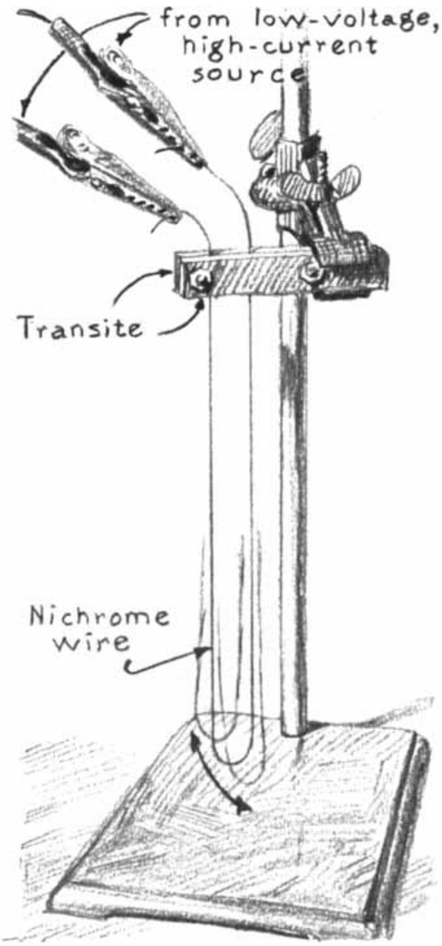
Patrick Peebles' flame oscillator

the flame and also the height at which it penetrates the flame.

The simplest of the three oscillators was brought to my attention by A. D. Moore, professor emeritus of electrical engineering at the University of Michigan. It consists of a *U*-shaped loop of wire suspended at the top by an electrically insulating clamp [*see illustration at right*]. When the wire is heated to a temperature of about 400 degrees Celsius by either an alternating current or a direct current, the loop vibrates like a child's swing. I have made a number of loops with Nichrome wire salvaged from replacement units for a 1,000-watt radiant heater.

I clamp the ends of the loop between two strips of quarter-inch Transite, a building material composed largely of asbestos. I make the loops about 10 times longer than their width. The lengths of my oscillators have ranged from 10 to 36 inches. The frequency of vibration varies inversely with the length of the loop.

Loops made of iron and other metals oscillate but not as vigorously as those made of Nichrome. The amplitude of vibration may exceed 15 angular degrees. For sources of power I have used both storage batteries and step-down transformers. Power requirements depend on the size of the loop but in general will be on the order of 10 amperes at 12 volts.

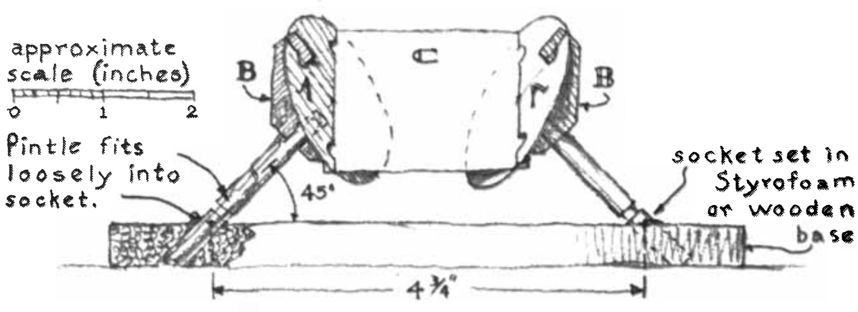


The hot-wire oscillator

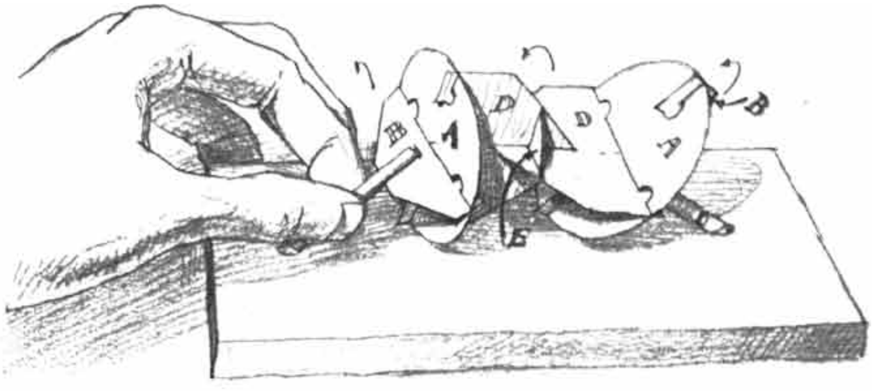
Why does the loop oscillate? Readers may enjoy discovering the answer at the workbench and validating it with at least two different experiments before Moore presents the explanation in this department next month.

An interesting new concept in the ancient art of making devices for transmitting power mechanically is submitted by Rick Freund of 273 Lawton Avenue, Cliffside Park, N.J. 07010. Essentially the mechanism consists of a pair of universal joints made from business cards, plastic soda straws and wooden dowels. Like the oscillators, Freund's gadget appears to have no practical application, but it does show that a constant-velocity, right-angle drive can be made from flat stampings.

Each of Freund's universal joints includes a hollow shaft that supports at one end a fork with two tines that engage slots in opposite edges of a disk. A second pair of slots in the disk are similar but are positioned at right angles with respect to the first set. The second pair of slots engage a cardboard link



Universal joints coupled by a flat link



Universal joints coupled by a right-angled link

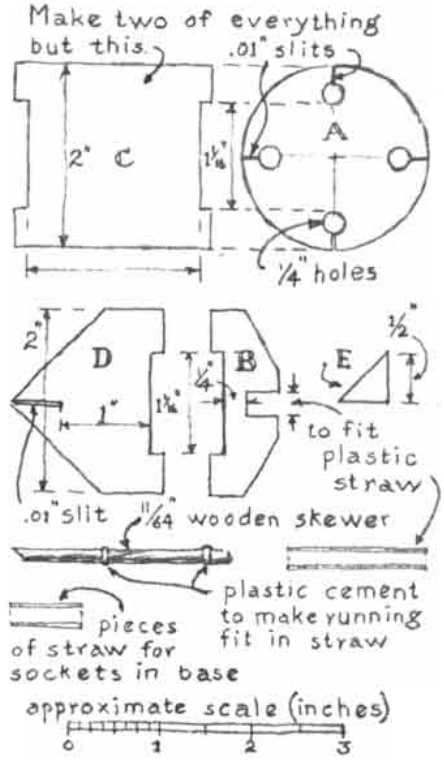
that transmits motion between identical disks. Links of two kinds are used [*see bottom illustration on page 232*]. One is a flat, rectangular card notched at opposite ends for engaging the disks. The other link consists of a pair of notched cards joined rigidly at right angles. The hollow shaft of each universal joint turns on wooden dowels supported at an angle of 45 degrees by a common base of Styrofoam.

With the flat link in place the assembly operates like a pair of crown gears: the motion of one shaft is transmitted uniformly to the other. According to Freund, when the mechanism is made of precision stainless-steel stampings with disks the size of a dime, it transmits eight inch-ounces of torque with little more play than a pair of mating gears. The behavior of the device can be altered significantly by substituting the right-angled link for the flat link. The mechanism is then analogous to a mating pair of elliptical gears. When one shaft is driven at constant speed, the other accelerates from maximum to minimum twice during each revolution. The ratio of maximum to minimum speed at the output shaft depends on the angle at which the shafts are supported by the base. The ratio varies from one, when the shafts are in alignment, to 16 to one at an angle of 60 degrees.

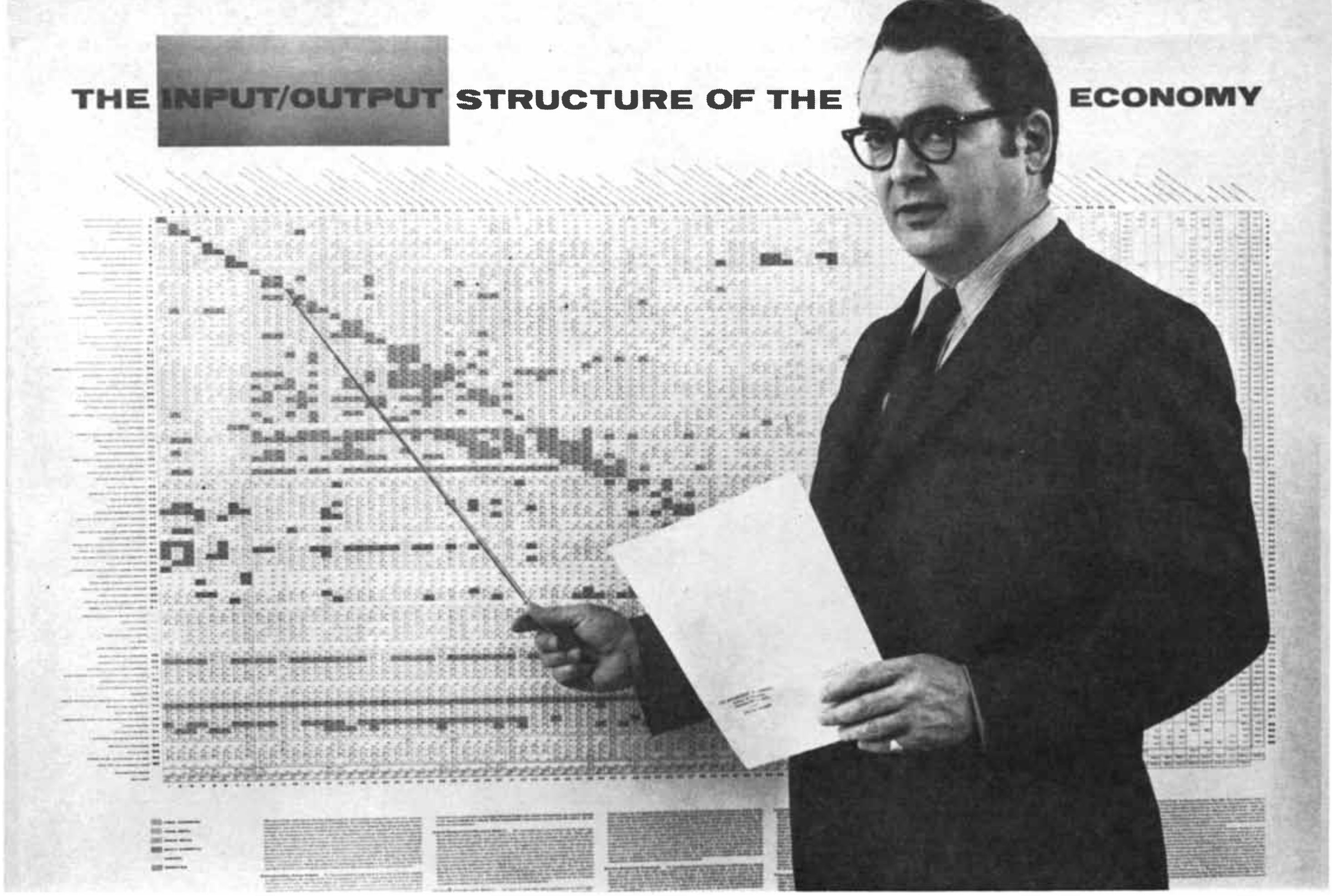
Roger Hayward, who illustrates this department, delved into the history of the universal joint and found that its invention is generally ascribed to the English physicist Robert Hooke. Hayward writes: "Volume 3 of *American Mechanical Dictionary* (Houghton, Mifflin & Co., 1876, page 2683) shows a pair of Hooke's joints. The article points out the need for symmetry with respect to the link and notes that the two shafts have to lie in the same plane. All of this is credited to Hooke.

"Because of Hooke's work in physics and mechanics I am inclined to believe he first recognized that accelerated motion induced in a system by a single universal joint can be canceled by the opposing acceleration of a second joint. That Hooke had no use for cyclically varying speed is to me rather trivial. You cannot figure out a way to eliminate an error without first understanding what the error is.

"Freund refers to his device as a toy. This makes me wonder what a toy is. Are my tools the toys that I really love, or are toys the things that I make with the tools? There must be a wide spectrum of items that are toys to some people, including Freund's interesting contraption."



Construction details of linkage



WHAT DOES IT TAKE TO PRODUCE A $1000-BILLION GNP?

The Editors of SCIENTIFIC AMERICAN have prepared a wall chart, based upon the latest Federal input/output table, displaying the interindustry flows of raw materials, intermediate products and business services required to carry the U.S. economy to the benchmark Gross National Product of $1000 billion.

Input/output tables provide management, government administrators, economists and market analysts with a powerful new tool for forecasting and measuring the indirect as well as the direct interindustry relationships that structure our industrial economy.

This handsome and informative wall chart (70" x 46", in eight colors) offers a unique entry into the rapidly developing discipline of interindustry (or input/output) analysis. Based upon input/output tables issued by the Office of Business Economics of the U.S. Department of Commerce, the chart can be used as a teaching tool and for study of practical and theoretical questions about the U.S. economy.

The chart presents an interindustry matrix of 99 rows and 99 columns; each of the nearly 10,000 cells in the matrix shows (1) the direct input/output coefficient, (2) the "inverse" coefficient and (3) the interindustry dollar flow for a $1000-billion Gross National Product. The input/output coefficients as published by OBE have been recomputed by the Harvard Economic Research Project to reflect gross domestic output. The 370 sectors of the detailed tabulations have been selectively aggregated to 99 sectors to provide maximum feasible detail for the wall chart. Where the ratio of input to output exceeds 1/100, the cell is tinted in the color-code of the industrial bloc from which the input comes. This device, combined with triangulation of the matrix, brings the structure of interindustry transactions into graphic visibility.

Offprints of five SCIENTIFIC AMERICAN articles on the technique of input/output analysis accompany the chart. The articles are:

Input/Output Economics
by Wassily W. Leontief

The Economic Effects of Disarmament
by Wassily W. Leontief and Marvin Hoffenberg

The Structure of Development
by Wassily W. Leontief

The Structure of the U.S. Economy
by Wassily W. Leontief

The Economics of Technological Change
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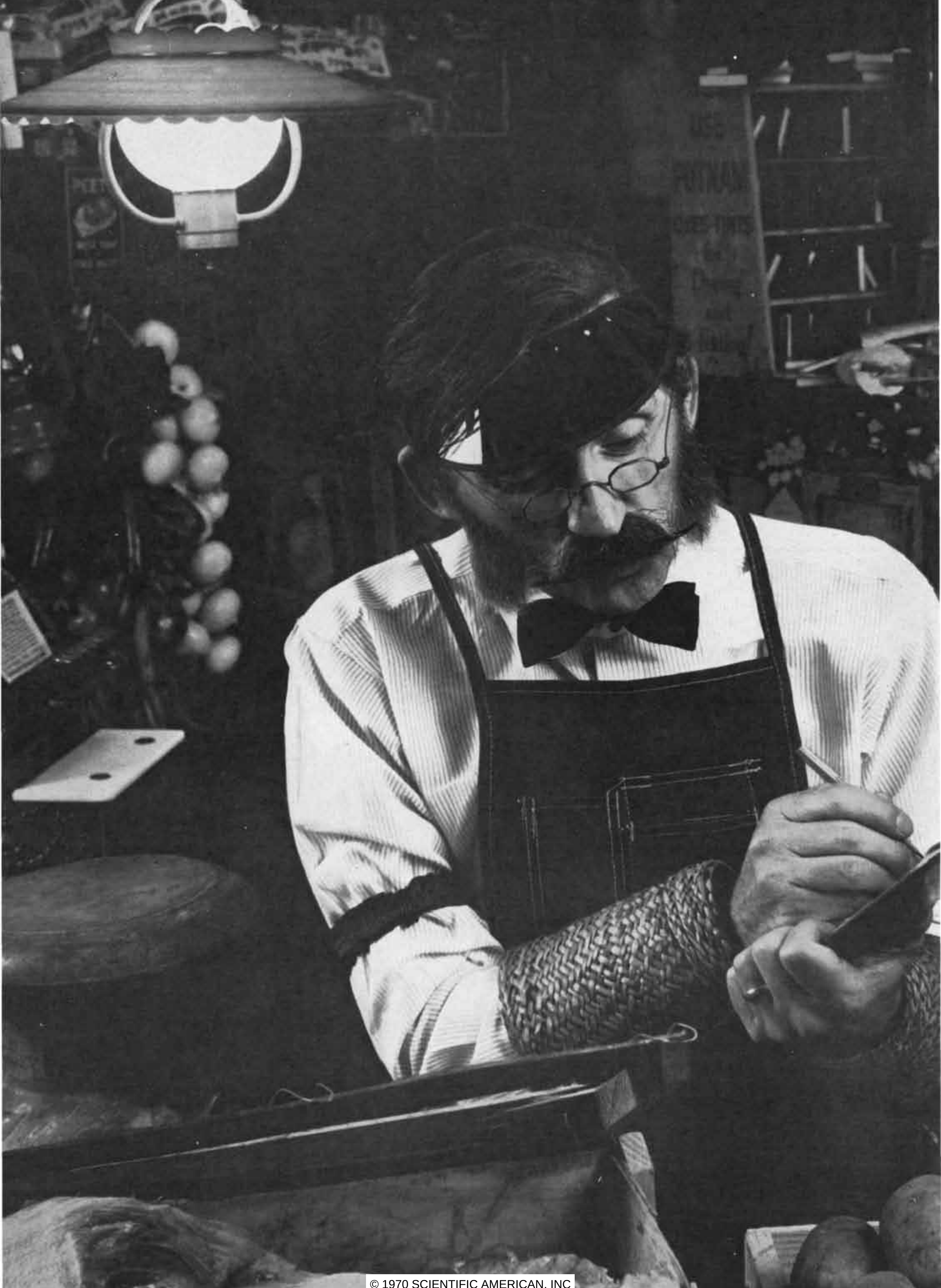

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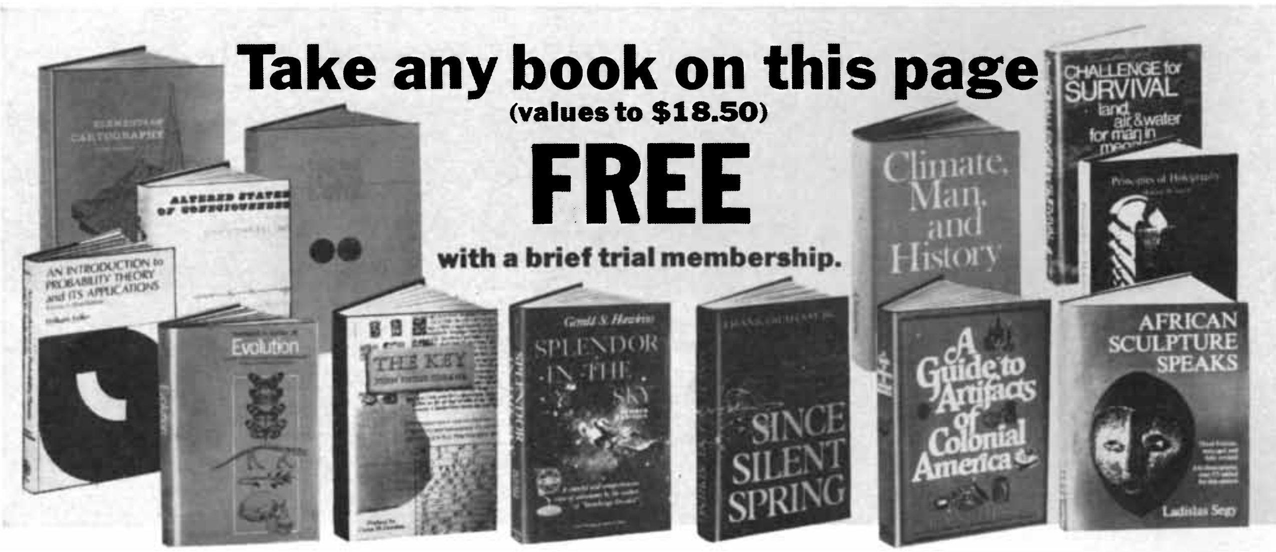

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Antarctic ecology, air pollution, chemical fallout, bamboo, palm and microorganism

by Philip Morrison

Antarctic Ecology, edited by M. W. Holdgate. Published for the Scientific Committee on Antarctic Research by Academic Press, Inc. (Volume I, $18.50; Volume II, $14). In the summer of 1968 there gathered in Cambridge a group of scientists, men and women from a dozen nations, with a stake in the polar region (plus one albatross expert now in Uganda). The Russian delegation was particularly strong. These two volumes, which make up one work with a single index, present substantial fare. They include longish review articles and a record of the candid international discussion after each group of related papers. The order of the volumes roughly follows the flow along the food chain. The first book opens with an appraisal of the geologic past, and goes on to the open sea and its life, to the bottom on the continental shelf, to the fishes and birds of the shore, to the freshwater life, to the soil and the vegetation and the land fauna (with scanning electron micrographs of a millimeter-long springtail, the one lonely year-round inhabitant of the tiny forest of the subantarctic moss). The final discussion takes up conservation. It is impressive to see how honestly these biologists practice what they preach: they limit themselves determinedly in taking specimens, in making helicopter flights over rookeries, in killing seals for handy dog food. "Scientists, like everyone else, must expect to justify their demands on the Antarctic fauna and be answerable for their conduct." Their rules are now a practical reality; the legal power flows from the international treaty that governs all land and shelf ice south of 60 degrees south latitude, even though that writ does not run on the high seas.

The oceanic loophole is of course a tragedy. Once before, by the year 1830, the million fur seals of Antarctica's offshore islands were "virtually eliminated"; only now are these animals beginning to recolonize their old range. The rich, cold antarctic seas held the great whales; the most poignant graph in the book shows the terrible decline in the total mass of the baleen whales. From the mid-1920's, once the factory ships began to supplant the old shore stations, the stock fell steeply. There was only one respite: war among men enforced a truce between man and whale. The whale stock fell from more than 20 million tons in 1920 to about a tenth of that value today. "Blue whales are now wholly protected, but it may be forty to fifty years before they can recover from such a low level." (The whaling nations met in June. Still pursuing their short-run profits, the three remaining active whaling powers are not yet willing to reduce quotas on species other than the blue. The populations of the lesser species are much reduced, but not yet decimated.)

The 100-ton blue whale feeds mainly on the half-gram crustacean *Euphausia superba,* named krill by the Norwegian whalers of long ago. *E. superba* is a herbivore: it feeds principally on the minute green diatoms it filters out of the water. In its lifetime of four or five years it pursues the phytoplankton up and down, in the depths by day and at the surface by night. Whales took 150 million tons of krill per year from antarctic waters; a huge human fishery for the krill is not incredible. It would be the first modern pelagic fishery, perhaps with lighted lures on automatic rafts, their pumps filtering organisms from the seawater, able on aerial command to seek out the slow, lens-shaped surface swarms of the krill. The devotion of the krill to a high density of its fellows (up to 20,000 per cubic meter, turning the seawater a couple of percent krill) is as unusual as its enormous total numbers. There is no sign that any known consumer has yet battened on the krill that once went to nourish the vanished whales; perhaps the krill have gone to the cold and sinister squid of the depths, about which no one knows very much.

The Russian workers have lately done a great deal of work on the krill, and the British have done much for more than 30 years. Before we fish for the krill our knowledge must increase; we cannot endure another overfishing disaster. P. A. Moiseev concludes that the krill fishery would "probably allow us to double the present catch of aquatic organisms from the world ocean." The annual production of this one species in the ring of nutrient waters around Antarctica can be roughly bounded; it is surely less than 500 million tons, but it is more than 75 million—some 10^{14} individual luminous, big-eyed, transparent quasi-shrimps. The present total world catch of all aquatic animals is about 60 million tons per year. Here is new protein for the billions.

It is at least a hope that there in the already demilitarized Antarctic, far from most borders, most legislators and most general staffs, the powers might join in an international goal: more protein to feed men. In order to reach the goal we would have to bring into being in a decade or two an adventuresome and arduous industry, accompanied by the kind and scale of resources for reconnaissance, communications, rescue, technical innovation, recruitment and skilled management that until now only a few large military organizations have been able to deploy so far afield. The worldwide net of the Strategic Air Command might gradually be transformed into SAK, a Service Aérienne du Krill. The overall investment in men and money would be similar; the daily tasks and the risks would not be so very different, but the deeper purpose would be transfigured. The road to the new world lies at least in part through the growth of what is clearly well begun: international research toward a thorough understanding of antarctic ecology.

Air Pollution, edited by Arthur C. Stern. Academic Press Inc. (Volume I, $32.50; Volume II, $35; Volume III, $47.50). Chemical Fallout: Current Research on Persistent Pesticides, edited by Morton W. Miller and George G. Berg. Charles C Thomas, Publisher ($22.50). The second edition of *Air Pollution,* completed in the fall of 1968, presents a very useful standard base line for thought and technology in this genuinely vital field. The authors are 60 experts, and their product is 54 substantial chapters. Most of the men work (as the general editor does) for university or government agencies concerned with this aspect of public health; there are a few men from corporations with special concerns, and a few from other university departments. There is one Kyoto filtration engineer; all the other contributors are Americans.

The book is directed to readers with technical fluency but not to specialists. Its detail is hardly dense enough to allow design or clear choice among specific alternatives, whether in practice or in theory, but it does provide invaluable orientation on underlying concepts and experience, and on the range of problems and paths to solutions. The three volumes contain many graphs, photographs of apparatus and landscapes, some color pictures and photomicrographs, plenty of tables, and detailed bibliographies.

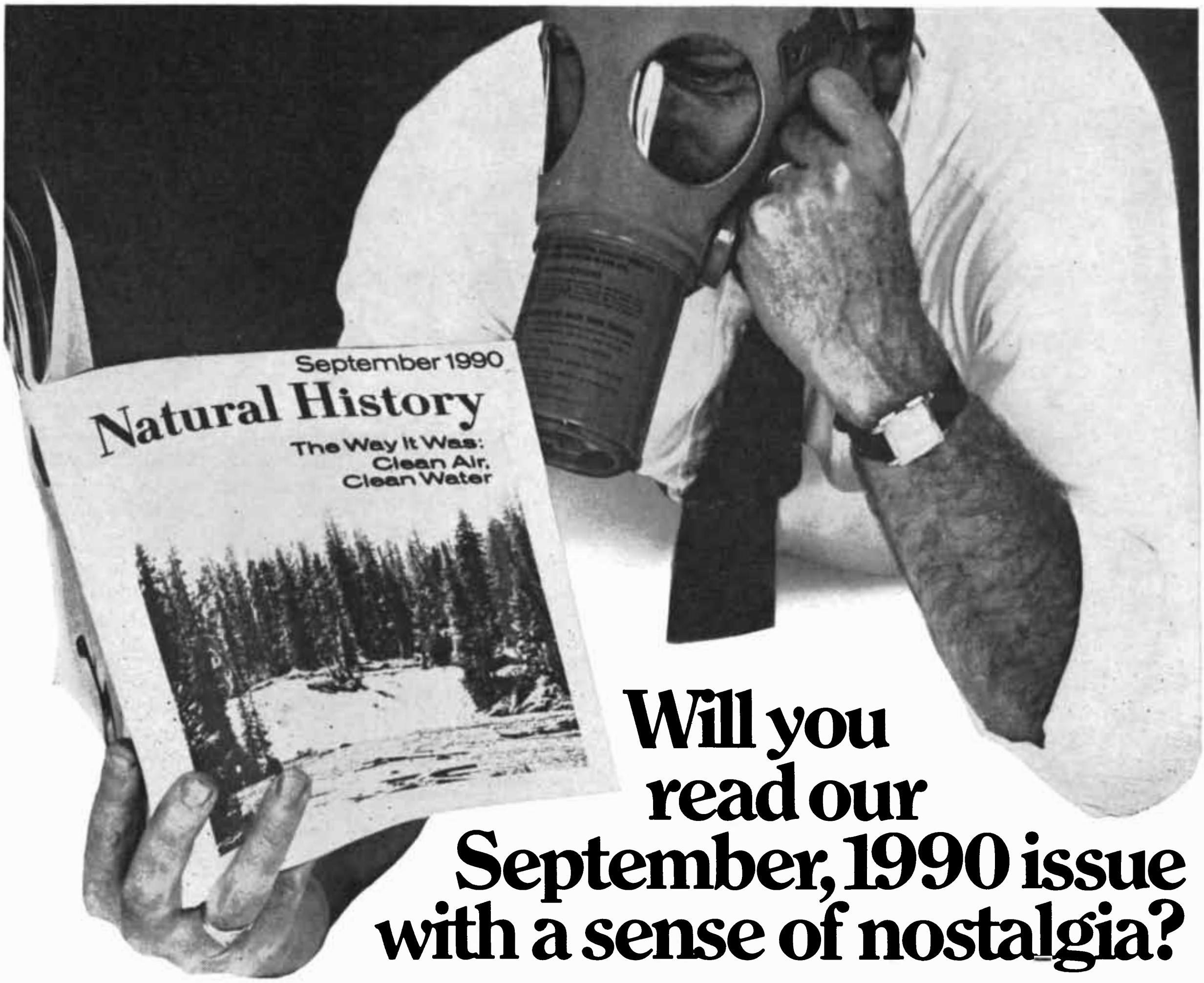
Volume I discusses the general categories of pollution, the mechanisms of its transport and its effects on visibility, on weather, on plants, on animals and on human health and wealth. Volume II tells how to sample, measure, monitor and survey. Volume III, the thickest (more than 860 pages), discusses pollution sources by type, the means of technical control at the source and the problems of legal and administrative organization needed to secure control. The work aims at being a handbook of air pollution, the first resort for any serious student of the thicket of problems that lies between us and clean air.

It is not possible to survey so many-sided a book. The flavor (smell?) of the work can perhaps be conveyed by drawing just one topic from each volume. In Volume I our first paladin against smog, A. J. Haagen-Smit (with a Los Angeles colleague, Lowell G. Wayne), describes the web of photochemical reactions the desert sunlight spins daily in the warm pool of Los Angeles air out of the hydrocarbons and nitric oxide from a million manifolds. It is a remarkable story: the reducing agents turn into fierce oxidants that crack rubber, irritate the eyes and yellow the citrus groves. The products are many, the reagents not few. Ozone and peroxyacetyl nitrate are two recognizable and voracious oxidants. The needed free energy comes from the sunlight; on a bad day 80 percent of the sun's ultraviolet has gone to stoke the reactor tank in which Los Angeles steeps. Control seems possible; it lies at the end of wise automobile design and management.

Volume II is a field and laboratory guide. One analytical technique is fascinating. A small disk of filter paper is placed on a tiny hot plate that heats it in a one-inch ring. A few drops of the dissolved sample are placed in the center, and the appropriate solvent is dropped on to wash the stuff out to the hot ring. The resulting ring spot can be tested in many ways; $100 or $200 worth of apparatus and reagents provides analysis for dozens of elements to an accuracy of 10 percent, even in samples as small as a tenth of a microgram. At another level of measurement the pattern of winds in a city, so complex and hard to know, have been checked by floating a Mylar tetrahedral balloon, ballasted to constant height, and following it by radar reflection from a dangling transponder. This scheme is expensive but powerful. (It might help to explain that notorious telescopic photograph of a polyhedral flying saucer, seen over London a decade ago.)

Volume III is perhaps the weakest. Foresight is never easy; the authors who wrote four or five pages on the chlorine industry never noted that the 1,000 tons of metallic mercury cathodes in our new electrolytic chlorine plants imply not a chlorine hazard but a mercury hazard. Yet in Japan escaped mercurials (catalysts from organic-synthesis plants) had already claimed deaths among the plant's fish-eating neighbors.

Chemical Fallout is an account of a contentious, even rather rude, 1968 meeting of 37 workers from Britain, Canada, Japan, Sweden and the U.S. (The date can only be inferred; that oversight is a small but serious flaw in the editing.) The topic is the distribution and the effects on the linked chain of being of two classes of persistent toxic compounds: organomercurials and organochlorines. Mercury compounds made by man enter the environment in the fungicides and mildew-proofers used on seeds and in pulp and paper plants, and as waste metal and vapors from battery and rectifier factories and electrolytic chlorine plants, even from hospital laboratories. Mercury impurities are found in bulk reagents such as sulfuric acid and thus also occur in synthetic fertilizer. The metal or ions spread in this way can be converted to organic and deadly form and then concentrated by the microorganisms of the mud, even more so by fish. The part-per-million mercury content found very widely in fish lies well above the "practical residue limit" for mercury in foods, set by a WHO-FAO board of experts in 1966, whose concern reflect-



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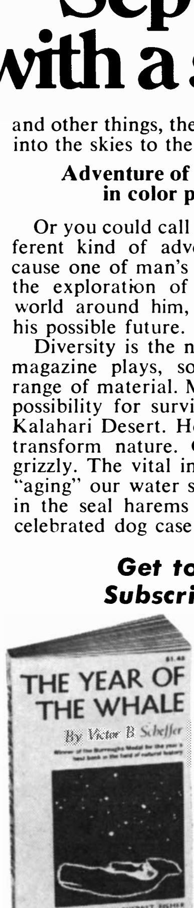

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ed the Japanese tragedy caused by this subtle intoxicant of the central nervous system. "If strictly adhered to, [this limit] would prohibit fishing not only in most lakes in Sweden but also in many other countries; furthermore, some ocean fish would also be in the risk zone (e.g., tuna fish in the Indian Ocean)." Fourteen states of the U.S. now have some condemned mercury-poisoned waters.

The DDT tale is better known, and it is rather well told here. It holds uncertainties still. One must note that the DDT made in the U.S. this year will be bought mostly for export by WHO and by the U.S. Public Health Service, for their antimalarial campaigns overseas. The irony of our world here lies very close to the surface; easy answers are not to be had, but shortsightedness and greed are plainly everyone's enemies.

Let one case be cited. "Azodrin [an organophosphate] was first registered for use against cotton insects in California in 1965...but in 1967 the material was applied to almost one million acres.... We could not recommend the use of this material.... At times, use of Azodrin aggravated the bollworm problem; on other occasions it had indifferent effects, while in one case its use resulted in a substantial increase in yield.... Against bollworm it is an example of a poor insecticide.... It has to be used repetitively.... It is highly destructive to...predators and parasites." So writes an ecologist of the University of California at Berkeley's College of Agricultural Sciences. How did it come to be so widely used, even though it was never recommended by the Agricultural Extension Service? "This came about in large measure through an aggressive sales program by the Shell Chemical Company, Azodrin's producer. Shell was aware of our research findings.... The California cotton growers,...in need of a replacement for the largely outlawed organochlorine insecticides, apparently eagerly accepted Azodrin.... No outstanding benefit occurred, since the 1967 cotton yield in the San Joaquin Valley was one of the lowest of the past decade." Wildlife suffered, and the crop-spraying pilots (together with the householders below them) were placed in hazard, as they are by all such high-concentration organophosphate sprays, which are so closely related to nerve gases.

BAMBOO, by Robert Austin and Koichiro Ueda. Photographs by Dana Levy. Walker and Company ($15). THE NATURAL HISTORY OF PALMS, by E. J. H. Corner. University of California Press ($12.95). In the years 1969 and 1970

three-quarters of the bamboo trees in Japan came to flower, and most of them died. They were the clusters of the long-jointed *madake* species, graceful arcs from 30 to 60 feet high. That exhausting flowering of the *madake* last took place before Commodore Perry's ships entered the port of Yedo. The more or less regular event has a cause that is unknown but inherited. Each species has its own inner time for flowering and death, and like a comet's plume in the sky its arrival is held by many to be a weighty omen. It will be a decade before such graceful stems again stand tall; the bamboo manufactures of Japan, heavily dependent on this form, will lack their usual crop of 300,000 or 400,000 tons.

This book is a kind of gentle elegy, a celebration of bamboo in picture and word. It is a book of many large photographs, some in color. What photographs they are! Three in particular—a side-lighted stem in the deepest of forest greens, a rain-spattered stem, drops lighted in exactly the grays of a cloud-hidden sky, and a smooth yellow cylinder to which the light snow subtly and delicately clings—are works of art, expressing with precision and love that strange union of the serene and the vital which bamboo holds.

Most of the photographs show the works of man, mainly the work of artful man in Japan, whose working substance is the bamboo. Here are the commonplaces: the bear's-paw rake, the table-towel baskets, the great scaffold lattice. We also have the craftsman's noblest pieces: the recurving Zen bows, the vertical *shakuhachi* flute with its five holes and its "sound of great beauty and sadness."

Bamboo is a remarkable plant. Somehow akin to the grasses, it grows and usually reproduces without seed, sending its great roots underground to burst out here and there in those tall stems. A single plant of *madake* (*Phyllostachys bambusoides*) may have nine tons of roots, a shallow underground network 10 miles in much-interlaced and folded total length, and may send up scores of leafy, smooth stems to construct two or three air-dried tons of bamboo per year. Those stems, growing as much as 60 feet high and seven inches across, achieve their entire growth in about two months' time and never again change their height or thickness throughout their long life! They dry, fray and toughen a little, but their function is constant and clear: they sustain the vital rhizomes under the ground. They work for the family.

The text of the book is two distinct essays, one surveying the bamboo in na-

ture, crafts, cuisine and poetry, the other outlining the growth and culture of the plant in some detail. The coauthors are an English writer-editor and a Japanese specialist in the growth of bamboo. Professor Ueda watched one *madake* stem in Kyoto grow a measured 47.6 inches in 24 hours. The photographer is an American living in Tokyo; this is his book by clear right. It was beautifully printed (the photographs are reproduced in five-color offset and gravure) and bound in Japan. It is a production worthy of the noble bamboo. There is no index.

The Natural History of Palms is related in topic but quite different in treatment. It is a thickish text, jagged with botanical Latin and Greek and replete with indexes and references. The pages are well illustrated, with a couple of dozen photographs and old drawings in black and white and 130 line cuts carefully marked to scale. The author, Professor of Tropical Botany at the University of Cambridge, is an investigator with decades of experience in tropical forests around the world. He writes with enthusiasm, learning and a wide view of his subject. Evolutionary, physiological, economic and distributional ideas are thoughtfully discussed, although the author's heart remains with the form and habit and hidden intricacy of the 2,000 species of this Mesozoic family, the oldest of the flowering plants. "A columnar stem crowned with giant leaves is the perfect idea, popular or philosophic, of what a plant should be. It suffers no attrition through ramification."

One sample topic will have to suffice for review. It is the sago palm, whose landscape is "one of the most fantastic and Paleozoic that can greet the eye." Like the bamboo, these palms flower only once before death. They represent an enormous biological investment; the genus *Metroxylon*, centered in eastern Malaysia but spread over the islands of the Pacific, bears after 15 or 20 years a huge inflorescence, raised 30 feet above the ground on a trunk two and a half feet thick. The palm then fruits and dies, its life consumed in making a panicle that spreads over a diameter of 30 feet, bearing 100,000 or so pea-sized fruits!

The fruit is not edible, but there are sago folk, who live on the long, thrifty life of the sago palm, as most other men are grass folk, living on the annual fruits of the grasses. A couple of years before the tree flowers the sago trunk is cut and split open. The starch fuel for the huge flowering is stored within as the pith of the trunk. Alfred Russel Wallace gave the best account of it from East Ceram in the easternmost part of Indonesia,

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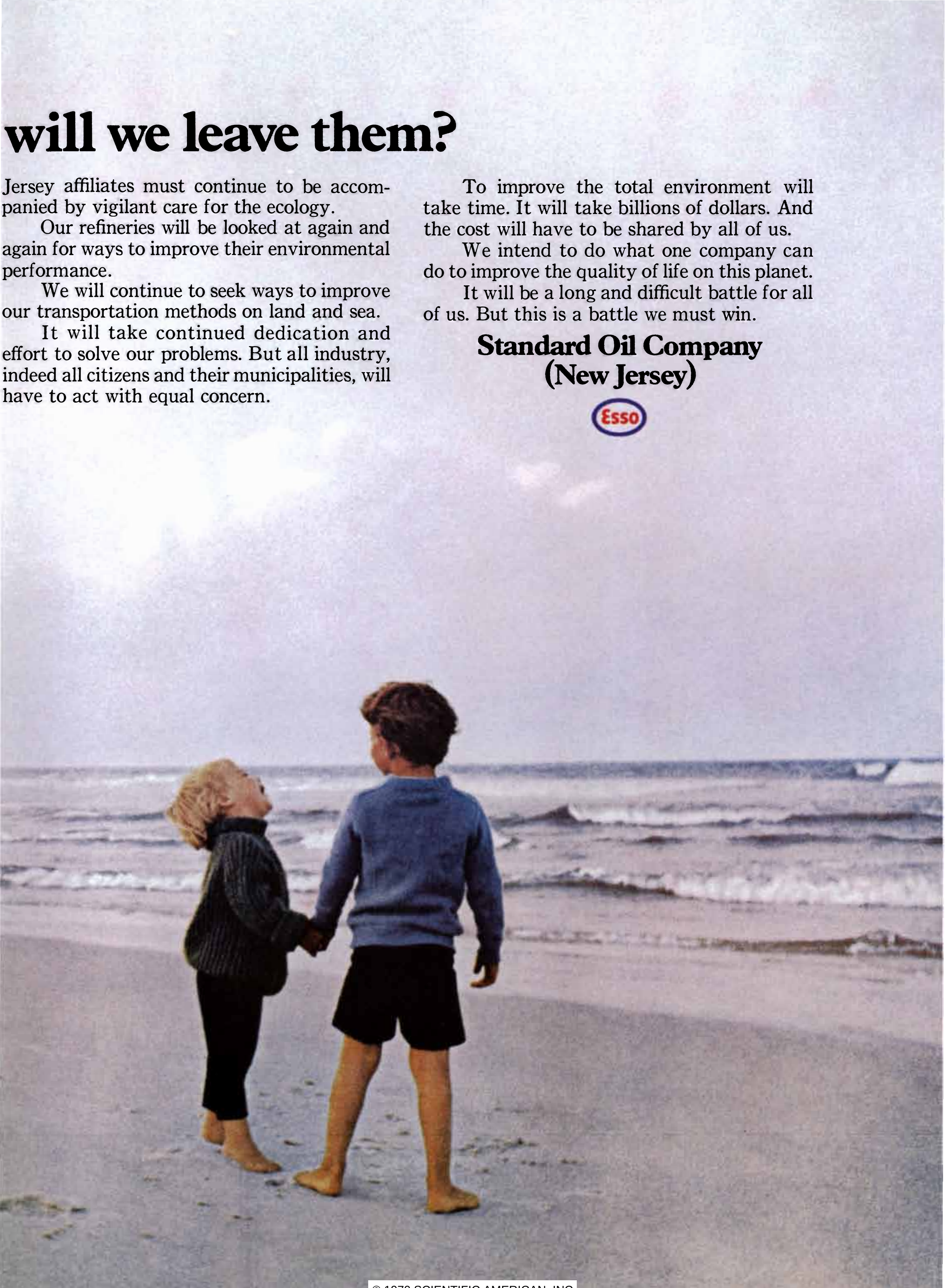
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a great sago district. "It is truly an extraordinary sight to witness a whole tree trunk . . . converted into food. . . . A good-sized tree will produce . . . 1,800 cakes, weighing six hundred pounds, [which] will supply a man with food for a whole year. . . . Two men will finish a tree in five days, and two women will bake the whole into cakes in five days more; but the raw sago will keep very well, and can be baked as wanted, so that we may estimate that in ten days a man may produce food for the whole year."

A good stand of sago will yield each year the calories to feed one man per acre and a half or so. The sago is all starch; it is commercially sold as a form of tapioca. Rice is better food, yields more per acre and is more prized. Nowadays the sago is used mainly by poor men or in times of hardship. The produce of the frail annuals has outstripped the ancient plan of a lifetime's legacy to maintain a tree-sized species.

Although palms are full of interest, they have been much neglected by botanists, men who work mostly in temperate climates and who are attached to collecting flowering parts for the herbaria. As a final word we can unite the palm and the bamboo in romance. Both make pearls. The fruit of the coconut palm sometimes holds a limy round pearl. The bamboo's pearl is more like an opal: it forms in a kind of silica gel sometimes found within the joint of the bamboo, whose tissues have a high silica content. In medieval times the bamboo pearl, called the tabaschir, was prized as an occult antidote for all poisons. So it may have been; a prepared silica gel is prescribed today as an effective adsorbent.

THE ANATOMY OF *PARAMECIUM AURELIA*, by A. Jurand and G. G. Selman. St. Martin's Press ($18). ORGANIZATION AND CONTROL IN PROKARYOTIC AND EUKARYOTIC CELLS, edited by H. P. Charles and B. C. J. Knight. Cambridge University Press ($16). Since Leeuwenhoek first looked at the small world in the 17th century, the slipper-shaped protozoon *Paramecium* has been the topic of what amounts by now to a 10-foot shelf of books and papers. This book, half text, half plates, is an atlas of the protozoon's inmost form, both on the micron scale (the beast averages 135 microns in length) and down to the intimacy of an ultrastructure about 100 times finer. The authors of *The Anatomy of Paramecium aurelia* have made most of the pictures; they are adepts of both light and electron microscopy, and of the subtle processes of staining and sectioning that give

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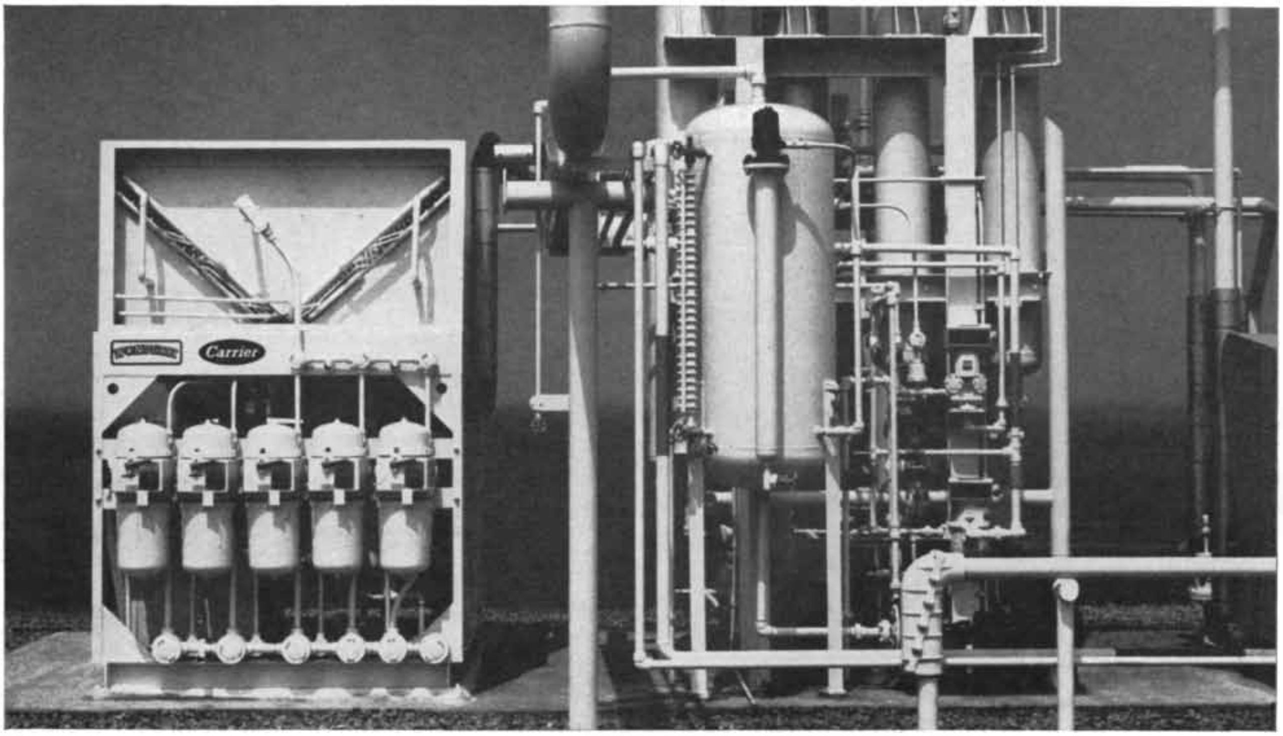

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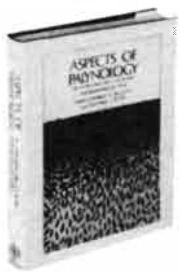

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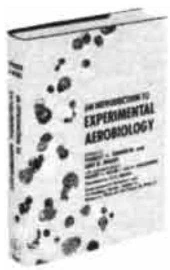

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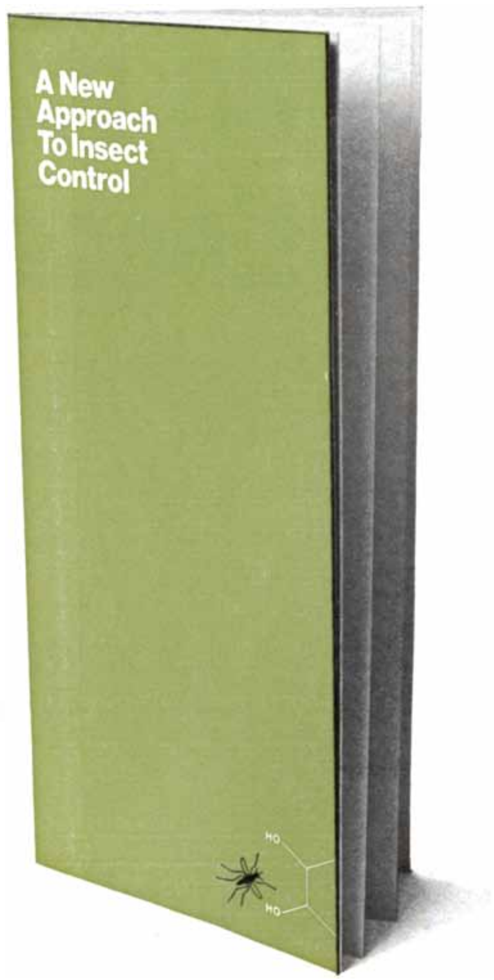
analytical point to the art of photomicrography.

The pellicle—the little pelt—of *Paramecium* is extraordinary. Fitted with a couple of thousand pairs of waving cilia, it is a hexagonal assembly of molded tiles of surprising complexity and beauty, wonderfully displayed here in picture and elaborate diagram. Just below the pelt lie some 1,500 carrot-shaped bodies, taking up about a fifth of the animal's volume. Each of these carroty objects bears a crystalline quill less than two microns long. When stimulated, paramecia can extrude these little spikes out to five or 10 times their length. No one has guessed any use for these elegant minimuscular harpoons. They do not protect; they do not attach themselves to surfaces; they do not aid or impair the rare but essential matings of paramecia.

The intricacy of *Paramecium* is not skin-deep. It has a gullet, and a number of vacuole-stomachs. Some of its internal organs—mitochondria and nuclei—are found in all higher forms of life. All the same, it is surprising to find both a macronucleus and micronuclei in a single paramecium. The big nucleus holds about 400 times more DNA than the little ones, but the macronucleus merely splits during the fission of the animal to form two half-sized daughter nuclei, whereas the micronuclei perform the ritual minuet of mitosis. The cell cannot live long with only a micronucleus, but with a macronucleus alone it can give rise to fission more than 100 times. Yet a macronucleus cannot ever produce micronuclei, whereas the micronuclei can make macronuclei after the act of conjugation. A paramecium is at once "both a germ cell and a somatic cell."

There are other life forms living permanently in some paramecia. A couple of dozen forms of distinct particles a few microns long have been found that grow and divide within the animals (when the genotype is right), one kind even in the macronucleus. These bodies contain their own DNA, and one class of them is shown here fitted with long whips of bacterial flagella. Such particles have been grown outside the protozoon on a cell-free medium. They still possessed their ability to infect paramecia and to confer their properties on them; the flagellate particles cause the release into the medium of a specific substance that kills other paramecia. Some of *Paramecium*'s symbionts have no known effects.

A leopard or a lemon tree hardly seems more complex than a paramecium examined so closely. There remains one great division within the continuity of



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life. All organisms (let us set viruses aside) belong to one of two primary groups. The electron microscope makes the division clear, although it was guessed long ago. The eukaryotic, or "well nucleated," cell always has some complement of definite membrane-bounded DNA-containing organelles within it, not only in its nucleus but also in other bodies, from the respiratory-enzyme machines called mitochondria and the photosynthesizing units called chloroplasts to symbionts such as the killer particles of *Paramecium*.

All the cells of all the higher plants and animals, of the protozoa, of the mosses, of the fungi and of most algae are eukaryotes. Only the bacteria and the blue-green algae are prokaryotes. In these simpler cells (which are also nearly always smaller, measuring a few microns across rather than 100 or more) there is no walled nucleus. If the cell photosynthesizes, it does so without chloroplasts. The DNA, which may well occur in clusters of genes resembling a chromosome, always involves a number of "interpenetrating genetic pools." Distinct gene pools exist within the specialized organelles of the eukaryotic cell, but they interact only in a restricted and one-sided way. The nucleus proper controls most of the cell's functions. The amount of DNA in a mitochondrion is only about 1 percent of the amount found in any free-living bacterial cell. The mitochondrial DNA seems to retain only a few functions. Such little organelles, essential to the eukaryotic cell, nonetheless resemble bacteria in scale, in growth and in reproduction. Are they the tamed descendants of ancient bacterial symbionts like the killer particles? Was the original integration of the higher cell the "progressive acquisition by the nucleus of genetic information from organelles"? Are we the product of a nuclear anthology compiled from ancient and diverse bacterial authors?

The 22 authors of this 1970 London symposium treat that question implicitly, and sometimes explicitly and speculatively. They approach the issue from every microbiological point of view save the paleontological, which is surely an oversight. The volume is good reading, although parts of it are too hard for the informed nonspecialist. It is the report of the 20th annual symposium of the Society for General Microbiology, whose powers are so strong and whose organization is so farsighted that this handsome hard-covered volume appeared the month of the symposium, of course without any account of the discussion.

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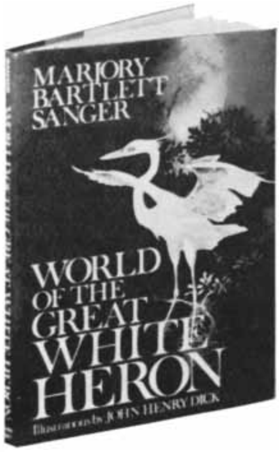

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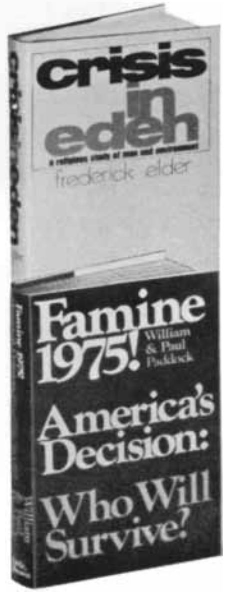

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City.................................... State................ Zip........

Send as first selections: ☐ ROAD TO RUIN ☐ FAMINE 1975!
☐ THE HUDSON RIVER ☐ CRISIS IN EDEN SA

It's working.

Reynolds reclamation plan for aluminum cans and other aluminum scrap.

In Los Angeles alone, Reynolds test program got people to redeem over 1,000,000 aluminum cans per month. Now we're working on sixteen more states.

Answers to the hard problems—such as litter and solid waste disposal—don't come easy. But, with effort and persistence, they do come.

Reynolds has working proof of this with its anti-litter, aluminum can recycling program. Starting in Miami over three years ago, we've developed approaches that are now about to be put to work in 16 states.

They'll be pulling used aluminum cans and other discarded aluminum products off the scrap heap and back to our reclamation plants. They'll be helping to clean up our streets and conserve our nation's resources at the same time.

Los Angeles gets involved.

We know these programs work. One plan, with a Reynolds promotion drive behind it, has Los Angeles citizens bringing more than *a million cans a month* into our plant there. It has not only made Los Angeles people more aware of their litter problem, it has *involved* them, stimulated them into doing something about it.

Now we're expanding our Miami effort to cover all of Florida. We'll be launching our campaign in New York City, and will move into northern New Jersey, Houston, San Francisco, and the Pacific Northwest.

In addition, we are working with Adolph Coors Company of Colorado to help reclaim their used aluminum beer cans. We'll be taking their cans from Arizona, Colorado, New Mexico, Wyoming, Utah, Nevada, Kansas, Oklahoma, Texas, and California.

Individuals and organizations bring all-aluminum cans to the Reynolds reclamation center.

Used cans pass through a magnetic separator and are then shredded.

After shipment to reclamation plants, the shredded aluminum is melted and cast into secondary ingots.

Used aluminum is valuable.

What makes the program work is the basic value of aluminum itself. Scrap aluminum is worth $200 a ton, because it can be melted down and reused so readily. Scrap steel, by comparison, brings only $20 a ton; paper, $16 a ton.

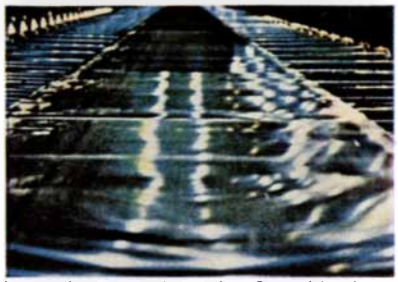
So used aluminum cans are worth picking up, worth saving and taking to a reclamation plant. Reynolds is able to offer ½¢ per can, and to suggest that Boy Scouts, hospital charity groups, and other organizations—and individuals—raise funds by collecting and returning aluminum scrap.

They're taking our suggestions. One million cans that don't show up in Los Angeles garbage heaps every month prove that.

Letters for anti-litter.

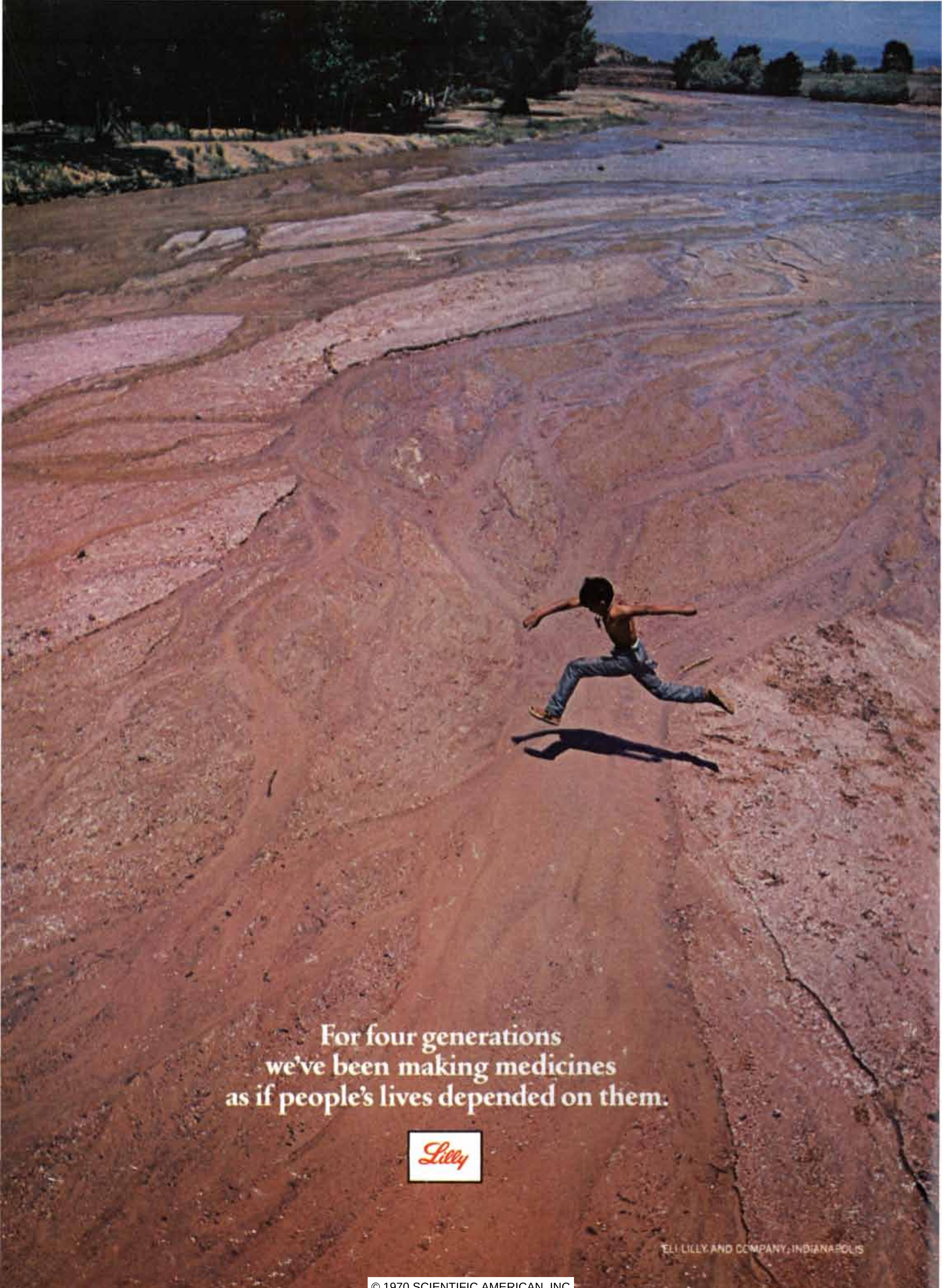
Our anti-litter efforts have brought us much applause from Boy Scout officials, Congressmen, Keep America Clean groups, civic leaders, and many others. But our chief satisfaction is in being able to help with this most difficult and important problem. We intend to keep at it, and to work even harder. Reynolds Metals Company, P.O. Box 2346-LS, Richmond, Virginia, 23218.

REYNOLDS
where new ideas take shape in
ALUMINUM



Ingots then move into other Reynolds plants to be formed into sheet, plate or other mill products.

The recycled aluminum re-enters the economy in a variety of attractive, durable new products.


For four generations
we've been making medicines
as if people's lives depended on them.
Lilly
ELI LILLY AND COMPANY, INDIANAPOLIS