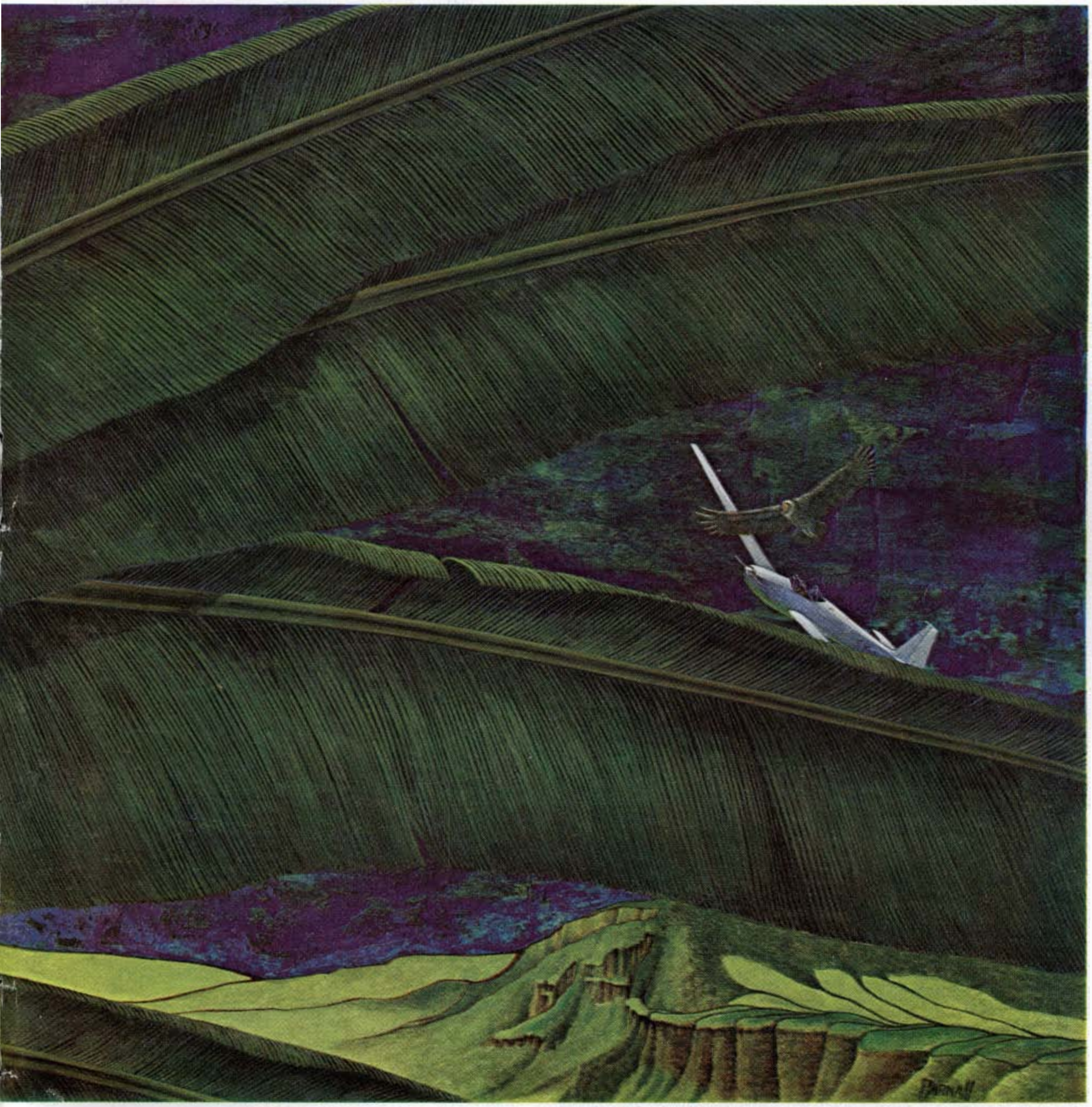
SCIENTIFIC AMERICAN



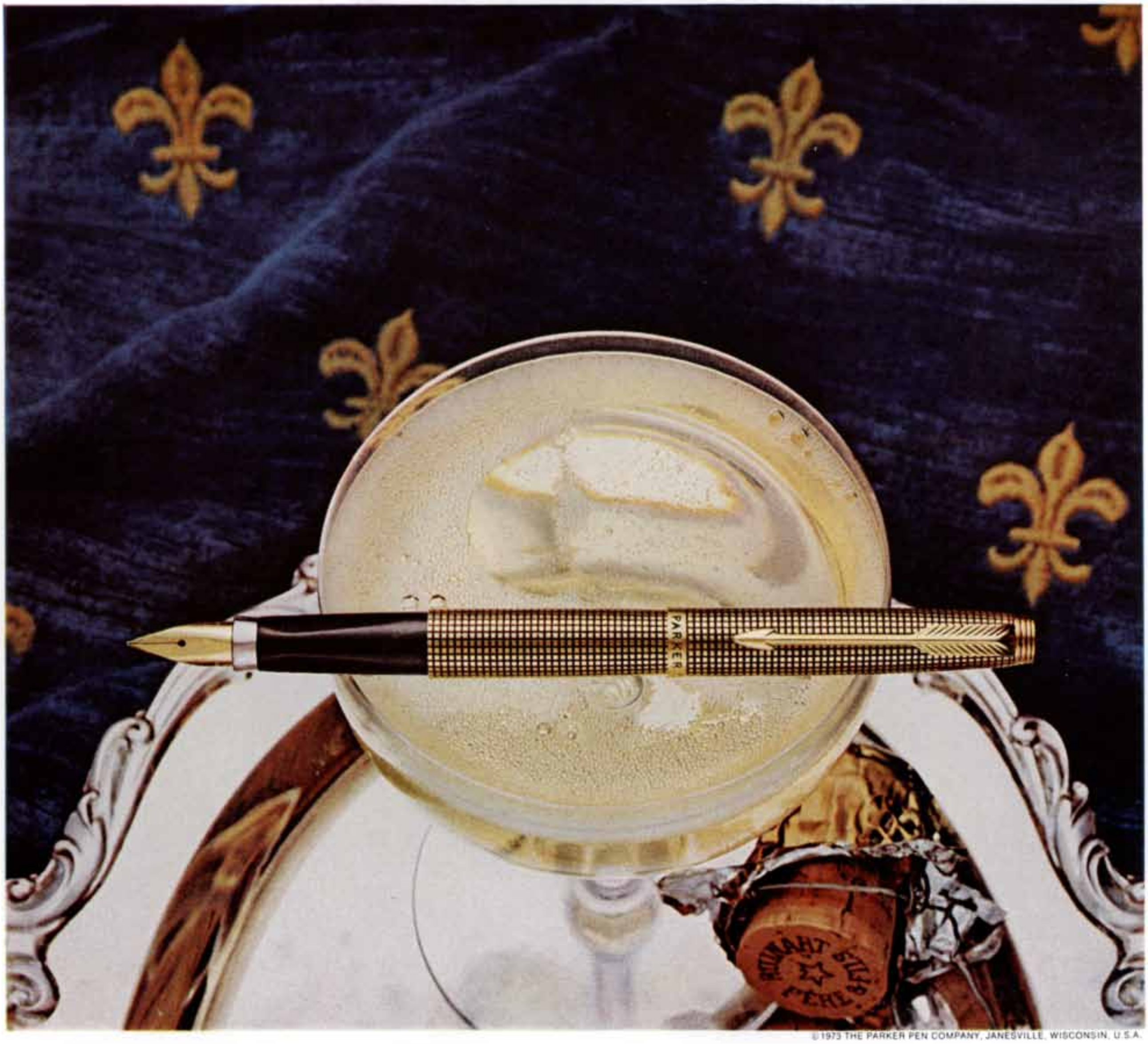
THE SOARING FLIGHT OF VULTURES

ONE DOLLAR

December 1973

© 1973 SCIENTIFIC AMERICAN, INC

PARKER 75



© 1973 THE PARKER PEN COMPANY, JANESVILLE, WISCONSIN, U.S.A.

It's almost a collector's item. The Parker 75 Pen in vermeil.

There is only one vermeil pen in the world—and Parker makes it. Because vermeil is expensive and little known here, we make only a limited number. Each is an impressive gift.

Vermeil comes into being when gold is applied to sterling silver, producing a soft, warm glow. Louis XIV used it freely at Versailles. And the Emperor Napoleon so treasured vermeil he had it cleaned only with champagne.

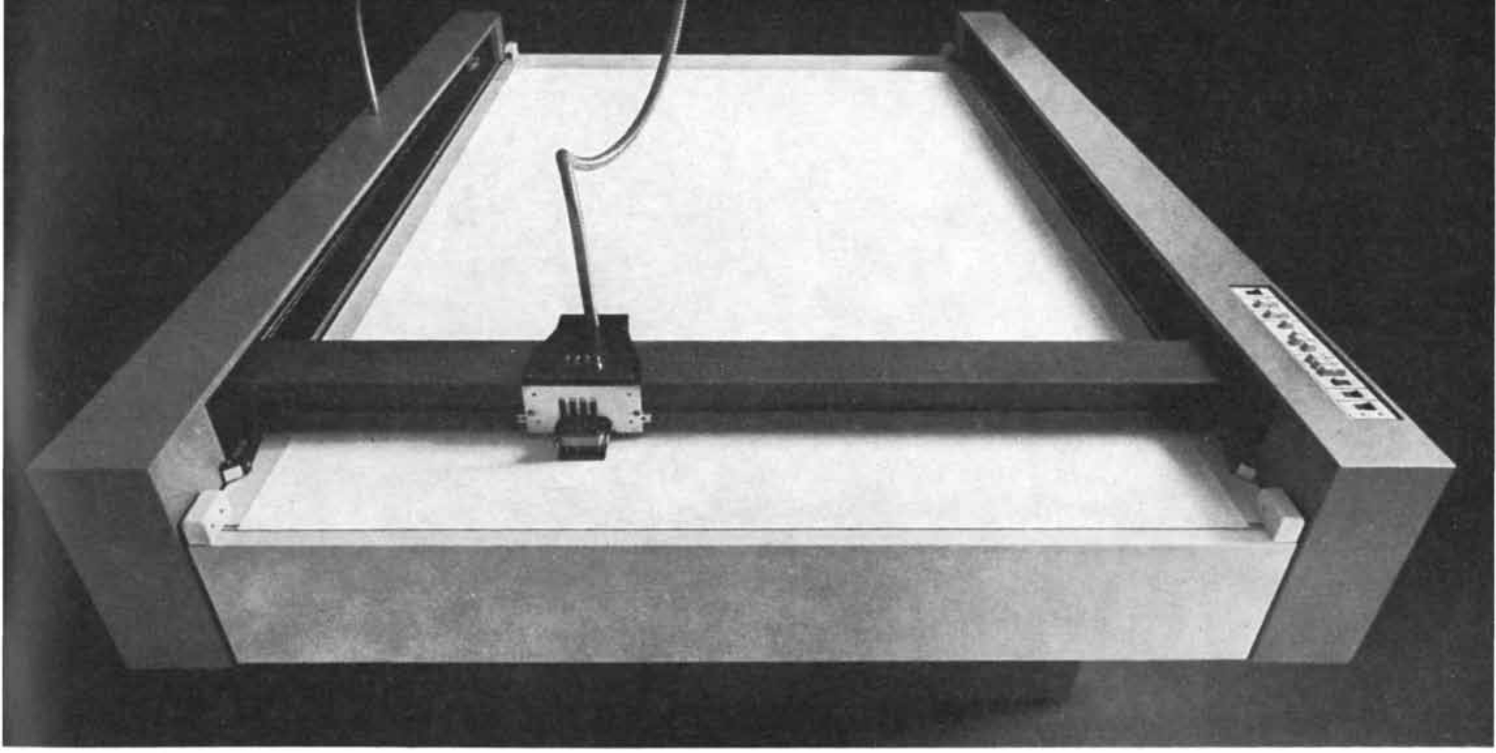
The pen you see here in our vermeil (solid sterling silver subtly electroplated with 22K gold) is the Parker 75. Much about it is exceptional. Instead of a fixed point, we gave the pen a 14K gold point that can be turned 360° until it meets the paper precisely, at whatever angle is most comfortable. We even sculpted the finger area to a tapered trefoil to provide a firm grip. The pen is guaranteed, of course. If it fails to perform due to defects, we will repair or replace it—free. At $50, the Parker 75 in vermeil is a gift fit for an emperor.

PARKER

World's most wanted pens

The Parker 75 Pen in vermeil is $50. Soft tip version, $45. Matching ball pen or pencil, $25. You'll find the distinctive arrow clip trademark on every Parker, from the famous $1.98 Jotter Ball Pen to the $150 Parker 75 Presidential Pen.

© 1973 SCIENTIFIC AMERICAN, INC



The four-fingered fast-drawing kid is coming to town.

We call it the 748. It's big. And it's fast.

Its 4 inking pens move at speeds over 40 inches a second. That's faster than ink flows, so we had to figure out a pressure inking system that lets the ink catch up to the pens.

If you make integrated circuits or maps. Or if you have precision drafting needs, this is the new tool.

The 748's plotting area is 48″x82″. It can scribe coated materials and cut strippable film. At peak speeds!

The quality of its line is not impaired by its incredible speed. And like all CalComp flatbed plotters, the new 748 offers easy-to-use software for most computers.

We service it in 29 countries. But the way we've made it, you won't be calling us very often.

Do call us to see it. Our number is (714) 821-2011. Or write California Computer Products, Inc., SA-12-73, 2411 West La Palma Avenue, Anaheim, California 92801.

CALCOMP

© 1973 SCIENTIFIC AMERICAN, INC

Efficiency expert.

What makes the new 3-liter BMW so remarkable is how well it does *everything.*

Its heart is an overhead camshaft engine employing triple-hemispherical swirl-action combustion chambers. So efficiently and so cleanly does it produce power from the fuel mixture that Road & Track says, "It is without a doubt the most sophisticated inline six in the world."

Suspension is fully independent, with spring struts forward, trailing arms aft. The rear axle is multi-jointed, to provide maximum road-grip on virtually any surface. The resulting cornering capacity is simply phenomenal.

Put these characteristics of engine performance and roadability together, and it's not surprising that BMW owners will tell you no other car comes close for combining brilliant responsiveness with precise control. It handles like nothing else.

Then consider how BMW rates in such factors as comfort, durability, finish, quality of construction, and economy of operation. Look at its safety features, including crush zones both in front of and behind the extremely rigid passenger compartment.

That's when you begin to see that for sheer refinement of every aspect of automotive engineering, BMW is something very special indeed. It's a car that isn't just outstanding in some areas, but in *all* areas.

Visit your BMW dealer. Tell him you want to test-drive the car that not only does all the things a great car ought to do, but does them far more efficiently.

BMW automobiles are available in four or six-cylinder models.
Sole U.S. Importer: **Hoffman Motors Corporation.**
375 Park Avenue, New York, N.Y. 10022;
12541 Beatrice Street, Los Angeles, Calif. 90066.
Dealers Coast to Coast.
Advantageous European Delivery Program.
Write for free brochure.

Canada: East: BMW Distributors Eastern Canada, Ltd. Ontario.
West BMW Distributors (Western) Co.
British Columbia

Bavarian Motor Works

BMW

© 1973 SCIENTIFIC AMERICAN, INC

Established 1845 **SCIENTIFIC AMERICAN** December 1973 Volume 229 Number 6

ARTICLES

DEPARTMENTS

BOARD OF EDITORS Gerard Piel (Publisher), Dennis Flanagan (Editor), Francis Bello (Associate Editor), Philip Morrison (Book Editor), Trudy E. Bell, Brian P. Hayes, Jonathan B. Piel, David Popoff, John Purcell, James T. Rogers, Armand Schwab, Jr., C. L. Stong, Joseph Wisnovsky

ART DEPARTMENT Samuel L. Howard (Art Director), Ilil Arbel, Edward Bell

PRODUCTION DEPARTMENT Richard Sasso (Production Manager), Leo J. Petruzzi and Carol Eisler (Assistant Production Managers), Pauline Ray Lipsher

COPY DEPARTMENT Sally Porter Jenks (Copy Chief), Dorothy Patterson, Candace E. Trunzo, Julio E. Xavier

GENERAL MANAGER Donald H. Miller, Jr.

ADVERTISING DIRECTOR Harry T. Morris

ASSISTANTS TO THE PUBLISHER George S. Conn, Stephen M. Fischer

CIRCULATION MANAGER William H. Yokel

PUBLISHED MONTHLY BY SCIENTIFIC AMERICAN, INC., 415 MADISON AVENUE, NEW YORK, N Y 10017 COPYRIGHT © 1973 BY SCIENTIFIC AMERICAN, INC. ALL RIGHTS RESERVED. PRINTED IN THE U.S.A. NO PART OF THIS ISSUE MAY BE REPRODUCED BY ANY MECHANICAL, PHOTOGRAPHIC OR ELECTRONIC PROCESS, OR IN THE FORM OF A PHONOGRAPHIC RECORDING, NOR MAY IT BE STORED IN A RETRIEVAL SYSTEM, TRANSMITTED OR OTHERWISE COPIED FOR PUBLIC OR PRIVATE USE WITHOUT WRITTEN PERMISSION OF THE PUBLISHER. SECOND-CLASS POSTAGE PAID AT NEW YORK, N.Y., AND AT ADDITIONAL MAILING OFFICES. AUTHORIZED AS SECOND-CLASS MAIL BY THE POST OFFICE DEPARTMENT, OTTAWA, CANADA, AND FOR PAYMENT OF POSTAGE IN CASH. SUBSCRIPTION RATE: $10 PER YEAR, U.S., POSSESSIONS AND CANADA; $12.50 PER YEAR, ALL OTHER COUNTRIES.

© 1973 SCIENTIFIC AMERICAN, INC

MONT BLANC

Brings out the hidden best in a man's handwriting

The Magnificent Diplomat 149 . . . $49

and the new Classic 146 . . . $44

No other fountain pen is "built" like the magnificent MONTBLANC Diplomat! Man-size to fill a man's grip, take a man's handling. Extra-large 18-karat gold point assures super-smooth writing action and gives a man a new "personality on paper." Giant ink capacity is a man-pleasing feature too!

Many pen experts here and abroad consider the Diplomat to be the finest pen ever designed. It's Europe's most prized pen, unmatched in writing ease. Nib sizes extra fine to triple broad – to suit every hand.

The NEW Classic 146 is an identical but slightly smaller version of the Diplomat 149. A great variety of other luxury fountain pens within the MONTBLANC assortment.

Imported by Koh-I-Noor Rapidograph, Inc., 202 North St., Bloomsbury, N. J. 08804. Beautifully gift boxed.

At fine stores, college stores, stationers and pen shops everywhere, including **Abercrombie & Fitch,** *N.Y.C., Chicago & San Francisco;* **Alfred Dunhill,** *N.Y.C., Beverly Hills, Chicago & San Francisco;* **Bloomingdale's, Goldsmith Bros.,** *N.Y.C.;* **Siegel's Stationery,** *Summit, N.J.;* **Golden Gate Pen Co., Haverhill's, J. D. Browne,** *San Francisco;* **Fahrney's,** *Wash., D.C.;* **Marshall Field, Mc-Lennon's,** *Chicago;* **A. Pomerantz,** *Phila.;* **Bromfield Pen Center,** *Boston;* **The Fountain Pen Shop, The Pen Shop,** *L. A.* **Sam Flax,** *N.Y.C. and Atlanta.*

THE COVER

The painting on the cover is an imaginative representation of a new kind of field investigation: the study of the soaring flight of birds by an observer who accompanies the birds in a high-performance glider (see "The Soaring Flight of Vultures," page 102). Seen in the gaps between the primary feathers of a soaring bird's wing (*foreground*) are a stretch of escarpment in Tanzania (*bottom*), a Schleicher ASK-14 powered glider with its engine turned off and its propeller feathered in a horizontal position, banking to remain in the area of "slope lift" provided by the movement of air over the escarpment, and a Rüppell's griffon, one of the commoner vultures of East Africa.

THE ILLUSTRATIONS

Cover painting by Peter Parnall

Page	Source
17–23	Dan Todd
25–26	F. W. Goro
27–33	Bunji Tagawa
34–35	Seymour Benzer
36	Bungi Tagawa
37	Seymour Benzer
38	Fritz Zwicky, California Institute of Technology
40–41	Allen Beechel
42	Halton C. Arp, Hale Observatories (*top*); Allen Beechel (*bottom*)
44–45	Allen Beechel
46	Hale Observatories (*top*); Sidney van den Bergh, David Dunlap Observatory (*bottom*)
47	Allen Beechel
48	Fritz Zwicky, California Institute of Technology (*top*); Halton C. Arp, Hale Observatories (*bottom*)

Page	Source
58	Paul W. Richards
60–67	Lorelle M. Raboni
69–85	Ilil Arbel
86	Harvard College Library
88	Charles Eames, courtesy of University of Uppsala Library
89	Gabor Kiss
90–100	Vatican Library
101	Gabor Kiss
103	H. F. Lamprey
104–108	Eric Mose
111	The Granger Collection
112–120	Graphic Presentation Services, Inc.
123	Bill Williams
124–127	Roger Hayward

© 1973 SCIENTIFIC AMERICAN, INC

Waste Watcher Israel Proler— he collects steel cans by the millions

Israel Proler is one of America's new breed of waste watchers. The Chairman of Texas-based Proler International Corp., he is concerned about America's environmental shape. And he is doing something about it by reclaiming everything from junked autos to used tin cans.

Hundreds of millions of tin cans are magnetically reclaimed each year from municipal garbage and then processed in Proler plants. Along with thousands of tons of scrap from canmaking lines, the used cans are then shipped to Arizona and New Mexico. There they are used as "precipitation iron" in a chemical process that recovers copper from low-grade ore.

Israel Proler is on the prowl for used steel cans which can be economically handled by his plants. The nation's copper mines can use an estimated 10-billion annually.

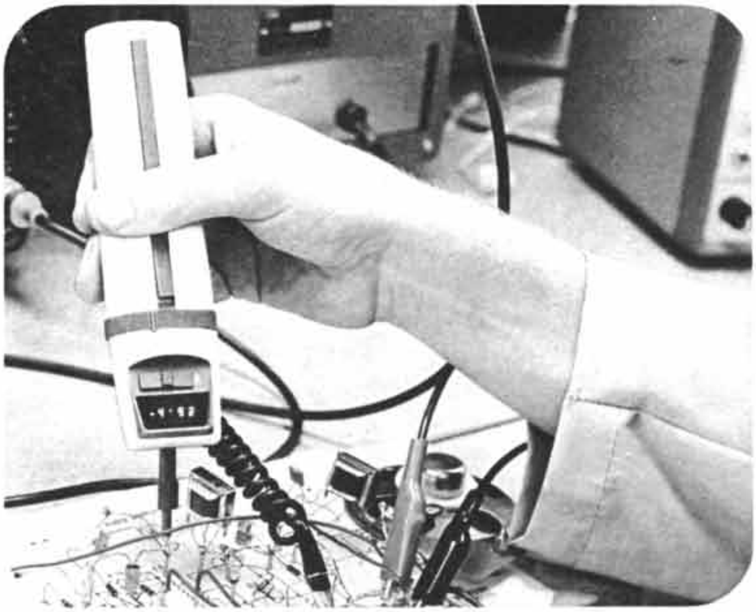
Reclaimed steel cans also are recycled by the steel industry, detinning plants and ferroalloy producers.

Mr. Proler and other waste watchers are reclaiming 3 billion steel cans in 20 cities by magnetic separation—the leading resource recovery system. Steel's unique magnetic property makes it possible.

If you would like to know more about "waste watching," write to: Tinplate Producers, American Iron and Steel Institute, 150 East 42nd Street, New York, New York 10017.

Tinplate Producers
American Iron
and Steel Institute

© 1973 SCIENTIFIC AMERICAN, INC



A small tool with a big impact on field service

To designers and technology buffs, the fascinating aspect of the new HP 970A Digital Multimeter is how we managed to squeeze a complete $3\frac{1}{2}$-digit autoranging DMM into a package that fits the palm of your hand. (The secret, briefly, is a unique thin-film IC that incorporates the equivalent of 3,000 transistors, and combines digital and analog circuitry, on the same hybrid substrate.)

To service technicians and engineers, those harried souls who keep electronic wizardry in good repair, the important news is how the 970A radically improves the measurement of volts and ohms. The battery-powered DMM goes wherever the work is to perform fast and accurate troubleshooting in hard-to-get-at places, and it does this so simply and easily that it's tough to make a measurement error.

To managers responsible for field service, and the customers they serve, the key benefit is the time that can be saved. Since half the cost of field service is labor, and the 970A speeds and simplifies a laborious task, its true value is often realized on invoices for service calls.

Whether a technician is toiling over a dishwasher, a television set, telephone switchgear or the most advanced computer, the 970A works the same way: he selects the desired function, attaches a clip lead to circuit common and touches the test point with the probe tip. A touch of the thumb on the DMM's bar switch,

© 1973 SCIENTIFIC AMERICAN, INC

and the measurement appears on the digital display. That's all. The rest is automatic. There's no need to select the proper knob, look for the right scale, figure out where the decimal point goes, or decide what the polarity is: the 970A does it all automatically.

Reading time is faster because the display is always in the line-of-sight, right next to the test point. Even if the 970A must be held upside down to reach a test point, the display can be electronically inverted so there's no chance of reading 6's for 9's.

Price is $275* including three interchangeable probe tips, built-in battery pack good for 2,000 measurements on a single overnight charge, charger, belt case, travel case and sun hood.

New portable spectrum analyzer "fingerprints" low-frequency signals

As its esoteric name implies, a spectrum analyzer is an instrument which separates and measures the individual frequencies that make up a complex electrical signal.

This ability to take apart and examine a waveform by spectrum analysis — to display, at one time, the frequencies and amplitudes of its individual spectral components — has been traditionally limited to the higher frequencies.

Now there's a low-cost way to do the same thing in the low-frequency range — the spectral deep where lurk such phenomena as mechanical vibrations, underwater sounds, communications signals and power line-related electrical interference. The new HP 3580A Spectrum Analyzer can look at a low-frequency event such as the signals produced by a jet engine or power plant generator and provide a signature analysis, or "fingerprint", containing important clues to how well it's working. The potential of using the 3580A for preventive maintenance — to help predict a failure before it occurs — exists in the instrument's use of digital storage.

Because necessarily slow sweeps of the frequency of interest are repetitively refreshed from the 3580A's digital memory, the CRT display is sharp and flickerless. This also allows a user to store a spectrum indefinitely, recall it whenever convenient, and even superimpose it on a new spectrum for comparison to see if there have been any tell-tale changes in the fingerprint.

Total analysis time is reduced by a factor of 10 or so through a technique called adaptive sweep. Akin to a "volume control" this sets a variable baseline high enough to exclude all noise and low-level signals that do not interest him and still obtain a full-resolution scan.

Fundamentally a precision instrument, the 3580A has a minimum bandwidth of 1 Hz (rather than the usual 10 Hz) over its entire range of 5 Hz to 50 kHz. It is thus capable of detecting spurious responses which can't be seen in the time domain or with older instruments.

The 3580A can be operated on line power or on internal rechargeable batteries. It weighs only 35 pounds and costs $3800*, plus $255* for the optional battery pack.

For more information on all of the above write to us. Hewlett-Packard, 1503 Page Mill Road, Palo Alto, Calif. 94304

*US Domestic Prices Only. 00402

Mail to: Hewlett-Packard, 1503 Page Mill Road, Palo Alto, CA 94304

Please send me information on:
☐ 970A Digital Multimeter ☐ 3580A Spectrum Analyzer

Name________ Title________

Company________

Address________

City________ State________ Zip________

HEWLETT hp PACKARD

Sales and service from 172 offices in 65 countries.

Palo Alto California 94304

© 1973 SCIENTIFIC AMERICAN, INC

LETTERS

Sirs:

Like others before him, Alexander Leaf ["Getting Old," SCIENTIFIC AMERICAN, September] apparently accepted uncritically assertions regarding the number of centenarians in the Caucasus without insisting on documentary or other comparable corroboration. In this region, moreover, documents themselves may be inaccurate, for it was a widespread practice in Czarist times to give newborn males the names of their elders, concealing their identities in order to mislead the authorities seeking youths for compulsory military service. Dr. Belle Boone Beard, who has interviewed centenarians in many parts of the world, did not find a disproportionate number of subjects for her research in the U.S.S.R., that is, people whose documents or other evidence met the requirements of her protocol.

THEODOR SCHUCHAT

Washington

Sirs:

Mr. Schuchat has of course raised an important point. He is quite right in pointing out, as I did, that we do not have birth records for very many of the old people we saw in the Caucasus or in Hunza. In the latter country the situation looked so impossible that I made no claim for the ages of the elderly people I saw there. I agree that the lack of written records considerably reduces credibility. Moreover, to accept the stated ages would be naïve. On the other hand, to exclude the possibility that such old people do exist in a different culture and environment than ours would in my view be too skeptical. One therefore does the best one can by interrogating the individuals at length.

This can be done in several ways, and we generally combined as many as we could with each individual. Thus age at marriage, the date when children were born and the age of the children was frequently helpful, since the age of the next generation was more frequently documented. The number of living generations also helped us, as did memories of historical events. Supporting information from relatives and neighbors was solicited. All of these were gone into very thoroughly to arrive at the best estimate we could of the age of the individual.

I think it is justifiable to retain a high degree of skepticism regarding the ages claimed for the very elderly. Such skepticism is supported by calculations that can be made from actuarial tables, from which one can estimate that only one person in 2.1 billion has the probability of attaining a life-span of 115. The probability of exceeding this figure would of course diminish rapidly. Such calculations, however, are made from life tables based on experience in advanced industrialized countries where adequate records have been kept. If there are communities with some unique factors or combination of factors that would favor longevity, then it no longer is valid to base the expectation of encountering centenarians in such a community on the experience gathered from the more advanced countries. The yardstick for one population may not be applied to the other. This constitutes a potential limitation on the application of actuarial tables derived from one population to a different population. The assumption that such a transfer can be made excludes the very possibility of there being a community somewhere on the earth where people live, under unusual circumstances, to ages beyond those observed in the advanced industrialized countries where the tables were developed.

Although such tables cannot be used to exclude the possibility of unusual longevity in other settings, neither do they help us to establish such longevity. Where written records are not available, one does one's best by careful interrogation of the individual, his relatives and neighbors. The result gives one a figure that in many instances may be off by some five to 10 years, but in the instances I have cited I believe this is the limit of the possible error.

Mr. Schuchat raises the possibility that ages of males were falsified upward in order to avoid military conscription; since the duration of military service was 20 years, the motivation for such falsification might be great. We were aware of this problem. It is of interest, however, that the figures obtained in the census reveal that in Soviet Georgia there were twice as many women over the age of 100 as there were men. Thus if the ages of males have been falsified upward, there must have been a comparable falsification in the ages of the elderly females.

ALEXANDER LEAF, M.D.

Jackson Professor of Clinical Medicine
Harvard Medical School

Chief of Medical Services
Massachusetts General Hospital
Boston

Sirs:

Philip Morrison's review of *Mars and the Mind of Man* [SCIENTIFIC AMERICAN, October] stimulated me into ordering a copy. However, I protest his description of Tarzan as "inarticulate." Tarzan is portrayed as such in the movies, but the film Tarzan has little relation to the Tarzan in the novels by Burroughs. Lord Greystoke was a highly intelligent person. He spoke the language of the australopithecoids who raised him. He taught himself to read English without having heard a word of it through use of some illustrated children's primers and the books in his dead parents' cabin. When he reached civilization, he quickly learned to speak and read English and French and later mastered a score or so of languages.

PHILIP JOSÉ FARMER

Peoria, Ill.

Scientific American, December, 1973; Vol. 229, No. 6. Published monthly by Scientific American, Inc., 415 Madison Avenue, New York, N.Y. 10017; Gerard Piel, president; Dennis Flanagan, vice-president; Donald H. Miller, Jr., vice-president and secretary; George S. Conn, treasurer; Arlene Wright, assistant treasurer.

Editorial correspondence should be addressed to The Editors, SCIENTIFIC AMERICAN, 415 Madison Avenue, New York, N.Y. 10017. Manuscripts are submitted at the author's risk and will not be returned unless accompanied by postage.

Advertising correspondence should be addressed to Harry T. Morris, Advertising Director, SCIENTIFIC AMERICAN, 415 Madison Avenue, New York, N.Y. 10017.

Offprint correspondence and orders should be addressed to W. H. Freeman and Company, 660 Market Street, San Francisco, Calif. 94104. For each offprint ordered please enclose 25 cents.

Change of address (or other subscription correspondence) should be addressed to Circulation Manager, SCIENTIFIC AMERICAN, 415 Madison Avenue, New York, N.Y. 10017. Please notify us four weeks in advance of change. If possible, kindly furnish an address imprint from a recent issue. Send both old and new addresses or complete and mail Post Office Form 3578.

☐ Please enter change of address.

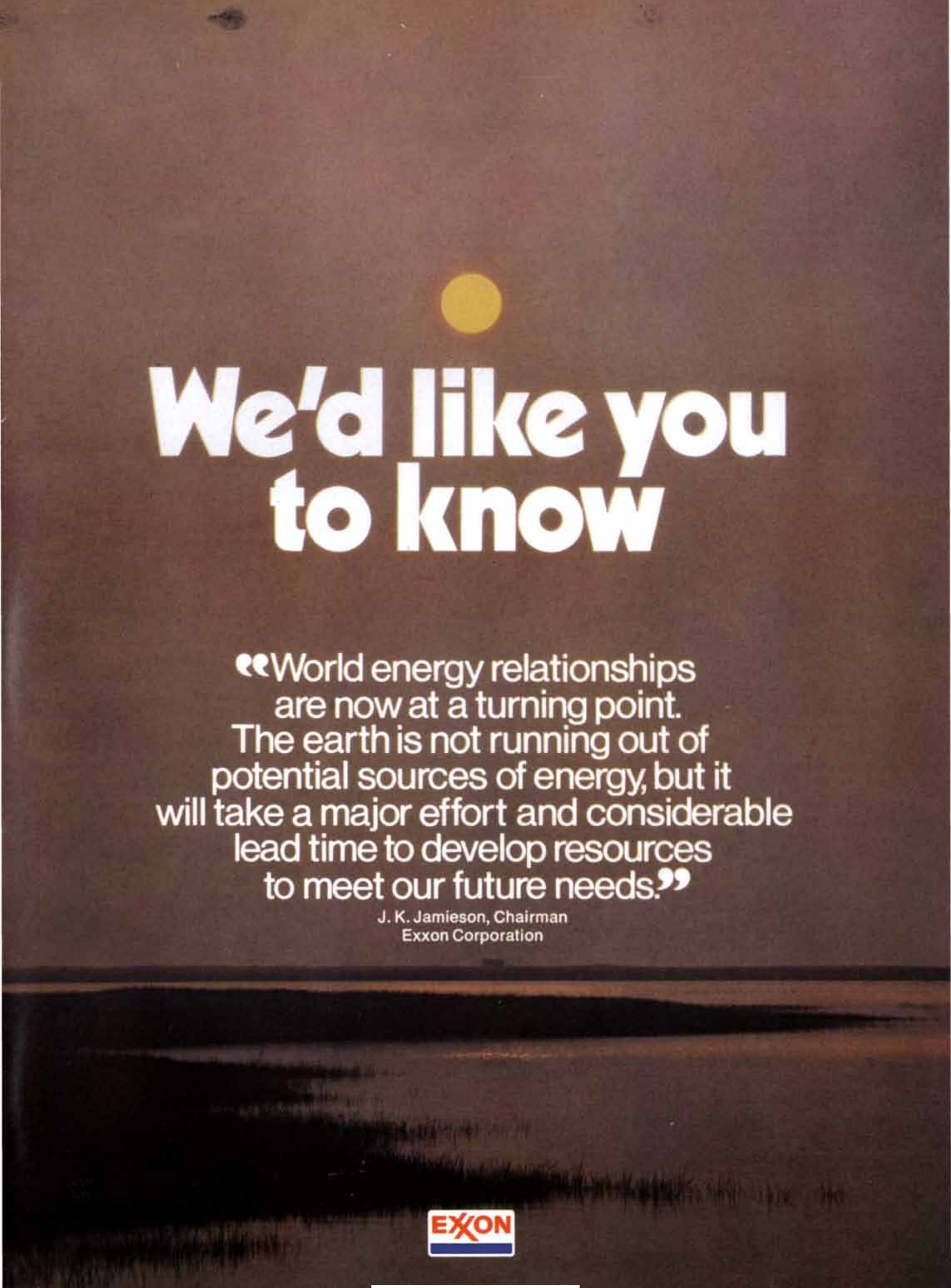
☐ Please enter subscription.
U.S. and Canada:
☐ 1 year, $10 ☐ 2 years, $18 ☐ 3 years, $25
All other countries:
☐ 1 year, $12.50 ☐ 2 years, $23 ☐ 3 years, $32

NAME

NEW ADDRESS

OLD ADDRESS

© 1973 SCIENTIFIC AMERICAN, INC



© 1973 SCIENTIFIC AMERICAN, INC

This Exxon refinery at Baytown, Texas is being expanded to boost production of gasoline and other products by 13 million gallons a day. Smaller expansion programs will take place at several of Exxon's other refineries in the United States and abroad.

Almost every American is aware that our country is facing a serious energy problem. But the fact is, the problem is not ours alone—it involves the entire world.

It is not easy to explain in brief how the situation came about. Complex factors are involved—ranging from increasing consumption to disappointing discoveries to environmental considerations to world political relationships. And solutions are not around the corner.

One thing is sure. The earth is not running out of potential sources of energy. But it will take a major effort and considerable lead time to develop resources to meet future needs.

On the following pages we review the energy situation, and tell what Exxon is doing both short-term and long-term to meet the needs of its customers.

We need all the energy we can get.

Looking first at the current supply-demand situation in the United States, it is clear that this country needs all the energy it can get from all available sources.

Exxon has responded to the immediate need by producing domestic crude oil at maximum efficient capacity. We have increased imports of crude oil and petroleum products, and have kept our refineries running at an all-out pace.

Exxon has a major refinery expansion program under way that will increase Exxon's U.S. capacity by almost 15 million gallons a day, or about 30 percent. A small part of the increase will be available soon, and the full amount by 1976.

Every day the average man, woman and child in the U.S. uses nearly four gallons of oil, 300 cubic feet of natural gas, 15 pounds of coal and smaller amounts of other energy. This is substantially more than the average of other industrial countries and eight times as much as the world average.

Until new domestic refining capacity is brought on stream, substantial volumes of imported petroleum products will be required to meet the needs of U.S. consumers. Even with the refinery expansions that Exxon and others have so far announced, it is not certain that the rapidly increasing demand anticipated for the next few years can be satisfied.

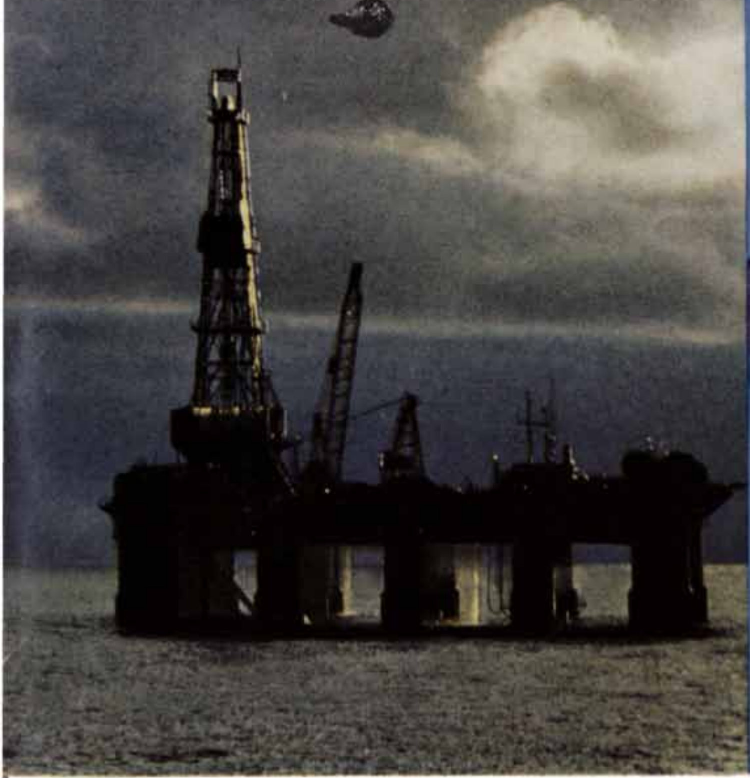
Raising U.S. refinery capacity to adequate levels on a basis that satisfies environmental requirements will not in itself end U.S. energy supply problems. Worldwide, crude oil supplies will be tight in relation to the high demand now forecast.

Demand rising 7% a year.

Oil and gas now account for about 65 percent of total world energy consumption, and their relative position is still increasing. Supplies of other fuels have not grown as fast as energy demand, and oil has been called upon to make up the difference. As a result, world petroleum demand, now rising at an annual rate of about 7 percent, could double by 1985.

EXXON

© 1973 SCIENTIFIC AMERICAN, INC



Exxon is looking for oil on land and off the coasts of more than 40 countries around the world. This platform is located in the North Sea where frequent storms bring 75-mile-an-hour winds and 65-foot waves.

On Alaska's North Slope the temperature may plummet to minus 60° in the winter. Industry production from the Slope is expected to total about 2 million barrels (84 million gallons) of oil a day.

The United States will remain the largest oil-consuming country during this period, and will become increasingly dependent on imported oil. Discoveries in the U.S. have not kept up with consumption for some time, and production is now actually declining.

An enormous goal.

Present and future demand for oil is massive. To meet the expected growth, the industry would have to add about 4 million barrels a day of producing capacity each year. To produce this much oil, the industry would have to find about 20 billion barrels a year—the equivalent of two fields the size of Alaska's Prudhoe Bay. By 1980, the required amount could be 30 billion barrels a year.

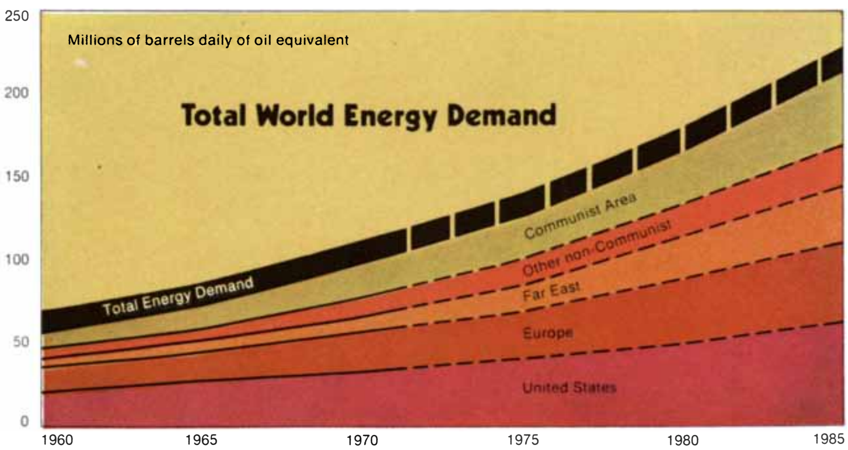
The physical and financial challenge of finding and producing this much new oil each year is enormous.

At the present time, about two-thirds of the world's known oil reserves are in the Middle East and North Africa. About half of total reserves are in the countries bordering the Persian—or Arabian—Gulf.

Despite the fact that significant recent discoveries have been made in the North Sea and other areas, they are small in relation to demand. Therefore the world will necessarily be dependent on the Middle East for an increasing share of its oil supplies for some years to come. Raising Middle East production at an adequate rate will require an all-out effort.

Even Middle East supplies are not limitless, and Middle East governments can be expected to watch closely the rate at which their resources are depleted. Furthermore, continued expansion in the Middle East could be affected by the concern of some Middle Eastern countries over their ability to invest additional income gained from increased oil production.

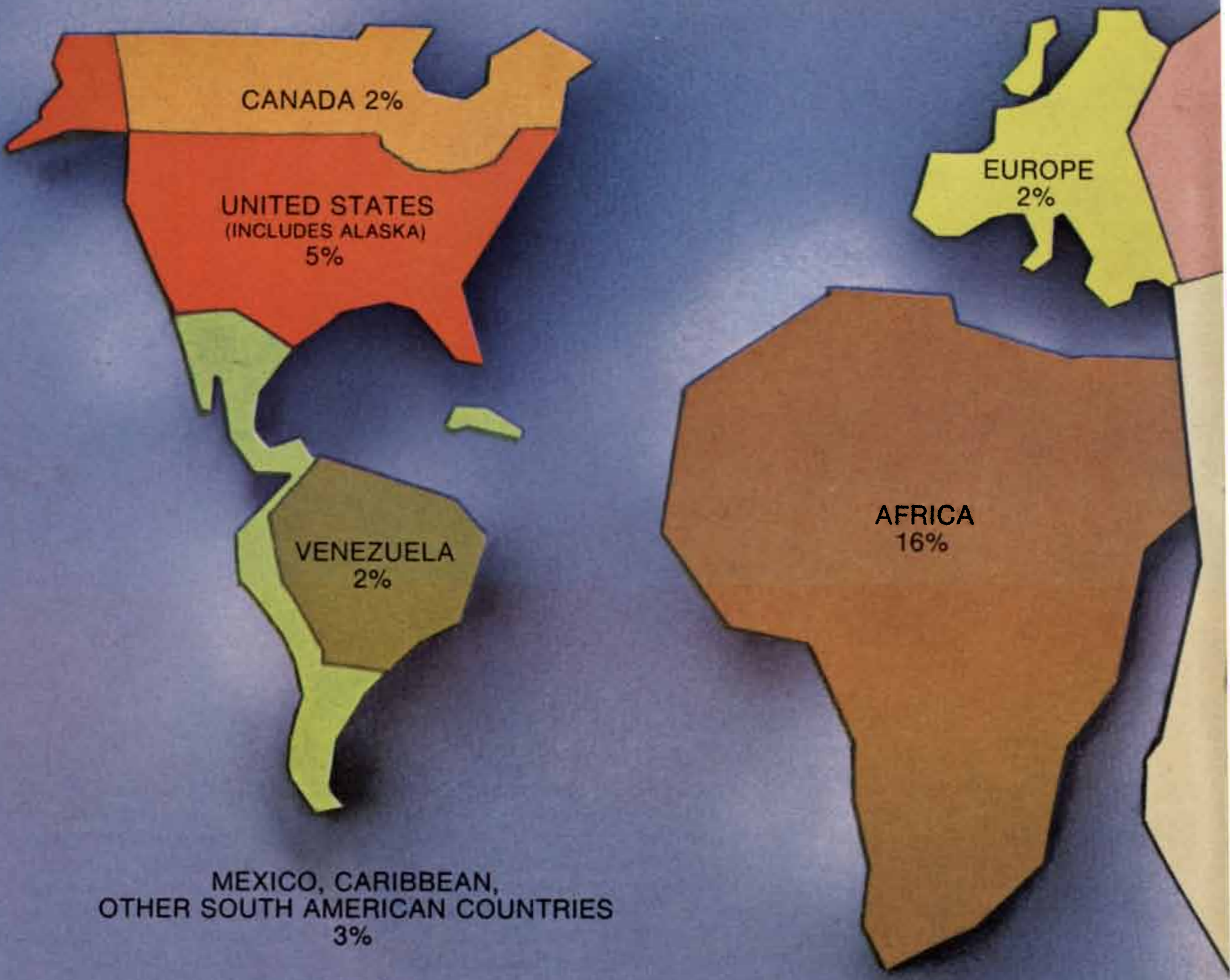
It is important then to continue our efforts to find oil in all parts of the world. Although the industry



Demand has been growing steadily. Assuming no significant limitations in available supply, the outlook is for sustained growth, almost doubling world consumption by 1985.

EXXON

© 1973 SCIENTIFIC AMERICAN, INC

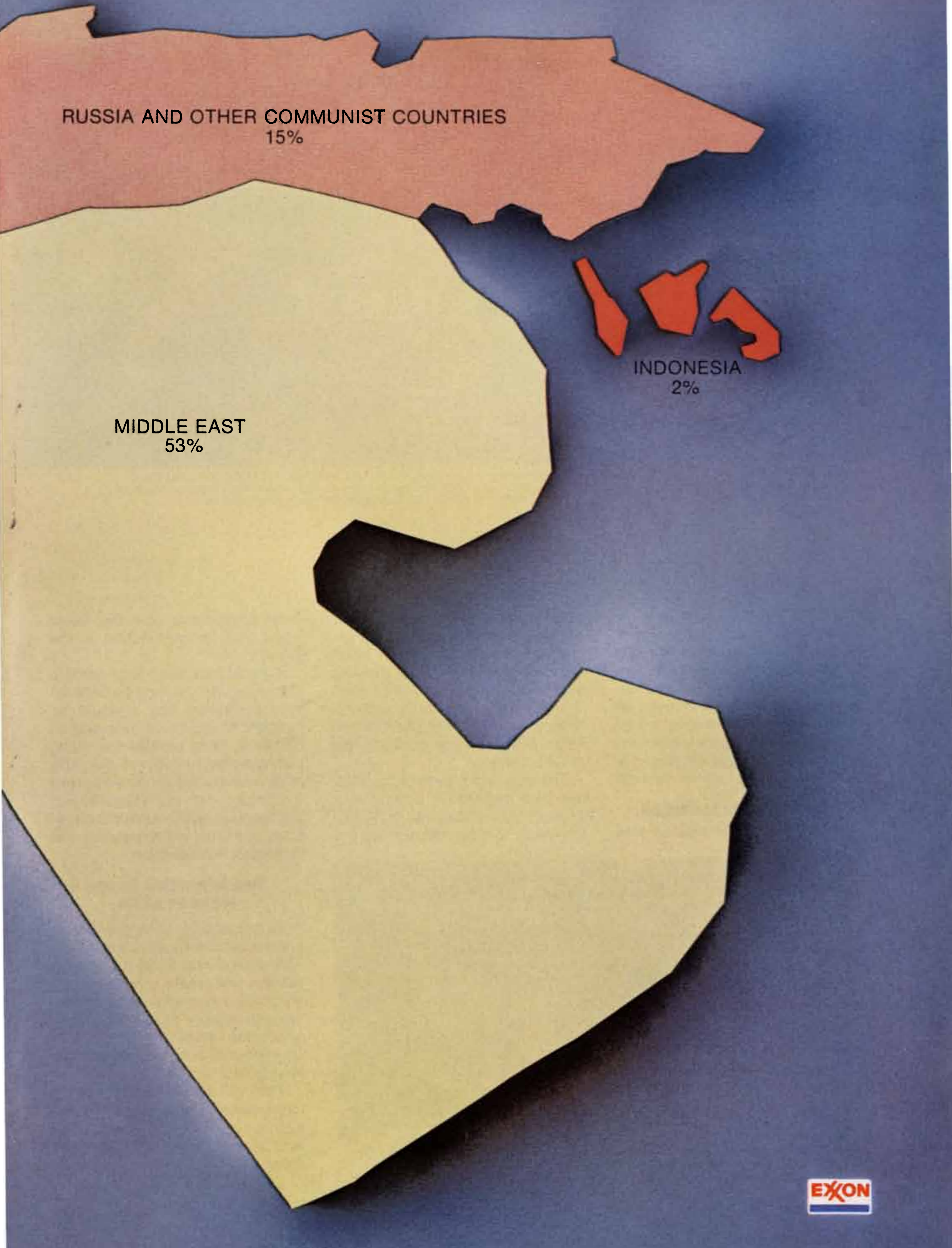


The world of known oil reserves.

Percentages are shares of the world's known, extractable oil reserves in each area.

SOURCE: *Oil & Gas Journal*—December 25, 1972

© 1973 SCIENTIFIC AMERICAN, INC



© 1973 SCIENTIFIC AMERICAN, INC

Extending beyond U.S. shores is an enormous undersea ledge called the continental shelf. This land mass is rich in oil and natural gas deposits. Some geologists estimate there may be nearly as much oil under this shelf as has ever been found onshore in the history of the U.S. To date there has been active exploration and production only off the coasts of Louisiana, Texas and California.

may find itself with a modest surplus from time to time, consumers will probably have to live with the fact that surges in demand, delays in planned oil-producing capacity, unexpected restrictions by governments of producing countries, or any other major supply disruption could lead to shortages in the U.S. and other world markets.

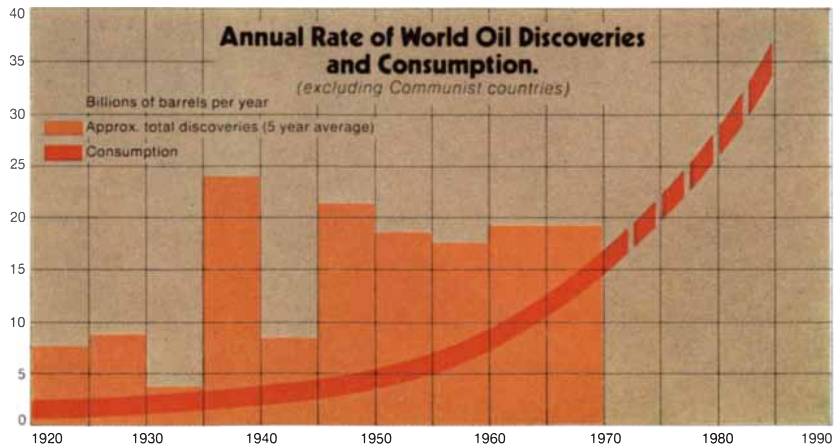
Why it's harder to find oil.

The effort to find new oil has been accelerating in recent years, but it's not as easy as it used to be. Our industry has to search in increasingly difficult environments such as the Arctic and North Sea.

Despite the industry's best efforts, oil findings (See chart below) have held at a fairly constant rate in recent years.

The very large fields of the Middle East represent discoveries whose size is unmatched in the history of oil. It is hard to foresee any other prospective area that could make such a contribution in the future.

It would thus seem imprudent to plan the world's energy supplies on the assumption that it would be possible to accelerate discoveries of crude oil to parallel the rising consumption. Even if demand growth is moderated—as we believe it must be—we need to face the fact that the world's conventional oil resources will not indefinitely support increases in production.



Oil discoveries until now have exceeded consumption. Most experts agree that future discoveries are unlikely to keep pace with consumption.

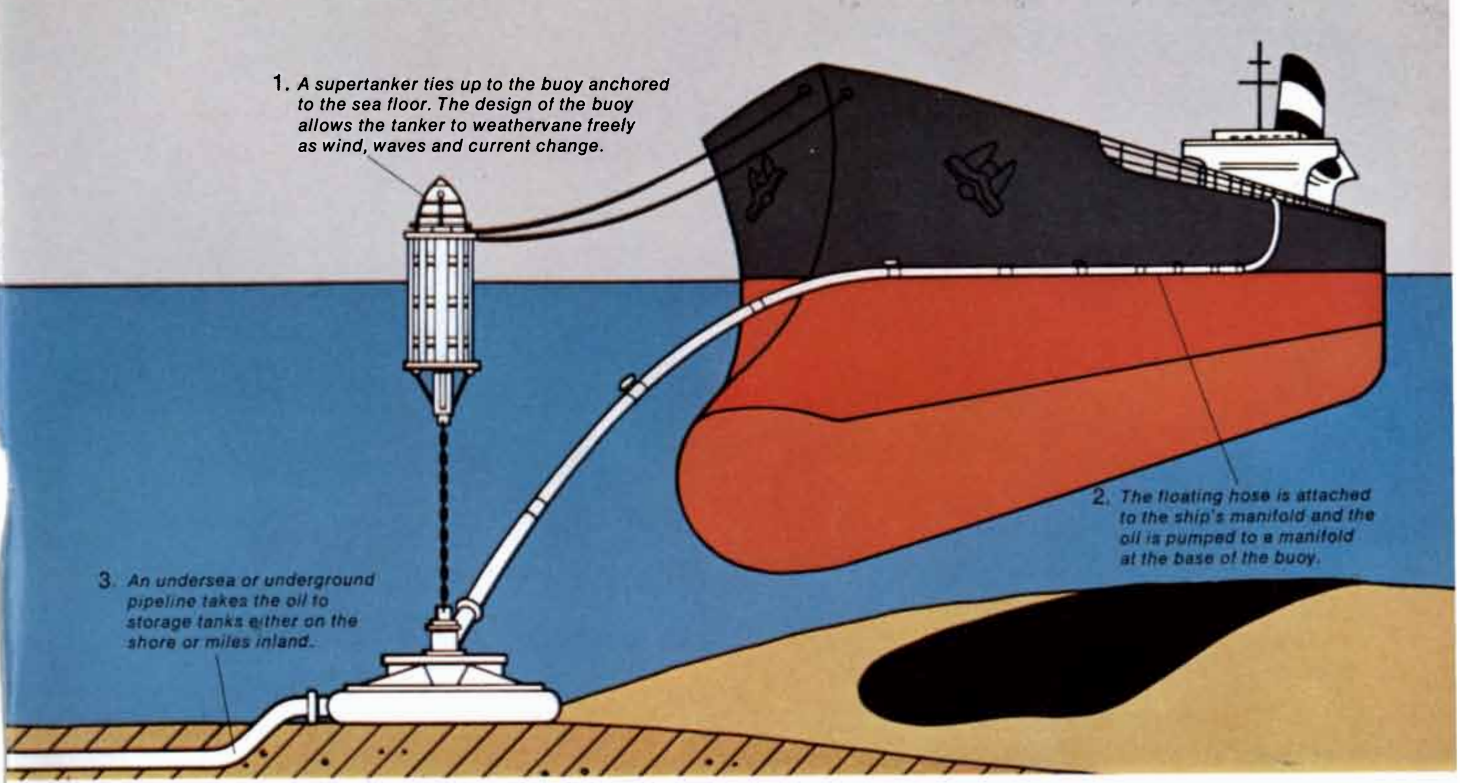
Two important things we must all do.

To prepare for such a situation, and for an orderly transition into a new energy era, every consuming nation must create a political and economic environment that will encourage energy conservation and speed the development of other conventional and nonconventional energy sources.

The U.S. has wider choices than many other nations because of the scale of our basic energy resources. We have such options as these:

EXXON

© 1973 SCIENTIFIC AMERICAN, INC



A deepwater terminal allows supertankers to load or unload miles from shore. There are over 100 deepwater terminals around the world. They permit countries that have no deepwater ports to take advantage of the economies of supertankers. Because the U.S. has no deepwater ports, this system is being proposed for sections of the East and Gulf Coasts.

■ Use more coal, both directly and as a source of synthetic oil and gas. America has perhaps a third of the world's coal supply.

■ Speed the pace of nuclear power plant construction. Increase research on more advanced nuclear technology and the direct recovery of solar energy.

■ Implement government programs to advance the commercial development of shale oil. Large deposits exist, but there are long-term technological and environmental problems to be solved.

■ Reduce gasoline consumption through the use of lighter, more efficient automobiles; car pools; better vehicle operation and maintenance; and auto emission controls and other devices designed with fuel economy in mind.

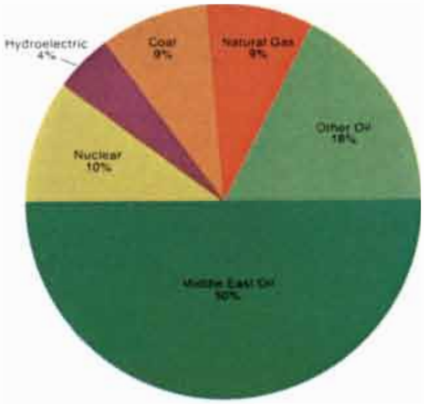
■ Improve rail and bus systems for short to moderate length interurban transportation, to provide a better balance with auto and air travel.

■ Rewrite residential and commercial building standards to save energy used for heating, air conditioning and lighting.

■ Develop new ways to generate power more efficiently, controlling air pollution and energy consumption at the same time.

■ Resolve conflicts between environmental goals and energy resource development through appropriate government processes.

There is no time to waste if the United States and other major energy-consuming countries are to adjust to the changed situation that lies ahead. Government leadership will be essential in setting goals and policies. In the United States a start on an energy program has been made.



Where the increase in the non-Communist world's energy supply might come from between now and 1976

These figures reflect economic, safety and environmental restrictions on the production and use of coal; reserve and transportation limitations on natural gas; and continued delays in nuclear power development.

In this context, the President has directed the council on Environmental Quality to prepare within one year environmental impact statements for exploration and development in the Atlantic and Gulf of Alaska outer continental shelf areas. This is a useful step even though significant production cannot be obtained from these areas in this decade.

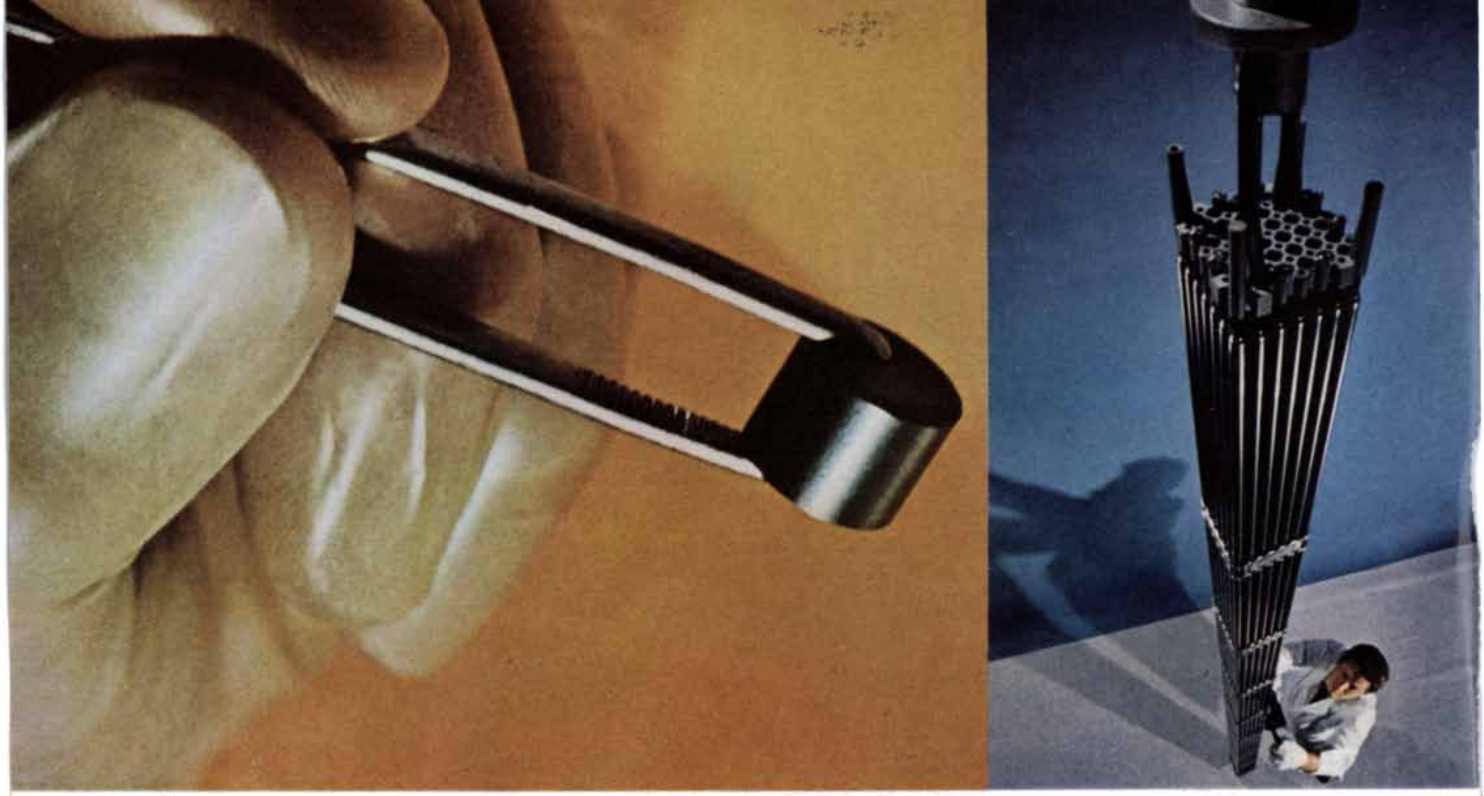
This country also needs deepwater terminals to handle—with greater safety and efficiency than existing facilities—increasing amounts of imported crude and heavy fuel oil.

It may be necessary for both American industry and citizens to alter some of the ways they work and live.

In our desire to achieve rapid economic growth and higher standards of living, we Americans have been prodigal with resources that

EXXON

© 1973 SCIENTIFIC AMERICAN, INC



Pellets of enriched uranium (left) and fuel assemblies (right) are made by Exxon Nuclear Company. The pellets are inserted into rods, and the rods are grouped to form assemblies which make up the core or "furnace" of a nuclear reactor. An assembly, like the one shown, can generate enough electricity to run 16,000 average homes a year.

once seemed limitless. Recent developments have made us all more conscious that energy resources, as well as air, water and usable space, are finite.

With new attitudes on these matters, it should be possible to achieve coordinated goals and a balanced, more satisfying way of life—without having to choose between running out of fuel or running out of clean air and water.

What Exxon is doing today for tomorrow.

We have already pointed out what Exxon is doing to increase its output of gasoline and other products for the next several years. Our efforts are also directed at developing alternate forms of energy and synthetic energy sources for the future. To highlight a few of those efforts:

■ Exxon is exploring for uranium in the U.S. and abroad. From our mine in Wyoming, we are extracting 2800 tons of uranium ore a day.

Exxon Nuclear Company is a major supplier of uranium and plutonium fission reactor fuels. We are providing finished fuel and services to ten nuclear plants in the U.S. and to three in Europe.

■ To date we have invested over $20 million in research aimed at converting coal into synthetic fuels. One process turns coal into a gas which can be upgraded to a fuel comparable to natural gas. Work at our pilot plant indicates that this process may be less complex and less expensive than other gasification processes being developed.

Another Exxon process turns coal into low-sulfur fuel oil or synthetic crude oil. This may be applicable to low- and high-sulfur coal.

It will take several years and over $150 million in development costs before either Exxon process is available for commercial use.

■ Exxon is also developing processes that would allow utility companies to use the high-sulfur coal that our country has in abundance. When high-sulfur coal is burned today, it produces sulfur oxides which can pollute our air.

One process, being developed for the U.S. Government, would reduce the formation of sulfur oxides as the coal is burned. The other process, being developed with a major power plant builder and several electric utilities, would remove most sulfur oxides from the flue gas—after combustion but before the gas escapes from the stack.

Again, both processes look promising, and one of them—flue gas desulfurization—is ready to be demonstrated commercially.

These are some of the things Exxon is doing to help expand our nation's energy supplies. We will continue to work on new energy technology and look for more efficient systems for the use of energy.

And we will be cooperating fully with the government and the public in this country, and in all the countries in which we do business, to help build a better economic and human environment.

EXXON

We'd like you to know.

If you would like more information, write: Energy, Exxon Corporation, 1251 Avenue of the Americas, New York, N.Y. 10020

© 1973 SCIENTIFIC AMERICAN, INC

50 AND 100 YEARS AGO

SCIENTIFIC AMERICAN

DECEMBER, 1923: "What are the spiral nebulae? Have we any idea of their real nature? The remarkable work of Sir James Jeans, one of the most distinguished of English mathematicians, offers a theory that, though not proved, commands the sympathy and indeed the belief of the most competent authorities. The abstract problem he was discussing was the old and intricate one of the behavior of a mass of rotating fluid. For slow rotation the cross section becomes an ellipse. If the rotation grows more rapid, a homogeneous mass will become more and more flattened at the poles. Finally the equatorial edge, at first rounded, becomes quite sharp. The outer edges in this critical state will be very sensitive, and the outcome is that the outflow of matter, thrown off by the rapid rotation, will take place at two opposite points on the equator, the 'high-tide regions.' The resemblance of the resulting picture to that actually presented by the spiral nebulae is striking to a degree. Almost every form predicted by the theory, from the globular mass, through the sharp-edged one, to the nucleus surrounded by innumerable condensations, can be found repeatedly on nebular photographs."

"Dr. J. R. Miner has presented the results of an extensive statistical analysis of the relation of suicide to climatic and racial factors and to industrialism, occupation, urban conditions, age and sex. The general trend of suicide rates has been upward during the past century, but the higher rates tend to become stabilized. Germany, France, Denmark and Sweden have high rates, Britain, Norway and the Netherlands low rates. Foreigners in New York show a higher suicide rate than in the countries from which they came. In the United States the rates are lowest in the south and highest in the west."

"Radio-acoustic marine direction-finding is a means of locating the position of a ship at sea by the emission of a radio 'dash' simultaneously with the firing of a small charge in the sea. A station on shore records the arrival of the radio signal, and also of the explosion wave at a number of hydrophones suitably disposed in known positions on the sea bed. The time of travel of the explosion wave, and hence the distance from the charge to each hydrophone, are indicated by a photographic recorder. It is possible to give a ship her location within a radius of half a mile, inside 10 minutes from receiving her request for a position. A nine-ounce charge can be located at a distance of 40 miles."

"Consider the bumper. It toils not, nor helps the motor to spin, yet every car owner knows that it is often a valuable thing to have upon his machine. When the companies issuing automobile collision insurance proposed to credit a reduction in the premium where approved bumpers are used, the task of testing such attachments seemed to be an easy matter. In actual practice, however, a number of difficulties developed. Instead of propelling a car against a stationary object, a blow is supplied by a massive pendulum. Pulled back from the perpendicular to a distance of 21 feet and released, it rudely swats the bumper with a force estimated to equal the impact of a 4,000-pound car traveling at a speed of four miles per hour. Under this test many bumpers have come through smiling. When the weight has been swung over a 30-foot arc, however, not one bumper has survived. This swing corresponds to the impact of a 4,000-pound car going eight miles per hour."

SCIENTIFIC AMERICAN

DECEMBER, 1873: "Scattered here and there through the sky are thousands of little luminous clouds. These are the nebulae, which to the modern astronomer are objects of great and increasing interest. The total number at present known is not quite 8,000. What are they? The elder Herschel, who was the first to make a careful study of the subject, concluded that many of them at least are masses of a peculiar cloud-like substance, mainly gaseous—the material out of which worlds are formed—and thought that in these objects we have instances of stars a-making. But when some 30 years ago it appeared that every increase of telescopic power resolved more and more of them into stars, certain astronomers jumped to the conclusion that all the nebulae are merely clusters of stars, the component stars themselves being as large as the other suns that constitute our stellar system, and separated from one another by intervals as vast, but so remote from us that even such suns and such abysses are confounded into these little whiffs of haziness. Fascinating as it is, this view of the matter is demonstrably incorrect, and Herschel's original doctrine is much nearer to the truth."

"We but reflect the sentiments of the whole country in expressing our deep regret at the news of the death of Professor Louis Agassiz. He died in his 66th year. The loss of the man who, above all others, has been universally considered the representative and exponent of American scientific progress, and to the grandeur and vastness of whose mastery over thought and knowledge the world did homage, will indeed be irreparable."

"The traffic in coal tar is a comparatively new industry, and its growth has been very rapid. From being considered but the worthless refuse resulting from the manufacture of gas, and of no commercial value whatever, it has within a few years attained an importance of no common order. The most remarkable product obtained from coal tar is the new article called anthracene, from which is produced the coloring matter known as alizarine, the identical substance that for 200 years has been found solely in madder. This article constitutes the base of all the madder colors—Turkey red, black, pink and purple."

"Science, with her intentions and processes, has extended her sway even to the worthless dust heaps, and from the filthy waste brings out the shining gold. The local authorities of London sell the privilege of removing dust and garbage from each district to a contractor, who carts it away to a large yard in the suburbs. There hill women, sieve in hand, separate the mass into component portions. The most valuable are the waste pieces of coal, and the breeze, or coal dust and half-burnt ashes. The amount of waste of the latter may be measured by the fact, that, after selling the larger pieces to the poor, the refuse breeze is sufficient to bake the bricks that are rebuilding London. The other constituents of the dust heap are separated by the sifters with the utmost rapidity: bones, rags, paper, old iron, glass and broken crockery."

© 1973 SCIENTIFIC AMERICAN, INC

An acoustic achievement destined to become the universally preferred sound reproduction system.

Too often these days superlatives are used to camouflage mediocrity. Let's just say you'll be excited with the magnitude of the achievement of the three new Pioneer series R speaker systems. We built in the sound most people prefer when compared with the conventional speakers now available.

Sound is a personal thing. Each individual sets up an arbitrary standard of his own. Prove it yourself. Take your favorite record or tape to a Pioneer dealer. Ask him to play it for you using one of the Pioneer series R speaker systems. In fact, listen to them all. Your Pioneer dealer will welcome your interest. For the first time you'll hear nuances in the sound that you never heard before. The bass notes will be impressively rich and robust rather than thumping like Godzilla's footsteps. The highs will sound crisp and clear instead of piercingly shrill.

Better still, play the same recording, alternating the series R sound with other brands of speaker systems. Here's where you'll really hear the difference. Precisely balanced sound that offers sharply defined separations of lows, midrange and highs, with an absolute minimum of distortion. That's why we say the new series R is destined to become the universally preferred sound reproduction system.

Pioneer has incorporated many meaningful refinements in the R series to achieve this exceptional sound reproduction. We'd be happy to send you complete specifications. But first make this test. Compare the R700 ($229.95), R500 ($159.95), R300 ($119.95) with similarly priced speaker systems at your Pioneer dealer. It's their absolute superiority in sound reproduction that will convince you to buy them.

U.S. Pioneer Electronics Corp., 178 Commerce Road, Carlstadt, N.J. 07072

PIONEER
when you want something better

Series R Speaker Systems

t: 13300 S. Estrella, L.A. 90248 / Midwest: 1500 Greenleaf, Elk Grove Village, Ill. 60007 / Canada: S. H. Parker Co., Ont.

© 1973 SCIENTIFIC AMERICAN, INC

THE AUTHORS

RICHARD F. POST and STEPHEN F. POST ("Flywheels") are father and son. Richard Post holds a joint appointment from the Lawrence Livermore Laboratory and the University of California at Davis, being research group leader at the laboratory and professor in residence at the university. He is a physicist whose professional work is in nuclear fusion; his interest in flywheels, he writes, "was stimulated by a joint interest with Steve in the electric car and in energy storage." Richard Post was graduated from Pomona College in 1940, taught there for two years, worked at the Naval Research Laboratory during World War II and then did his graduate work at Stanford University, where he received his Ph.D. in 1950. Stephen Post writes that he "spent four years as a physics-math major at Whitman College, where I still have an important interest (a fiancé), and currently I am working toward a degree in mechanical engineering at California State University at San Luis Obispo."

SEYMOUR BENZER ("Genetic Dissection of Behavior") is professor of biology at the California Institute of Technology. He was originally trained in physics at Purdue University, where he was a member of a group that worked out the properties of germanium semiconductors and solid-state devices during World War II. Captivated by reading Erwin Schrödinger's book *What Is Life?*, he turned to bacterial viruses, working at Cal Tech, the Pasteur Institute, the University of Cambridge and Purdue. He says he is "fond of movies, music and my vivacious wife, Dorothy."

ALAR TOOMRE and JURI TOOMRE ("Violent Tides between Galaxies") are brothers who were born in Estonia and came to the U.S. as boys with their parents. Alar Toomre is professor of applied mathematics at the Massachusetts Institute of Technology; Juri Toomre is associate professor of astro-geophysics at the University of Colorado at Boulder and a member of the Joint Institute for Laboratory Astrophysics. The brothers did their undergraduate work at M.I.T. and received their Ph.D.'s in England at the University of Manchester and the University of Cambridge respectively. Alar Toomre writes that he likes to "travel and read history, play tennis and bridge and chess and help to raise three

The new Wang System 2200. What you see is what you get. You get a lot for under $7,000.*

Big 16 Lines (of 64 Characters) CRT Display: It's hard to crowd this tube. You'll get ample space for monitoring programs, and results. Remaining storage is automatically displayed as the last line on every program. It tells you where you've been, where you are and how far you can go. You can go a long way on the Wang System 2200.

BASIC Programming With Hard Wired R/O Memory: You get 4K (field expandable to 32K) of fully accessible memory. And BASIC programming; the easiest to work with language yet developed.

Programming Doesn't Byte Off Much Storage: In the Wang 2200, program statements are a single keystroke and single byte. Example: The statement PRINT USING takes only one byte of memory; not ten! This almost doubles capacity compared to the usual system. Plug in the new Wang 2200 and you're in business. If your data handling has been constantly delayed or reshuffled by crowded, expensive time-sharing . . . here's a cost/efficient alternative.

If you are thinking of time-sharing to meet growing needs: here's a way to beat high terminal cost and programming time. If you run a smaller engineering or technical/scientific group: the Wang 2200 may be all the computing power you will ever need.

Drives Wide Range of Peripherals: Our new 2200 gives you more ways to solve problems. We have 15 (more soon) peripheral devices like flat bed plotters, additional mag tape cassette drives, a typewriter that makes graphs, a 4.9 mega-byte high speed disc, matrix ROMs and more.

A Low Cost Alternative To Time-Sharing: Since the 2200 can tackle big problems many users are installing them to replace more expensive time-sharing terminals. And, they are eliminating the waiting, scheduling and priority problems of time-sharing. They're getting more done at lower cost.

Faster Problem Solving: "Basic" programming on the 2200 is almost literal. You get to the heart of problems and examine alternatives faster. And, the Wang *special function* feature gives you 32 additional keys that allow you to "tailor" the system to facts, figures and constants that are particular to your business or your company . . . or your department.

For under $7,000, Try To Match The Wang 2200 For Price/Performance and Flexibility. Even if you call the 2200 a small system, you've got to admit it's a big idea.

*U.S. List Price: 4K CPU & CRT with mag tape drive and choice of data entry keyboards.

For More Information

☐ Please send me full details on the Wang System 2200.

☐ Please have your representative call me at (phone):____________

Name____________

Title____________

Company____________

Street____________

City____________

State____________ Zip____________

SA-12

WANG

Laboratories, Inc.

836 North St., Tewksbury, Ma. 01876

Telephone (617) 851-4111

© 1973 SCIENTIFIC AMERICAN, INC

Minolta helps you celebrate the morning.

You can find the wonder in a new day with a camera that doesn't hold you back, a camera fast enough to catch the fleeting moment.

From the moment you pick it up, you're comfortable with a Minolta SR-T. This is the 35mm reflex camera that lets you concentrate on mood and insight. The viewfinder gives you all the information needed for correct exposure and focusing. Because you never have to look away from the finder to adjust a Minolta SR-T, you're ready to catch the one photograph that could never be taken again.

And when subjects call for a different perspective, Minolta SR-T cameras accept a complete system of interchangeable lenses, from "fish-eye" wide angle to super-telephoto.

Next time you're up with the dawn, be ready with a Minolta SR-T. For more information, see your photo dealer or write Minolta Corporation, 200 Park Avenue South, New York, N.Y. 10003. In Canada: Anglophoto Ltd., P.Q.

Minolta SR-T 101/Minolta SR-T 102

When identified by a factory-sealed "M" tag, Minolta 35mm reflex cameras are warranted by Minolta Corp. against defects in workmanship and materials for two years from date of purchase, excluding user-inflicted damage. The camera will be serviced at no charge provided it is returned within the warranty period, postpaid, securely packaged, including $2.00 for mailing, handling and insurance.

children." Juri Toomre writes that his work centers on the "astro" part of his title and that the "geo" part "concerns predicting the structure of the ocean's thermocline." He adds: "I have enjoyed sailing, soaring and the opera; now in Boulder there are the pleasures of living in a high mountain house, hiking and cross-country skiing with the family and a fondness for cooking and Afghan hounds."

PAUL W. RICHARDS ("The Tropical Rain Forest") is professor of botany at University College of North Wales. He was educated at the University of Cambridge, where he obtained his bachelor's degree in 1930, his master's in 1934, his Ph.D. in 1936 and his Sc.D. in 1954. Before going to University College of North Wales in 1949 he was for seven years a university demonstrator in botany at Cambridge and for four years a university lecturer in botany there. He has worked in a number of tropical countries. In addition he is concerned with conservation and was for some years chairman of the Nature Conservancy's Committee for Wales.

M. S. FELD and V. S. LETOKHOV ("Laser Spectroscopy") are respectively associate professor of physics at the Massachusetts Institute of Technology and vice-director of the Institute of Spectroscopy of the Academy of Sciences of the U.S.S.R. They began their collaboration through an interacademy exchange between the U.S. and the U.S.S.R. Feld was graduated from M.I.T., where he received his bachelor's degree in the humanities and science and his master's degree in physics in 1963 and his Ph.D. in physics in 1967. Besides teaching at M.I.T. he is active in advancing the institute's efforts in equal employment opportunity and in technical training of the disadvantaged. He writes that in Newton, Mass., where he lives, he works toward the construction of housing for families of low and moderate income and that he and his nine-year-old twin sons "are very much into karate." Letokhov, who heads the laser spectroscopy laboratory at his institute, was graduated from the Moscow Physico-Technical Institute in 1963. He writes that for his work in laser physics he received his Ph.D. in 1969 and his Sc.D. and the title of professor of physics in 1970.

OWEN GINGERICH ("Copernicus and Tycho") is an astrophysicist at the Smithsonian Astrophysical Observatory and also serves as professor in both the department of astronomy and the de-

© 1973 SCIENTIFIC AMERICAN, INC

SCIENCE/SCOPE

A polyurethane foam retainer to lubricate ball bearings for spacecraft was described by Hughes engineers at a recent symposium. The circular ring device serves as a lubricant reservoir as well as a retainer and separator for the bearing balls. The tough polyurethane material is chemically inert to hydrocarbons, stores 60 times more oil than the commercially produced cotton phenolic now widely used for bearing retainers, and shows virtually no wear after a year's operation. The new retainer may have applications in the aircraft, automobile, and machinery equipment industries

Only the information an aircraft pilot requires at the moment is presented on the cockpit TV screen of a computer-controlled electronic map display developed by Hughes in a company-funded project. It stores data digitally, eliminating printed and microfilmed graphics. The map shows aircraft position and course and is updated every two seconds. It can be oriented "north up" or "heading up". The pilot has a choice of five scales, from one to 40 nautical miles to the inch. The EMD's magnetic tape unit can store up to 15 million bits of data (enough to cover the continental U.S.). A civilian version has been delivered to the FAA for testing; a military version has been developed for Air Force and Navy flight test programs.

Greater flight dependability for America's burgeoning air traffic is the goal of a 27-month project by Hughes engineers to develop specifications and a handbook for the Federal Aviation Administration's National Airspace System (NAS). Handbook will detail how the FAA can identify, handle, and strengthen any weak links in the system or equipment elements. The project is aimed at existing as well as future air traffic control systems, whose operations are expected to more than double in volume in the next 10 years.

High-speed functional testing and troubleshooting of printed circuit boards is the function of a new computer-controlled digital logic test system developed by Hughes. The Hughes 1024 is a diagnostic system with advanced disk software and dynamic response measurement at programmable rates to 10 MHz. Its software-controlled probe rapidly isolates manufacturing failures. The solid-state system provides up to 1024 bi-directional input/output lines and is expandable to three independently operated test stations using a common minicomputer.

Hughes needs a Senior Communications Project Engineer to take charge of a communication satellite subsystem. Technical responsibilities: direction of circuit design, packaging, testing. Administrative responsibilities: project direction and coordination of fabrication and assembly, date of requirements, contractual matters. Requirements: 5-15 years experience in project engineering hardware development, U.S. citizenship. Please send resume to: Mr. D.D. Rossier, Hughes Aircraft Company, P.O. Box 92919, Los Angeles, CA 90009. An equal opportunity M/F employer.

A twin radome-covered antenna test range to measure radiation patterns of communication satellite antennas during development and manufacturing is now in operation on the roof of the 12-story Hughes Space & Communications Group building in El Segundo, Calif. The 30-foot-diameter radomes enable space engineers to test antennas on a daily basis despite high winds or adverse weather. The new test facility includes a penthouse laboratory housing data-recording electronics and remote control equipment.

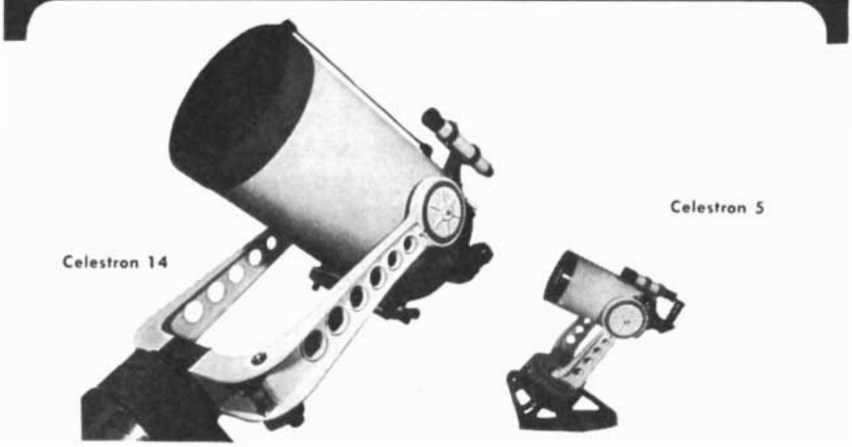
Creating a new world with electronics

HUGHES

HUGHES AIRCRAFT COMPANY

© 1973 SCIENTIFIC AMERICAN, INC

Celestron® Multipurpose TELESCOPES



Large observatory telescopes optically folded into compact portables. Razor-sharp Schmidt-Cassegrain optics. Apertures sufficiently large to make higher powers really worth using in telescopes light enough to pack away on vacation. *Plus* sharper images over a wider flat field than any other commercially available telescope.

Celestron 5. A table-top observatory, bannister telescope or telephoto lens to observe or photograph Moon, planets and nebulae, or the veined wings of a bee at 12 feet. (Useful powers: 25-300X, Wt.: 12 lbs., Base Price: $625)

Celestron 8. A portable observatory in a suitcase for amateur astronomers to observe or record planetary features, compact star clusters, filamentary details of nebulae. (50-500X, 23 lbs., $895)

Celestron 14. The world's largest one-man-portable telescope. High-transmission optics reveal delicate contrast levels of planetary markings, nebulae and spiral galaxies. (50-850X, 108 lbs., $3,600)

Free color catalog available on request.

Celestron Pacific **2430 Amsler Box 3578 A Torrance, Calif. 90505**

d→ DEG RAD REC POL
arc log sin ln cos a^x tan e^x

Our new printer is a math brain at heart.

The new Canola F-10P from Canon is the only scientific-engineering calculator that offers you printout capability. This 12-digit, one-memory model computes in totally algebraic logic and is equipped with all trig, log, conversion and exponential functions.

So that equations as complex as

$$\sqrt{2\cdot\sqrt[3]{\log_{10} 5.3216}+\sqrt[3]{\log_e 1.4265}}$$

are solved simply and in seconds, like this:

2 [x] 5.3216 [log] [∛] [+] 1.4265 [ln] [∛] [=] [√] 1.582965893

For all its sophistication, the F-10P retains the comfortable, responsive and well-spaced keyboard that Canon has become famous for.

For details on the Canola F-10P, just send us this coupon.

Canon® ELECTRONIC CALCULATORS Canon USA, Inc., Electronic Calculator Division, 10 Nevada Drive, Lake Success, New York 11040.

Name________ Title________

Company________ Street________

City________ State________ ZIP________

partment of the history of science at Harvard University. He was graduated from Goshen College in 1951, receiving his master's degree at Harvard in 1953 and his Ph.D. there in 1962. Except for the period from 1955 to 1958, when he was director of the American University Observatory in Beirut and assistant professor of astronomy at the American University of Beirut, and 1958–1959, when he was lecturer in astronomy at Wellesley College, he has worked at Harvard and the Smithsonian Astrophysical Observatory. He writes that his research interests "range from the recomputation of an ancient Babylonian mathematical table to the interpretation of the solar ultraviolet spectrum."

C. J. PENNYCUICK ("The Soaring Flight of Vultures") is lecturer in zoology at the University of Bristol. "I took my first degree at the University of Oxford in 1955," he writes, "and then served briefly in the Royal Air Force, qualifying as a pilot in 1957. After leaving the R.A.F. I went up to the University of Cambridge, where I took my Ph.D. in 1962. I joined the staff of the University of Bristol in 1964. From 1968 to 1971 I was seconded to the University of Nairobi in Kenya and from 1971 to 1973 to the Serengeti Research Institute in Tanzania. I was introduced to gliding by the University of Cambridge Gliding Club. My other main amusement is bird-watching. I have also kept up my power flying and am the fortunate owner of a 1947 Piper Cruiser, which I flew back to England from Nairobi."

VICTORIA A. FROMKIN ("Slips of the Tongue") is professor of linguistics and chairman of the department of linguistics at the University of California at Los Angeles. She writes: "My first degree was in economics, earned at the University of California at Berkeley many years ago. After one year of graduate work in economics and a few years working in labor research, I retired to raise a family and become a part-time dilettante pianist-painter. Recognizing that this life was not enough, and having become 'turned off' by economics, I was not sure what I wanted to be. Owing to strange and mysterious factors I was persuaded to go into linguistics." She received her master's degree at U.C.L.A. in 1963 and her Ph.D. there in 1965. "I was elected a Fellow of the Acoustical Society of America this year," she writes, "which prompts my husband, who is a neurophysiologist, to refer to me, too often, as 'my wife, who is a fellow.' "

© 1973 SCIENTIFIC AMERICAN, INC

READ THE FUTURE EVERY MONTH.

The future is what FORTUNE Magazine is all about.

Because every business decision is based on your ability to read the future correctly.

So every month, FORTUNE does its probing, relentless, clear-eyed best to help decision-makers see what's around the next corner. And the next after that.

Where's the economy headed? Every six months, FORTUNE forecasts for the next year-and-a-half. What new technologies could affect your business? FORTUNE often gives you the story before the specialized journals, but in non-technical language.

New markets for your products? New trade barriers? New sources of raw materials? New monetary policies? Social and political trends that could affect your decision-making? Good places to invest your personal funds? Corporate practices you could apply to your own business?

FORTUNE is *everything* that can help you make profitable, efficient, responsible decisions. So FORTUNE is the short-range and long-range future.

The attached card will bring you 21 months of FORTUNE for only $14.75. As compared to our regular rate for one year for $12, you get an extra nine months of FORTUNE for just $2.75. We think that's a miniscule price, compared with everything you could gain from this unique magazine.

Will you profit from FORTUNE? Try it and see.

© 1973 SCIENTIFIC AMERICAN, INC

The people we hire are different in a lot of ways. But the same in one.

Ours is a unique company. So the people we want working with us must be unusual, too.

And we don't care about their skin color. Or about their religion. Or what country they or their parents were born in. Or how old they are. Or whether they're men or women.

Our people are expected to handle each project right the first time.

But there's one thing that must be common to them all. Each must be the best there is for the available job, with the desire and drive always to handle each assignment or project right the first time, every time.

Our company is constantly growing. That means we always have need for experienced executives at the upper levels.

For the same reason, we always need people for middle management jobs. We want them to be innovative. And move ahead.

What does it take to work for us —and move ahead?

We have plants or facilities in 93 countries and sales outlets in 39 others. And we're in a wide variety of businesses—from telecommunications and food processing to hotels, community development and publishing.

It's a highly competitive, demanding world we live in. So we insist that our 428,000 employees, worldwide, do the best they can so we can do the best for them.

If you come with us, you'll have a future with far more than ordinary promise.

A future with us holds more than ordinary promise.

But you'll have to be the best there is for the job—and realize that you're consistently going to perform much better than you think you can now.

International Telephone and Telegraph Corporation, 320 Park Avenue, New York, N.Y. 10022.

ITT
SERVING PEOPLE AND NATIONS EVERYWHERE

© 1973 SCIENTIFIC AMERICAN, INC

Established 1845 SCIENTIFIC AMERICAN December 1973 Volume 229 Number 6

Flywheels

Advances in materials and mechanical design make it possible to use giant flywheels for the storage of energy in electric-power systems and smaller ones for the propulsion of automobiles, trucks and buses

by Richard F. Post and Stephen F. Post

In technology, as in women's fashions, old concepts have a way of turning up again, brought up to date and refurbished. The flywheel, which is one of the oldest of human inventions, may be such a concept. Recent developments in materials and mechanical design suggest that the flywheel can help to solve two contemporary problems: the steady increase in the use of energy and the impact of that use on the environment. Specifically, the flywheel offers the prospect of providing (1) an efficient means of storing energy on a large scale to help electric utilities handle peak loads and (2) compact units to power electric vehicles having a range and performance comparable to those of the automobiles, trucks and buses on the roads today.

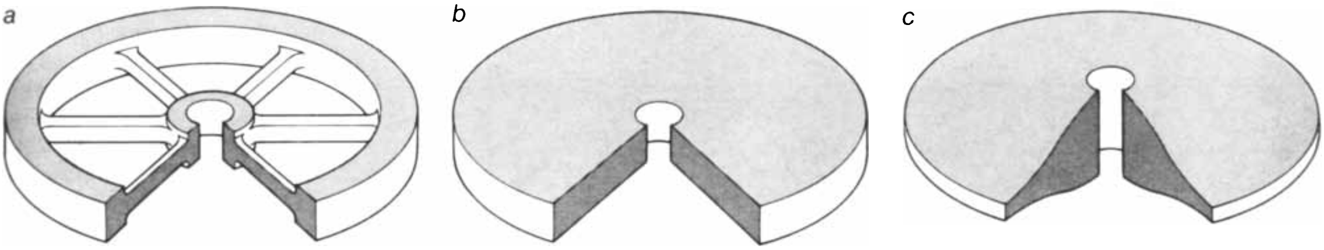
The principle of the flywheel, which must have been recognized very early in human history, is that a spinning wheel stores mechanical energy—energy that can be put in and taken out, as water is stored in and recovered from a reservoir. Flywheel action plays an essential role in the ancient potter's wheel, keeping it spinning between the occasional kicks of the potter's foot. Considering the age of the potter's wheel (which is mentioned in the Old Testament), it is plain that men understood the basic principle of mechanics exemplified by the flywheel long before Newton formalized it in his laws of motion.

The flywheel also played an essential role in the mechanical developments that underlay the Industrial Revolution. The steam engines that powered the factories and mills of those days could not have functioned without the steadying influence of their flywheels. Even today the internal-combustion engines of automobiles, trucks and diesel locomotives rely on energy stored in flywheels to carry the rotation between pulses of energy delivered by the pistons.

Until recently it was thought that employing flywheels to store energy in a wider range of applications was out of the question because of cost and because not enough energy could be stored for a given flywheel weight to satisfy the foreseeable needs. The picture has been radically changed by advances in materials technology [see "Advanced Composite Materials," by Henry R. Clauser; SCIENTIFIC AMERICAN, July]. Most of these advances have resulted from work in aerospace technology.

To see what developments affecting materials have to do with inertial energy storage, which is another name for what a flywheel does, one must consider the factors that govern the action of a flywheel. Imagine a simple flywheel in the form of a circular rim or hoop connected by thin spokes to a hub.

The amount of energy stored in such a flywheel depends on the mass of the rim and on how fast the wheel is spinning; the storage varies as the square of the rotation speed. In principle one could store as much energy as one wishes simply by spinning the wheel faster, but of course it does not work that way. The limit to the amount of energy stored is



FLYWHEEL DESIGNS for flywheels made of conventional materials include a heavy-rim wheel (*a*), an almost solid disk (*b*), which can store more energy, and a disk that is thickened toward center (*c*) to relieve stress concentration and increase storable energy.

© 1973 SCIENTIFIC AMERICAN, INC

ultimately set by the tensile strength of the material from which the rim is made.

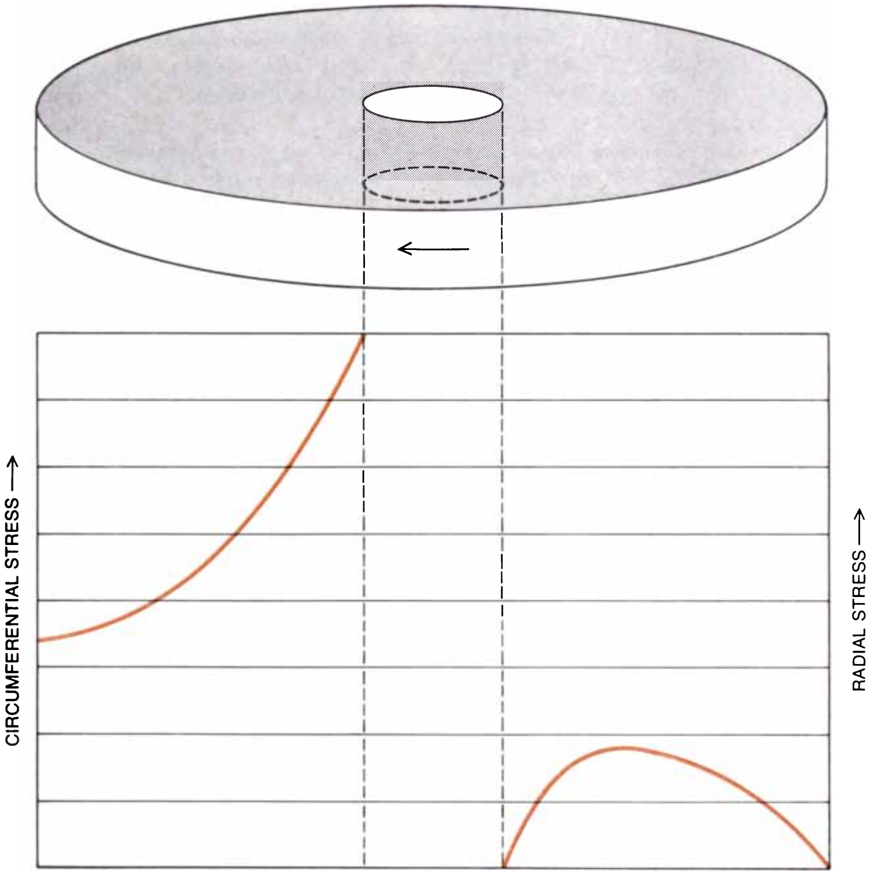
In particular the tensile strength must be sufficient to withstand the "hoop stress" resulting from centrifugal forces, otherwise the wheel would fly apart. As with the energy stored, these forces are proportional to the mass of the rim and increase as the square of its rotation speed. One therefore sees that two properties of the material determine the amount of energy that can be stored in a flywheel: mass density, which provides kinetic energy, and tensile strength, which resists centrifugal forces.

In terms of these properties, what materials are best for storing the most energy for a given weight of material? Contrary to what intuition might suggest, one wants the lightest (lowest density) strong material available.

To understand this surprising fact consider again the simple thin-rim flywheel. Suppose one were to make two such flywheels, identical in dimensions and design but fabricated of two different materials having equal tensile strength but being unequal in density. In other words, one wheel would be made of heavy material and the other of light material.

Now begin to spin up these flywheels, keeping the speeds equal. Under these conditions the heavy flywheel will of course store more energy than the light one, in direct proportion to its greater mass. Note, however, that the tensile stresses from centrifugal forces will also be greater in the heavier rim than in the lighter one, again in direct proportion to the relative mass. As one continues to speed up both wheels, the heavy one will be the first to approach its maximum speed as limited by its tensile strength. In other words, it will be the first to approach the limit of its energy storage.

At the same speed of rotation the lighter flywheel experiences much weaker centrifugal stresses. Therefore it can be speeded up still more before it reaches its limit of tensile strength. When the limit is reached, the light flywheel at its higher speed will be storing the same total amount of mechanical energy as the heavier one at its lower speed. Here, however, is where the advantage of light materials appears. If the light material is, say, 10 times lower in density than the heavy material and both have the same tensile strength, a flywheel made of the light material will require only 10 percent as much mass to store the same amount of energy as the flywheel made of the heavy material. High strength at low density is thus the proper criterion for choosing materials for energy-storing flywheels.



OPERATING STRESSES on a thick-rim flywheel are charted. Circumferential stress is highest at inner hole and radial stress is highest midway between inner and outer edges of disk.

Flywheels have traditionally been made of metal, particularly high-strength steel. Because its density is high, however (eight grams per cubic centimeter), even the strongest alloy steel is not what one wants for making a flywheel capable of storing a large amount of energy for a given weight of flywheel. Per unit of energy stored, steel is too heavy, too expensive and too difficult to fabricate for the demanding applications we envision in this article.

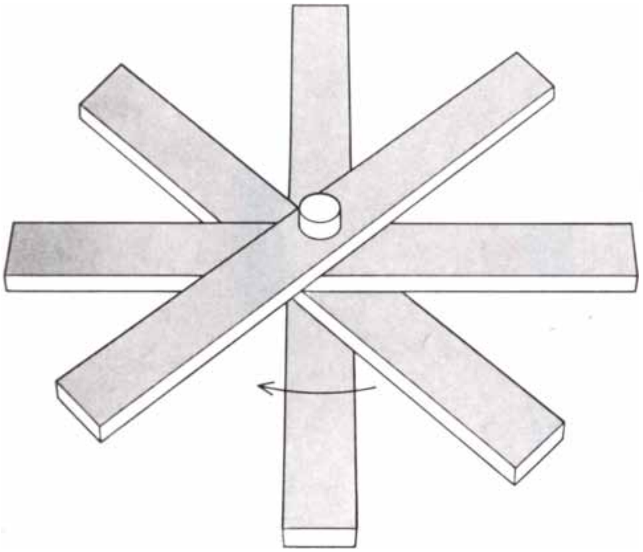
The fiber composites developed initially for aerospace needs have exactly the properties required. They are lower in density than steel by four to six times. Moreover, some of them are far stronger in tension than the strongest steel.

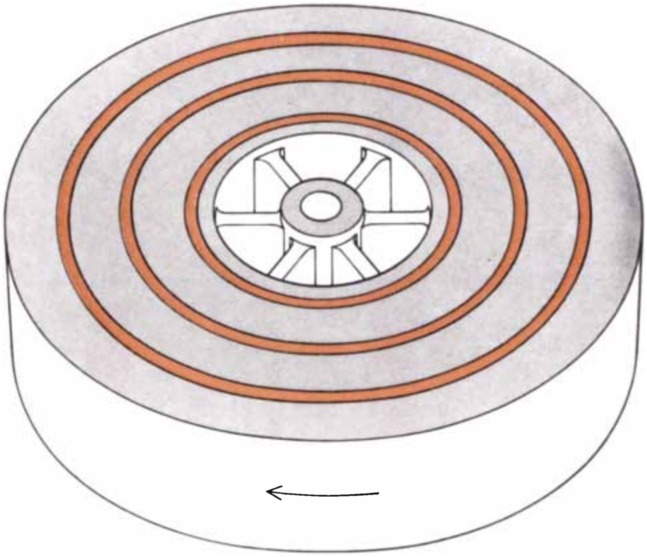
In quantitative terms the limiting amount of energy that can be stored per unit weight of flywheel material is equal to half the tensile stress at the breaking point divided by the density. (The mathematical expression is $U_{max} = 1/2(K_{max}/\rho)$, where U_{max} is the maximum stored energy per unit weight, K_{max} is tensile stress at the breaking point and the Greek letter rho is density.) In metric units this relation is expressed in ergs per gram, but we shall employ a more practically oriented unit: watt-hours per kilogram. The values we discuss are upper limits; practically realizable values will be from 40 to 60 percent of the upper limits. Nonetheless, the maximum value (U_{max}) represents a useful index of the relative ability of materials to store mechanical energy.

Comparing certain fibers with high-strength metals in terms of properties suitable for flywheels, one finds a remarkable showing by the fibers [*see bottom illustration on page 20*]. For example, *E* glass (a commercial fiber produced on a large scale) can store four times as much energy per unit weight as high-strength maraging steel, yet the price of the fiber at the factory is only 15 percent of the price of the alloy steel.

A particularly interesting fiber, which is now coming into production on a large scale for automobile tires and aerospace applications, is PRD-49. This fiber, which was developed by Du Pont, has recently been given the trade name Kevlar. This fiber and similar ones under development by Monsanto are members of a new generation of high-strength polymer fibers: the "aromatic polyamides," descendants of the nylon family. PRD-49

© 1973 SCIENTIFIC AMERICAN, INC





NEW DESIGNS FOR FLYWHEELS have been made with the aim of taking advantage of the light weight and great strength of fiber-composite materials. At left is a rimless, multi-spoke "superflywheel" designed by a group at the Applied Physics Laboratory of John Hopkins University. Wheel at right has concentric rings of fiber composite separated by small gaps filled with bonded resilient material. The design minimizes radial stresses that would cause delamination and makes efficient use of the wheel's volume.

can store seven times as much energy per unit weight as alloy steel.

Fused silica may turn out to be the best of all the fibers for inertial storage. Its estimated maximum energy storage is based on laboratory tests of carefully prepared fibers, so that it cannot be compared directly with fibers already in commercial service. If silica fibers came into use on a commercial scale, however, flywheels incorporating them could store from 10 to 15 times more energy for a given weight of fiber than flywheels made of the best alloy steel.

To take advantage of fiber composites in storing inertial energy, it will be necessary to discard old concepts of how flywheels should be made and to adopt new designs that are tailored to the characteristics of the fiber composites. The problems can be seen by considering again the simple flywheel consisting of a hoop connected by spokes to a hub. Such a flywheel does not have a suitable geometry for the purposes we are discussing; its mass is concentrated in the rim, and the rest of the volume, lying between the rim and the hub, is useless, being mostly empty space.

One's first thought on improving the design might be to fatten the rim, making it into a disk with a hole [*see illustration on page 17*]. Now, however, a new problem appears: since the outer regions of a thick ring necessarily experience greater centrifugal forces than the regions near the center, they will attempt to expand away from the inner portions. This action will set up restraining forces in the radial direction within the body of the ring. These forces will in turn act to intensify the stresses at the inner hole. The resulting stresses, both radial and circumferential, are higher than those in a thin rim rotating at the same speed, and now the highest stress comes at the inner hole. Therefore, because of the uneven distribution of stress, the thick ring is an inefficient shape for a metal flywheel that must store a high density of energy. It is also far too naïve a design for a flywheel fabricated from fiber composites, as will become apparent below.

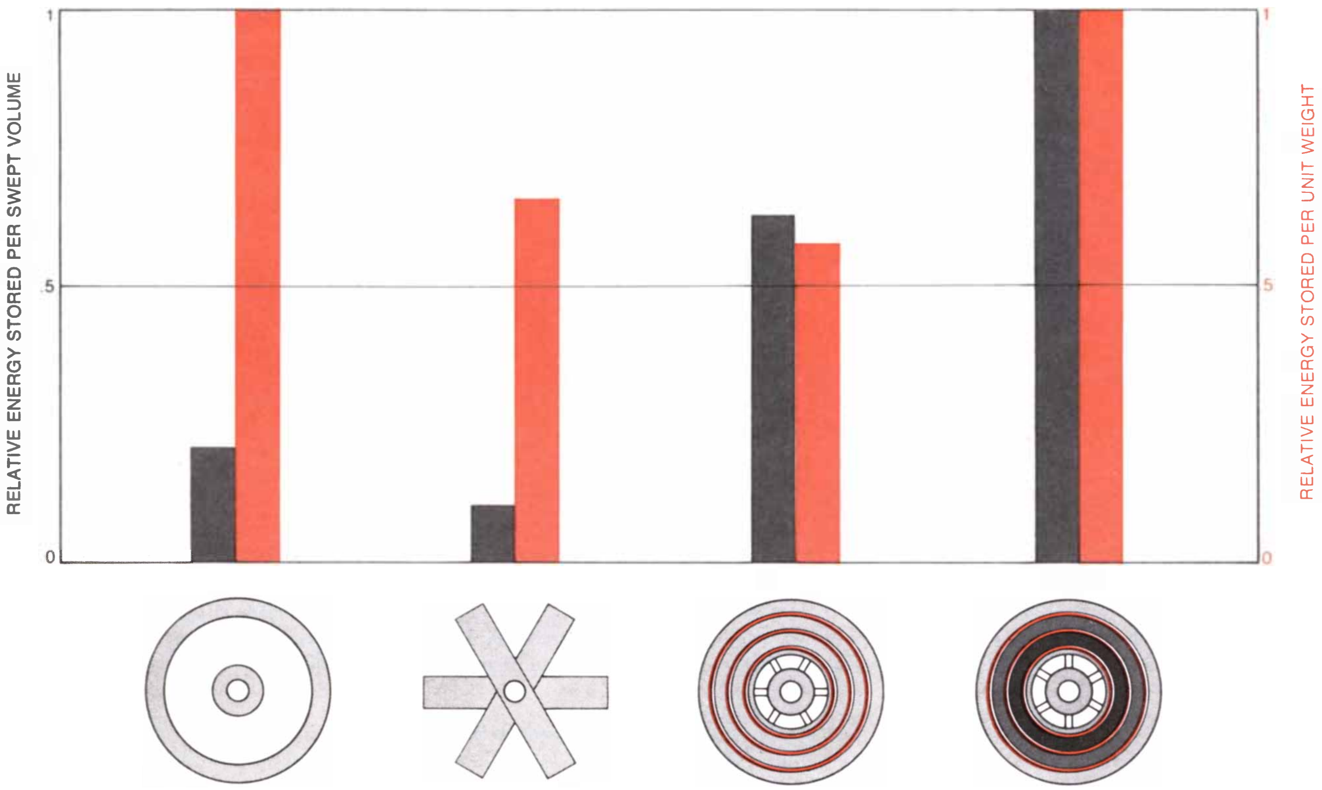
Pursuing for the moment the matter of metal flywheels, there is a better way to design a disk-shaped flywheel as long as it is relatively thin at its outer edge. It was pointed out a long time ago that for one-piece disks made of a homogeneous material, such as solid metal, the problem of concentrated stress near the center of the disk can be relieved and the distribution of stress made more uniform by progressively thickening the disk toward its center, where the most concentrated stresses appear. Indeed, this concept appears in the design of high-speed turbine wheels. Although the tapered design is optimal for metal flywheels, it is inherently unsuitable for fiber-composite flywheels.

What are the special properties of the fiber composites that demand new approaches to flywheel design? Since the strength of fiber composites derives from the strength of the fibers in them, they will develop maximum strength in tension when all the fibers lie parallel to one another, lined up in the direction of the applied tensile force. The bonding material in which the fibers are embedded (usually an epoxy resin) mainly serves the function of protecting them and transmitting relatively weak forces between adjacent fibers. In such unidirectional fiber composites the tensile strength perpendicular to the direction of the fibers is essentially only that of the bonding material—typically only 1 or 2 percent of the tensile strength of the composite material parallel to the fiber direction. Therefore in order to employ fiber composites at full effectiveness in flywheels it is imperative that this inequality of longitudinal and transverse strength be explicitly taken into account.

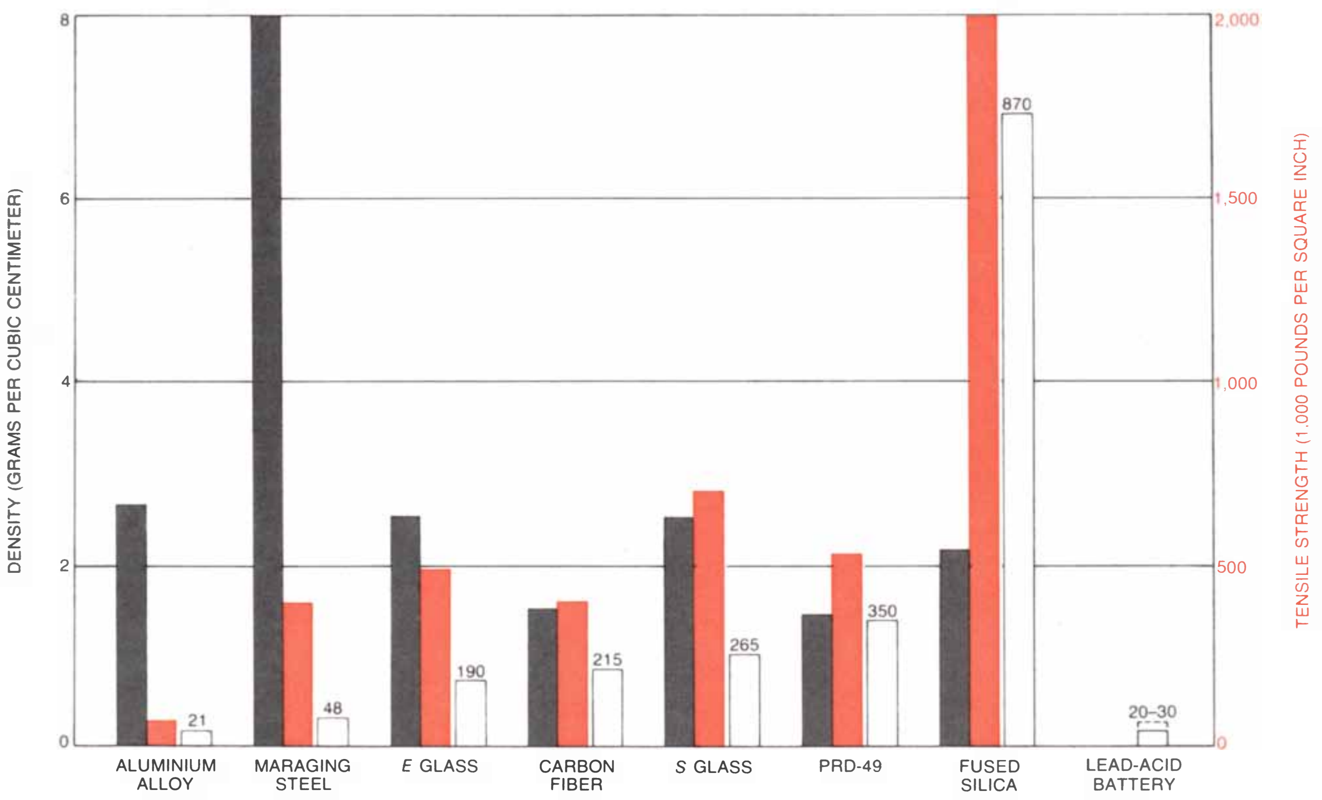
The first attempts to construct fiber-composite flywheels capable of storing a high density of energy were made several years ago in work sponsored by the U.S. Navy. The efforts failed because they were based on the old principles of flywheel design. Solid flywheels of the thick-ring configuration were made from circumferentially wound glass fibers and epoxy. When they were spun up, they failed at speeds far below the limit set by the tensile strength of the fibers. The cause of failure was progressively worsening radial delamination within the body of the flywheel.

A group at the Applied Physics Laboratory of Johns Hopkins University, doubtless aware of such problems, proposed a radically different approach. Their energy-storage rotor, which they called the "superflywheel," consists of a rimless wheel with many spokes [*see illustration at left above*]. Each spoke is a bar or rod fabricated of fiber-composite material, with the direction of the fibers

© 1973 SCIENTIFIC AMERICAN, INC



ENERGY STORAGE of fiber-composite flywheels is depicted on the basis of the volume swept out by the outer edge (*gray*) and on the basis of unit weight of fiber (*color*). From the left the wheels are respectively the thin-rim design, the superflywheel, the concentric-ring flywheel and a similar type of flywheel whose inner rings are loaded with weight to distribute the stresses more evenly.



PROPERTIES OF MATERIALS for flywheels are compared. All the materials except the first two are high-strength fibers for use in fiber composites. For each material the first bar relates to density, the second to tensile strength and the third to maximum energy stored per unit weight of the material when it is incorporated in a flywheel. Numerals express the maximum storage in watt-hours per kilogram. At far right the energy-storage capacity of a lead-acid battery per unit of weight is shown for comparison purposes.

© 1973 SCIENTIFIC AMERICAN, INC

being parallel to the length of the rod. In such a whirling pincushion centrifugal forces result in radial (pure tension) forces in each rod.

Although this approach avoids the delamination problem and thereby comes closer to effective utilization of a fiber composite, it has certain drawbacks. First, as with the thin-rim flywheel, the volume efficiency (the fraction of the volume containing useful material) is low, since the rods occupy only a small portion of the volume swept out by their ends. The result is a marked increase in the volume needed to store a given amount of energy, so that cost and applicability are adversely affected. A second difficulty is that the rods are stressed unevenly along their length, with the portions nearest the hub being the most highly stressed. The result is a lowering of the efficiency of utilization of the high-strength material. Finally, the necessity of anchoring the ends of the rods at the hub (or piercing them at their centers to allow space for an axle) gives rise to difficult problems of design because of the stress concentrations involved.

Is it possible to avoid the problem of delamination and still obtain a fiber-composite flywheel that provides for efficient use of the fibers and high volume efficiency? Let us construct a flywheel by assembling several rings concentrically [*see illustration at right on page 19*]. Each ring would fit inside the next one with a small gap between them. To hold the flywheel together and to allow for relative expansion of the rings under centrifugal force, resilient elements, such as bonded bands of rubberlike material, would be put in the gaps. This design solves the delamination problem because the individual rings would be thin enough to minimize internal radial stresses, and no such forces would be transmitted from ring to ring. A multiring flywheel would also exhibit good volume efficiency.

Such a coupled-ring assembly represents a practical construction for a fiber-composite flywheel but does not achieve the optimum. Since centrifugal effects are weaker at smaller radii, the inner rings are less stressed with respect to the outer ones and so do not store their full share of energy. Moreover, the inner rings, being less stressed, expand less than the outer ones under centrifugal forces, leading to a disproportionate separation between the rings as the rotor is speeded up.

One more step achieves a design that overcomes these problems. Each ring is fabricated so that the ratio of its elastic modulus (resistance to stretching under tensile force) to its mean density (mass divided by volume) is smaller than it is in the ring immediately surrounding it. One way to satisfy this requirement would be to add increasing amounts of a dense loading material, such as lead or iron in powder or strip form, to the inner rings. Another way would be to choose fibers with graded elastic moduli. (The polyamide fibers, among others, provide this possibility.) Preferably a combination of the two stratagems would be employed. The main result would be to make fiber stress more nearly uniform from ring to ring and also within the rings, thus maximizing the efficiency of utilization of the high-strength material (the fibers). In addition varying the modulus-to-density ratio in the manner described substantially reduces the expansion of the rings with respect to one another so that simpler coupling structures between rings can be used. A comparison of the configurations we have been discussing shows that the storage efficiency of the graded-ring flywheel is superior to all the others [*see top illustration on opposite page*].

Having arrived at a configuration that is nearly ideal from the standpoint of high density of stored energy and high efficiency in the utilization of flywheel material, what special problems must be taken into account? One that will occur to mechanical engineers is the question of the stability of multiring rotors against internal vibrations. Conventional flywheels and their axle and bearing systems have "critical speeds" at which the rotation speed of the motor, as it is being spun up, momentarily matches a natural vibration frequency of the axle-shaft-flywheel mass system. Such resonances can lead to the buildup of destructive oscillations that must be damped or otherwise circumvented in the design. Although the problem is well understood and can be avoided in conventional flywheel systems, might it not be worrisome with a multiring rotor, which might exhibit new mechanical resonances? This problem has been analyzed theoretically, and the analysis has been checked against model flywheels by the engineering firm of William M. Brobeck and Associates. (The work was supported by a joint research grant from the Pacific Power and Light Company and the San Diego Gas and Electric Company.) The results showed that readily achievable design criteria can be specified for multiring flywheels to ensure that all natural resonant frequencies of the rotor lie well above the highest operating speed.

The use of fiber composites, as workers at Johns Hopkins have demonstrated, minimizes another problem of older flywheel systems: safe containment of flywheel fragments in case of mechanical failure. When fiber composites are overstressed, they fail by shredding or turning to powder rather than by breaking into large chunks, as is the case with steel flywheels.

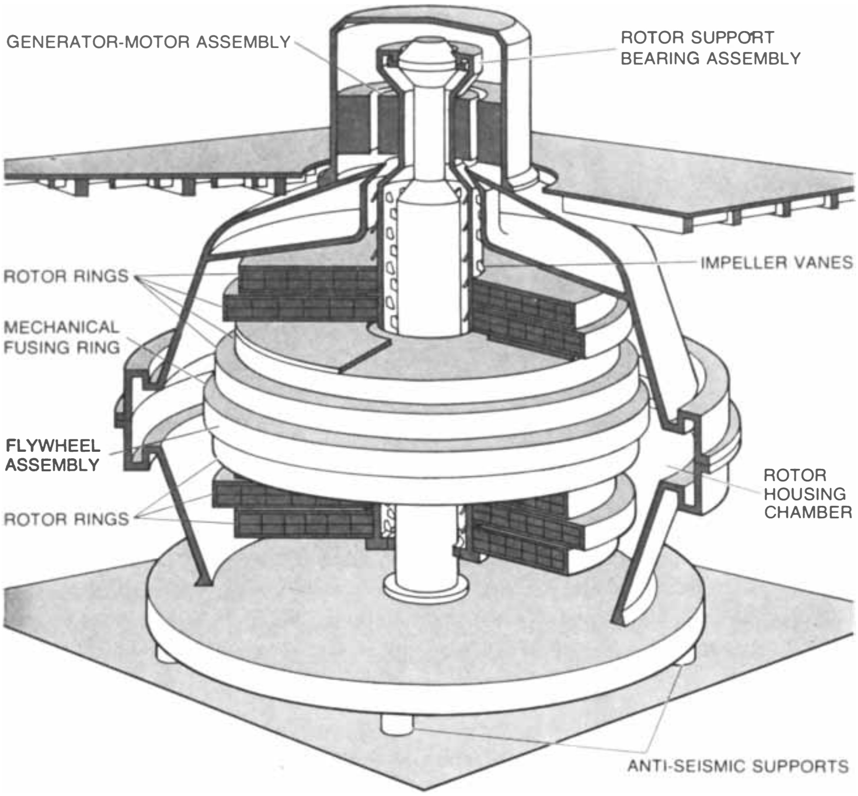
Flywheels of the kind we have described offer a means for electric utilities to cope with peak loads. The problem the power companies face is that peak demands are growing (for such purposes as air conditioning) while environmental concerns have delayed the moves the companies might make to expand capacity by building new "base load" plants. The companies have tended to deal with the problem by installing peaking units near the areas of demand. The units, which are commonly gas-turbine-driven generators, are turned on only during the hours when demand is heaviest. Capital costs for such units tend to be high (because of low utilization), and fuel costs are also high because gas turbines must burn fuel oil, which is not only expensive but also now increasingly in short supply.

The peaking problem is not basically caused by an energy shortage; except for temporary shortages there is enough coal, residual oil and nuclear fuel to power present base-load plants. If the utilities could run these plants at full output around the clock, storing the extra energy produced in off-peak hours, they could meet the peak loads with the help of the stored energy. One solution has been pumped storage: with base-load power water is pumped uphill to a reservoir during off-peak hours, and during peak hours it flows back down, powering a hydroelectric generating plant. The trouble here is that there are few places where pumped storage is geographically, environmentally and economically practical.

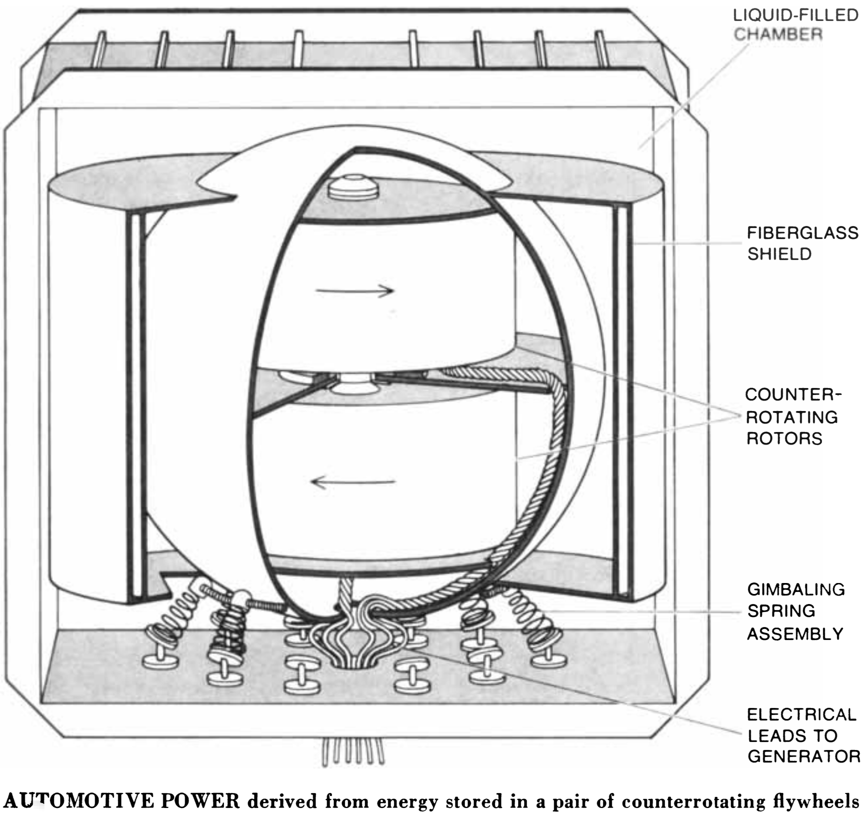
What is needed is an energy-storage system of high efficiency and compactness and with characteristics that allow it to be installed almost anywhere in a short time (a year or less) between the placing of the order and the start-up of the unit. Pumped storage is relatively inefficient, takes up a lot of land and requires years of planning and site preparation. Flywheel storage offers all the desirable characteristics, and we believe it can achieve them at lower capital cost than is required for the pumped-storage plants now under construction.

A flywheel system of energy storage

© 1973 SCIENTIFIC AMERICAN, INC



PEAK-POWER UNIT that would store energy from an electric-power plant during off-peak hours and would generate energy at times of peak load is visualized. The fiber-composite flywheel would be some 15 feet in diameter and weigh some 200 tons. It would be coupled to a generator-motor that would function as a motor when the flywheel was being spun up to store energy and as a generator when the system was drawing on the flywheel's stored energy.



AUTOMOTIVE POWER derived from energy stored in a pair of counterrotating flywheels would employ a system of this kind. The flywheels, sealed in a partial vacuum to reduce air friction, would be coupled to a generator-motor. To store energy in the flywheels the system would be plugged into an electric outlet. Power produced by the system would be delivered to electric drive motors. The gimbal mounting would reduce the gyroscope effect.

for a power company would consist of several individual units. The flywheel in each unit would be housed in a sealed enclosure and coupled directly to a variable-speed generator-motor, which would function as a generator when the system was drawing on the energy stored in the flywheel and as a motor when energy was being stored in the flywheel by spinning it up. The flywheel and the generator-motor would operate in an atmosphere of inert gas (hydrogen or helium) below atmospheric pressure in order to reduce losses from air friction. Each flywheel would be from 12 to 15 feet in diameter and would weigh from 100 to 200 tons. Each unit would store from 10,000 to 20,000 kilowatt-hours of energy at full charge (a rotation speed of about 3,500 revolutions per minute). A utility system might employ 100 or more such units, dispersed throughout the system at substations.

Based on the costs of materials, fabrication of the flywheel and the electrical components and installation, the capital cost of a unit storing 10,000 kilowatt-hours of energy, having a power rating of 3,000 kilowatts and operating at an in-out efficiency of 93 to 95 percent can be estimated at $325,000. The corresponding capital cost per kilowatt would be $110—lower than that of pumped storage. Additional advantages over pumped storage would result from local siting, which would reduce transmission costs, and from the fact that a flywheel unit would take up far less land. (For each 10,000 kilowatt-hours of stored energy a pumped-storage system typically requires from two to four acres of reservoir area; a flywheel unit storing the same amount of energy would occupy a cell approximately 20 by 20 feet in size.) Moreover, the capital costs of pumped storage are rising, whereas one can expect the capital cost of flywheel storage to decline as new and better fibers are brought into large-scale production.

Powering vehicles with flywheels is not a new idea, but so far all the vehicles thus powered have had steel flywheels. Several years ago Swiss engineers developed a bus that ran on flywheel power between stops, recharging the wheel with an electric motor at each stop by bringing an overhead trolley in contact with a power line. Similar buses, which will have alloy-steel flywheels of improved (thickened hub) design, are now being developed for San Francisco.

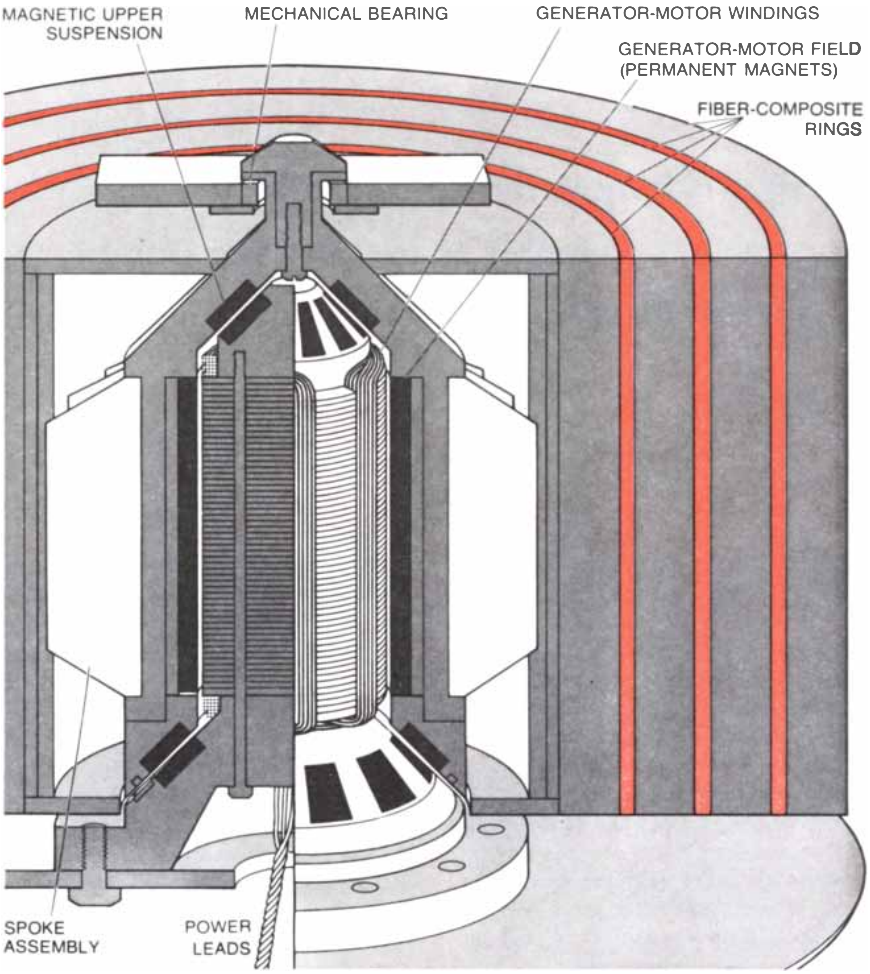
The real potential of flywheel power for vehicles will appear with the advent of fiber-composite flywheels. Then it will be possible to drive automobiles with flywheels. One would spin up the fly-

© 1973 SCIENTIFIC AMERICAN, INC

wheel with a motor running on power drawn from an electric outlet, and then the energy stored in the flywheel could drive the car with the motor operating as a generator to supply power to smaller motors, one on each wheel.

The economic and social advantages of flywheel-driven automobiles would be considerable because the vehicles would operate at high efficiency and would not give rise to pollutants. The internal-combustion engine in an automobile typically converts only from 10 to 15 percent of the energy in gasoline to motive power, whereas modern electric-power plants burning fossil fuel have efficiencies of 40 percent or better. Moreover, combustion can be better controlled in a central power plant than in an automobile, at least at present. Therefore a high-efficiency system such as a flywheel-driven automobile that stored energy from electric-power plants and used it to drive vehicles would result in greatly improved efficiency in terms of fossil fuel consumed per vehicle mile. In these terms one barrel of crude oil burned in an electric-power plant would be the equivalent of up to five barrels sent to a refinery to produce gasoline. It follows that any new demands for electric power arising from the use of flywheel-electric automobiles could be met readily within the present resources of fossil fuel.

An automobile flywheel system would, like the peak-storage system, include a flywheel and a motor-generator sealed in an evacuated chamber. About 30 kilowatt-hours of stored energy would be needed to provide reasonable performance by a small automobile: a range of 200 miles at 60 miles per hour, which is comparable to the performance of today's internal-combustion automobile on one tank of fuel. Obtaining this amount of energy from conventional lead-acid storage batteries would require a bank of batteries weighing more than 2,000 pounds. A flywheel containing 130 pounds of fused-silica fibers or 280 pounds of PRD-49 could store the same amount of energy. (The weight of the total drive system would be between 500 and 600 pounds.) Another advantage of the flywheel system over a battery system is that energy can be taken out of or put into a flywheel rapidly. A battery cannot deliver the high power needed for rapid acceleration, nor can it take the high rate of charge that would be necessary to make an electric automobile suitable for long-distance driving. A flywheel system, however, could accept a full 30-kilowatt-hour charge in five minutes or less. Furthermore, it could deliver high enough outputs of horsepower to satisfy the most demanding driver.



GENERATOR-MOTOR UNIT for the flywheel system designed to drive an automobile, a bus or a truck is visualized. Suspension is magnetic except for the mechanical bearing at top.

Since the flywheel system has a projected electrical efficiency exceeding 95 percent, a flywheel-driven automobile could take effective advantage of regenerative braking. A regenerative braking system would employ the vehicle's electric motors as generators during braking or downhill driving, thus putting the kinetic energy of the vehicle back into the storage system. With batteries, which under such high rates of charge would typically return only 50 to 75 percent of the charging energy put into them, a large fraction of the regenerative braking energy would be lost. With a flywheel system, however, the range of the car could be increased by from 25 to 50 percent through regenerative braking.

Since the flywheel system in an automobile would be sealed in a partial vacuum, the loss of power from friction while the car was not in use could be made very low. For example, a family could leave a flywheel car at an airport for the summer while taking a trip abroad, and when they came back, the flywheel would still have ample energy to get them home. The rundown time for a rotor in a vacuum chamber is estimated at from six to 12 months.

A sealed flywheel unit would also require nothing in the way of maintenance except an occasional check on the vacuum. Indeed, from calculations of the tensile-strength fatigue rate of the materials in a flywheel unit one can project a lifetime of several years for the unit. One can even envision transferring the unit from one vehicle to another when the body of the first vehicle wears out.

Beyond the needs of today lie the energy-storage requirements of the future. As increasing emphasis is laid on conserving mineral resources, using energy efficiently and curbing pollution, energy storage will become increasingly important. For example, one can envision the development of solar power and perhaps wind power. For such intermittent sources of energy to become practical, economical and efficient, means of storing energy must be available. The improved flywheels we have described will meet this crucial need.

© 1973 SCIENTIFIC AMERICAN, INC

GENETIC DISSECTION OF BEHAVIOR

By working with fruit flies that are mosaics of normal and mutant parts it is possible to identify the genetic components of behavior, retrace their development and locate the sites where they operate

by Seymour Benzer

When the individual organism develops from a fertilized egg, the one-dimensional information arrayed in the linear sequence of the genes on the chromosomes controls the formation of a two-dimensional cell layer that folds to give rise to a precise three-dimensional arrangement of sense organs, central nervous system and muscles. Those elements interact to produce the organism's behavior, a phenomenon whose description requires four dimensions at least. Surely the genes, which so largely determine anatomical and biochemical characteristics, must also interact with the environment to determine behavior. But how? For two decades molecular biologists were engaged in tracking down the structure and coding of the gene, a task that was pursued to ever lower levels of organization [see "The Fine Structure of the Gene," by Seymour Benzer; SCIENTIFIC AMERICAN, January, 1962]. Some of us have since turned in the opposite direction, to higher integrative levels, to explore development, the nervous system and behavior. In our laboratory at the California Institute of Technology we have been applying tools of genetic analysis in an attempt to trace the emergence of multidimensional behavior from the one-dimensional gene.

Our objectives are to discern the genetic component of a behavior, to identify it with a particular gene and then to determine the actual site at which the gene influences behavior and learn how it does so. In brief, we keep the environment constant, change the genes and see what happens to behavior. Our choice of an experimental organism was constrained by the fact that the simpler an organism is, the less likely it is to exhibit interesting behavioral patterns that are relevant to man; the more complex it is, the more difficult it may be to analyze and the longer it takes. The fruit fly *Drosophila melanogaster* represents a compromise. In mass, in number of nerve cells, in amount of DNA and in generation time it stands roughly halfway on a logarithmic scale between the colon bacillus *Escherichia coli* (which can be regarded as having a one-neuron nervous system) and man. Although the fly's nervous system is very different from the human system, both consist of neurons and synapses and utilize transmitter molecules, and the development of both is dictated by genes. A fly has highly developed senses of sight, hearing, taste, smell, gravity and time. It cannot do everything we do, but it does some things we cannot do, such as fly and stand on the ceiling. Its visual system can detect the movement of the minute hand on a clock. One must not underestimate the little creature, which is not an evolutionary antecedent of man but is itself high up on the invertebrate branch of the phylogenetic tree. Its nervous system is a miracle of microminiaturization, and some of its independently evolved behavior patterns are not unlike our own.

Jerry Hirsch, Theodosius Dobzhansky and many others have demonstrated that if one begins with a genetically heterogeneous population of fruit flies, various behavioral characters can be enhanced by selective breeding pursued over many generations. This kind of experiment demonstrates that behavior can be genetically modified, but it depends on the reassortment of many different genes, so that it is very difficult to distinguish the effect of each one. Also, unless the selective procedure is constantly maintained, the genes may reassort, causing loss of the special behavior. For analyzing the relation of specific genes to behavior, it is more effective to begin with a highly inbred, genetically uniform strain of flies and change the genes one at a time. This is done by inducing a mutation: an abrupt gene change that is transmitted to all subsequent generations.

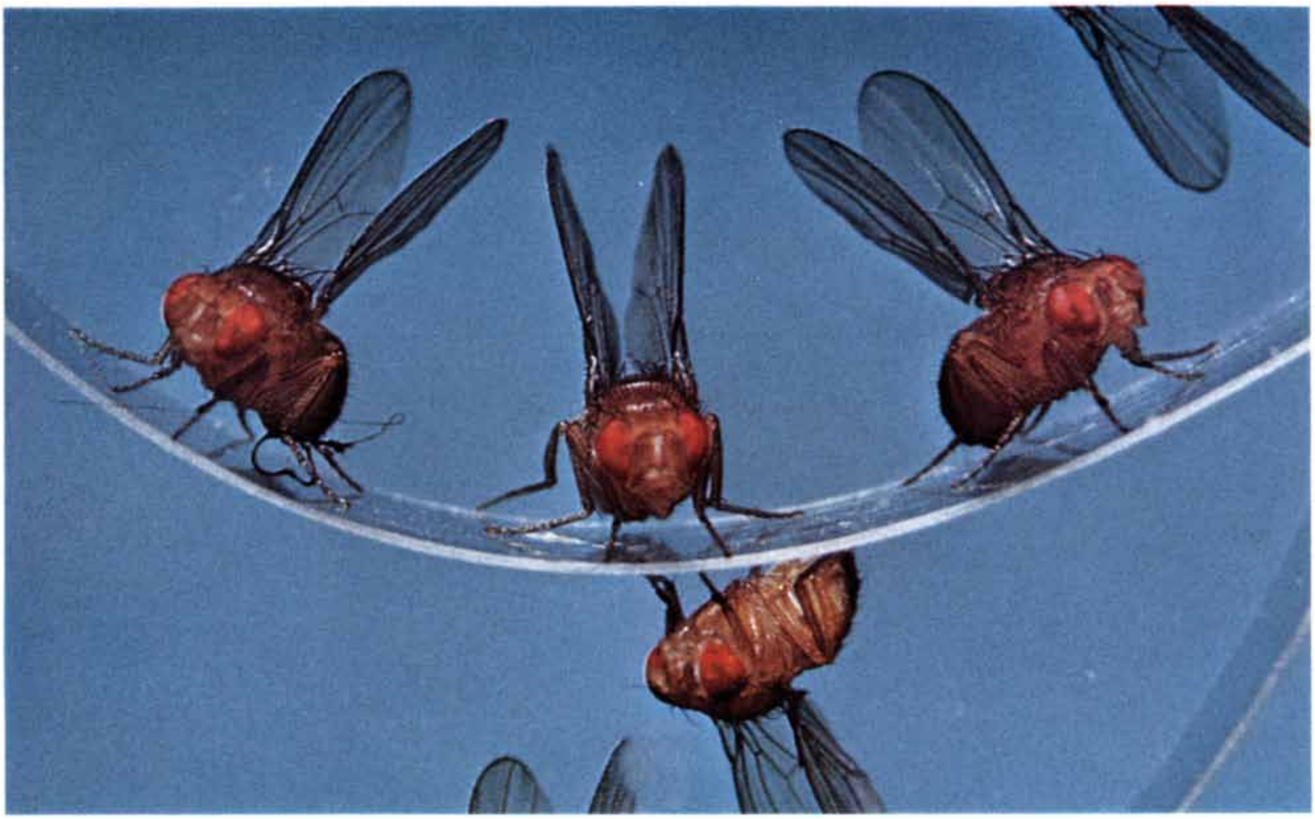
A population of flies exposed to a mutagen (radiation or certain chemicals) yields some progeny with anatomical anomalies such as white eyes or forked bristles, and it also yields progeny with behavioral abnormalities. Workers in many laboratories (including ours) have compiled a long list of such mutants, each of which can be produced by the alteration of a single gene. Some mutants are perturbed in sexual behavior, which in normal *Drosophila* involves an elaborate sequence of fixed action patterns. Margaret Bastock showed years ago that some mutant males do not court with normal vigor. Kulbir Gill discovered a mutant in which the males pursue one another as persistently as they do females. The mutant *stuck*, found by Carolyn Beckman, suffers from inability to disengage after the normal 20-minute copulation period. A converse example is *coitus interruptus*, a mutant Jeffrey C. Hall has been studying in our laboratory; mutant males disengage in about half the normal time and no offspring are produced. Obviously most such mutants would not stand a chance in the competitive natural environment, but they can be maintained and studied in the laboratory.

As for general locomotor activity, some mutants are *sluggish* and others, such as one found by William D. Kaplan at the City of Hope Medical Center, are *hyperkinetic*, consuming oxygen at an exaggerated rate and dying much earlier than normal flies. Whereas normal flies show strong negative geotaxis (a tendency to move upward against the force of gravity), *nonclimbing* mutants do not.

© 1973 SCIENTIFIC AMERICAN, INC

BEHAVIOR of a normal and of a mosaic fruit fly is demonstrated in an experiment photographed by F. W. Goro. Normal flies move toward light and upward against the force of gravity. A normal fly that is placed in a glass tube with a light at the top and photographed by successive stroboscopic flashes traces a line straight up the tube (*left*). A mosaic fly, with one good eye and one blind eye, also climbs straight up if there is no light, guided by its sense of gravity. If there is a light at the top of the tube, however, the mosaic fly traces a helical path (*right*), turning its bad eye toward the light in a vain effort to balance the light input to both eyes.

© 1973 SCIENTIFIC AMERICAN, INC



"WINGS-UP" FLIES are mutants that keep their wings straight up and cannot fly. Such behavior could be the result of flaws in wing structure, in musculature or in nerve function. Mosaic experiments in the author's laboratory have traced the defect to the muscle.

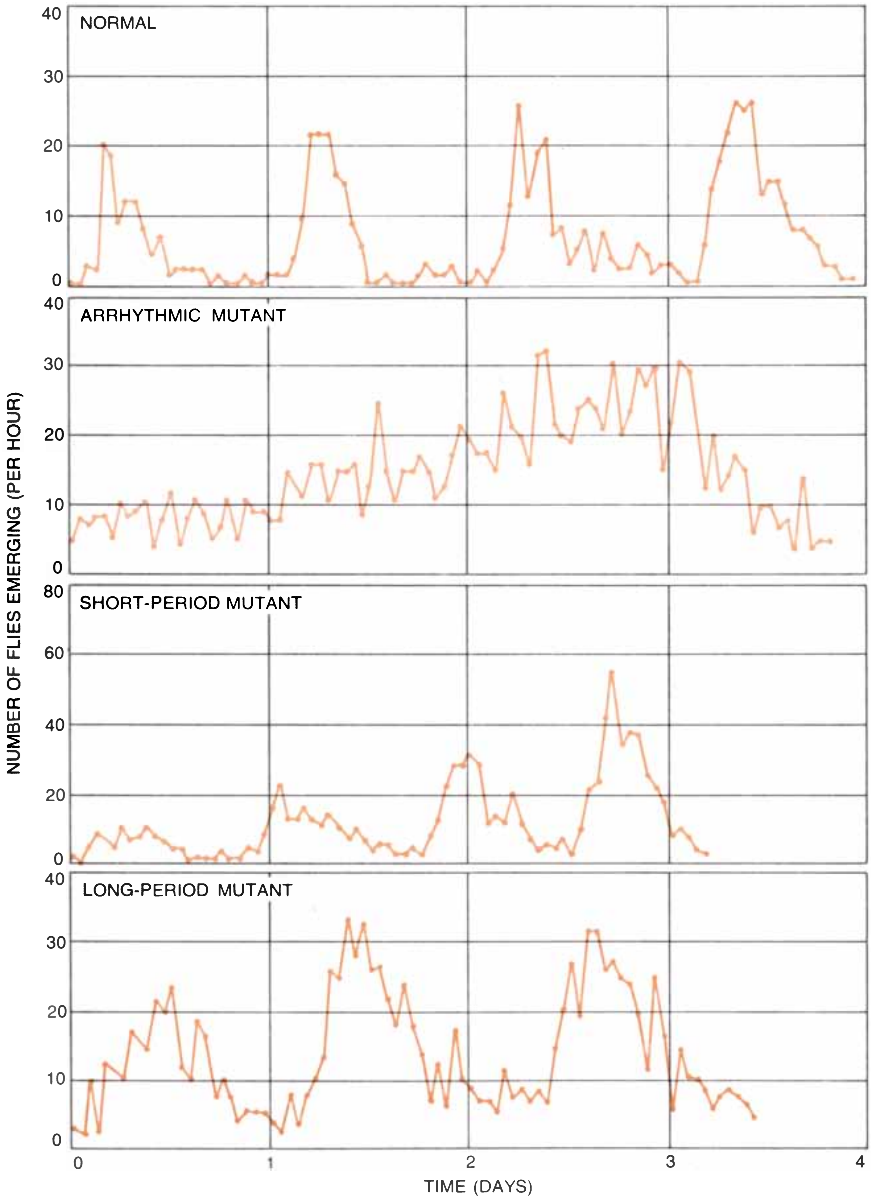
MOSAIC FLIES used for investigating behavior are gynandromorphs: partly male and partly female. The female parts are normal, the male parts mutant in one physical or behavioral trait or more. These flies have one normal red eye and one mutant white eye, and the male side of each fly also has the shorter wing that is normal for a male fly. The flies are about three millimeters long.

© 1973 SCIENTIFIC AMERICAN, INC

Flightless flies do not fly even though they may have perfectly well-developed wings and the male can raise his wing and vibrate it in approved fashion during courtship. Some individuals that appear to be quite normal may harbor hereditary idiosyncrasies that show up only under stress. Take the *easily shocked* mutants we have isolated, or the one called *tko,* found by Burke H. Judd and his collaborators at the University of Texas at Austin. When the mutant fly is subjected to a mechanical jolt, it has what looks like an epileptic seizure: it falls on its back, flails its legs and wings, coils its abdomen under and goes into a coma; after a few minutes it recovers and goes about its business as if nothing had happened. John R. Merriam and others working in our laboratory have found several different genes on the *X* chromosome that can produce this syndrome if they are mutated.

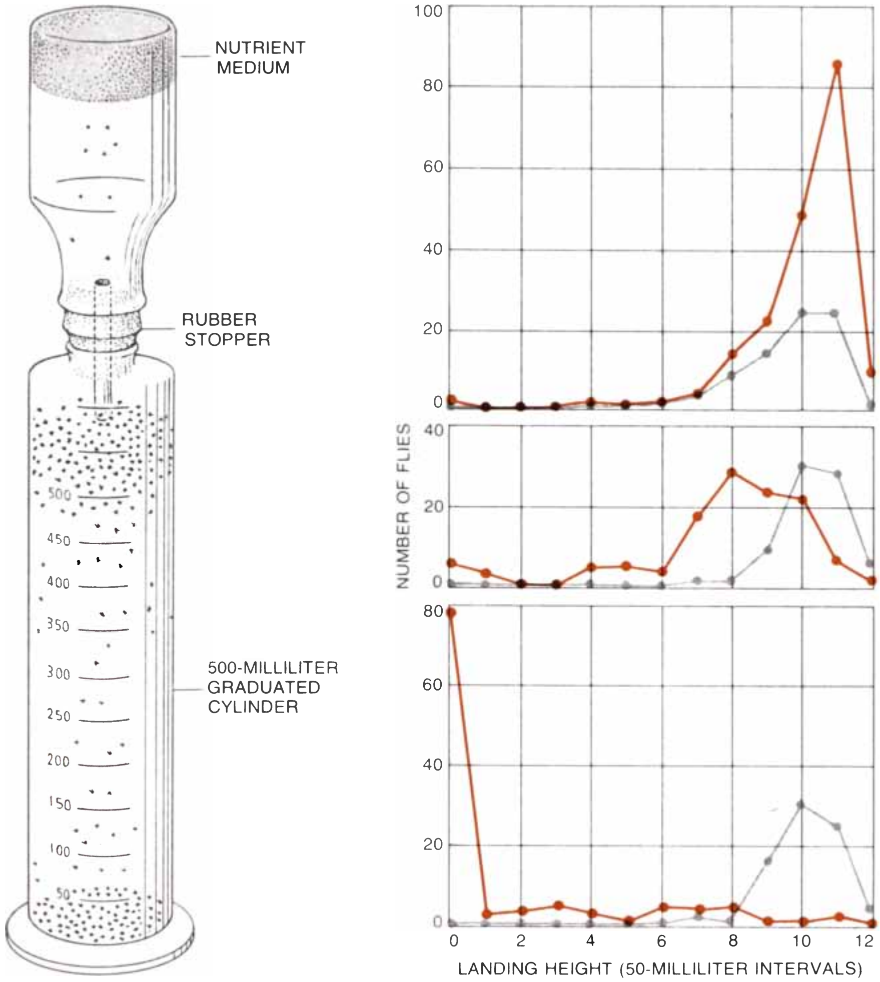
In many organisms mutations have been discovered that are temperature-sensitive, that is, the abnormal trait is displayed only above or below a certain temperature. David Suzuki and his associates at the University of British Columbia discovered a behavioral *Drosophila* mutant of this type called *paralyzed:* when the temperature goes above 28 degrees Celsius (82 degrees Fahrenheit), it collapses, although normal flies are unaffected; when the temperature is lowered, the mutant promptly stands up and moves about normally. We have found other mutants, involving different genes, that become similarly paralyzed at other specific temperatures. In one of these, *comatose,* recovery is not instantaneous but may take many minutes or hours, depending on how long the mutant was exposed to high temperatures. Recent experiments by Obaid Siddiqi in our laboratory have shown that action potentials in some of the motor nerves are blocked until the fly recovers.

An important feature of behavior in a wide range of organisms is an endogenous 24-hour cycle of activity. The fruit fly displays this "circadian" rhythm, and one can demonstrate the role of the genes in establishing it. A fly does well to emerge from the pupal stage around dawn, when the air is moist and cool and the creature has time to unfold its wings and harden its cuticle, or outer shell, before there is much risk of desiccation or from predators. (The name *Drosophila,* incidentally, means "lover of dew.") Eclosion from the pupa at the proper time is controlled by the circadian rhythm: most flies emerge during a few hours around dawn and those missing that interval tend to wait until dawn on the following day or on later days. This rhythm, which has been much studied by Colin S. Pittendrigh of Stanford University, persists even in constant darkness provided that the pupae have once been exposed to light; having been set, the internal clock keeps running. The clock continues to control the activity of the individual fly after eclosion, even if the fly is kept in the dark. By monitoring the fly's movement with a photocell sensitive to infrared radiation (which is invisible to the fly) one can observe that it begins to walk about at a certain time and does so for some 12 hours; then it becomes quiescent, as if it were asleep on its feet, for half a day. After that, at the same time as the first day's arousing or within an hour or so of it, activity begins anew. Ronald Konopka demonstrated the genetic control of this internal clock as a graduate student in our laboratory. By exposing normal flies to a mutagen he obtained mutants with abnormal rhythms or no rhythm at all. The *arrhythmic* flies may eclose at any time of day; if they are maintained in the dark



"BIOLOGICAL CLOCK" is an example of a behavioral mechanism that is genetically determined. It governs the periodicity of the time flies eclose from the pupa and also their daily cycle of activity as adults. The curves are for the eclosion of flies kept in total darkness. Normal flies emerge from the pupa at a time corresponding to dawn; those that miss dawn on one day emerge 24 hours later (*top*). Mutants include arrhythmic flies, which emerge at arbitrary times in the course of the day, and flies with 19-hour and 28-hour cycles.

© 1973 SCIENTIFIC AMERICAN, INC



FLIGHT TESTER is a simple device for measuring the flying ability of normal and mutant flies. It is a 500-milliliter graduated cylinder, its inside wall coated with paraffin oil. Flies are dumped in at the top. They strike out horizontally as best they can, and so the level at which they hit the wall and become stuck in the oil film reflects their flying ability. The curves compare the performance of female control flies (*gray*) with that of males (*color*) that fly normally (*top*) or poorly (*middle*) and with male *flightless* mutants (*bottom*).

after emergence, they are insomniacs, moving about during random periods throughout the day. The *short-period* mutant runs on a 19-hour cycle and the *long-period* mutant on a 28-hour cycle. (May there not be some analogy between such flies and humans who are either cheerful early birds or slow-to-awaken night owls?)

Let me now use a defect in visual behavior to illustrate in some detail how we analyze behavior. The first problem is to quantitate behavior and to detect and isolate behavioral mutants. It is possible to handle large populations of flies, treating each individual much as a molecule of behavior and fractionating the group into normal and abnormal types. We begin, using the technique devised by Edward B. Lewis at Cal Tech, by feeding male flies sugar water to which has been added the mutagen ethyl methane sulfonate, an alkylating agent that induces mutations in the chromosomes of sperm cells. The progeny of mutagenized males are then fractionated by means of a kind of countercurrent distribution procedure [*see illustration on opposite page*], somewhat as one separates molecules into two liquid phases. Here the phases are light and darkness and the population is "chromatographed" in two dimensions on the basis of multiple trials for movement toward or away from light. Normal flies—and most of the progeny in our experiment—are phototactic, moving toward light but not away from it. Some mutants, however, do not move quickly in either direction; they are *sluggish* mutants. There are *runners*, which move vigorously both toward and away from light. A *negatively phototactic* mutant moves preferentially away from light. Finally, there are the *nonphototactic* mutants, which show a normal tendency to walk but no preference for light or darkness. They behave in light as normal flies behave in the dark, which suggests that they are blind.

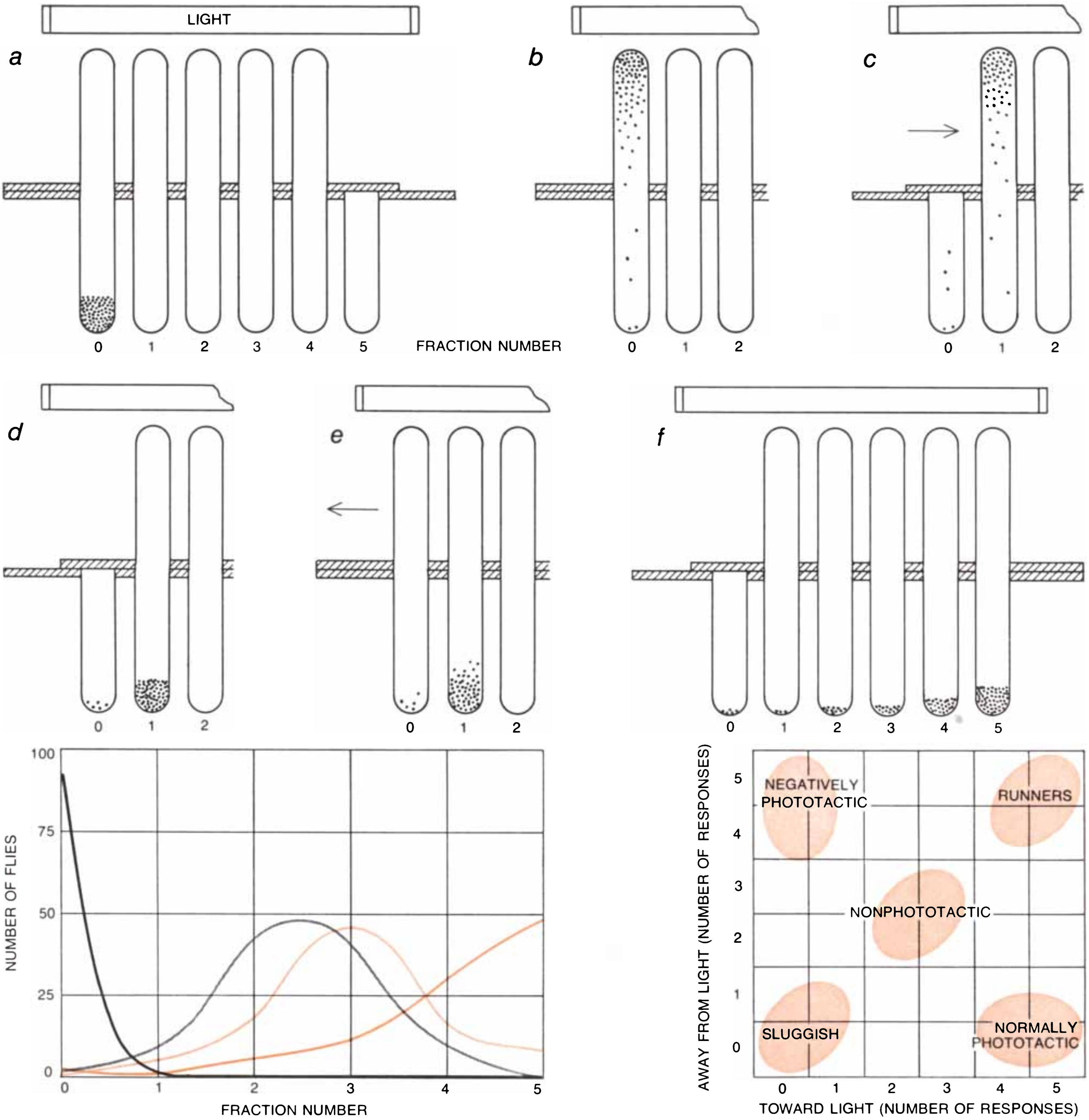
My colleague Yoshiki Hotta, who is now at the University of Tokyo, and I studied the electrical response of the nonphototactic flies' eyes. Similar mutant isolation and electrical studies have also been carried out by William L. Pak and his associates at Purdue University and by Martin Heisenberg at the Max Planck Institute for Biology at Tübingen, so that many mutants are now available, involving a series of different genes. The stimulus of a flash of light causes the photoreceptor cells of a normal fly's eye to emit a negative wave, which in turn triggers a positive spike from the next cells in the visual pathway; an electroretinogram, a record of this response, can be made rather easily with a simple wick electrode placed on the surface of the eye. In some nonphototactic mutants the photoreceptor cells respond but fail to trigger the second-order neurons; in other cases the primary receptor cells are affected so that there is no detectable signal from them even though they are anatomically largely normal. These mutants may be useful in understanding the primary transduction mechanism in the photoreceptor cells. Mutant material provides perturbations, in other words, that enable one to analyze normal function. When Hotta and I examined the eyes of some of the nonphototactic mutants, we found that the photoreceptor cells are normal in the young adult but that they degenerate with age. There are genetic conditions that produce this result in humans, and it may be that the fly's eye can provide a model system for studying certain kinds of blindness.

Now, if one knows that a certain behavior (nonphototactic, say) is produced by a single-gene mutation and that it seems to be explained by an anatomical fault (the degenerated receptors), one still cannot say with certainty what is the primary "focus" of that genetic alteration, that is, the site in the body at which the mutant gene exerts its primary effect. The site may be far from the affected organ. Certain cases of retinal degeneration in man, for example, are due not to any defect in the eye but to ineffective absorption of vitamin A from food in the intestine, as Peter Gouras of the National Institute of Neurological Diseases and Blindness has demonstrated. In order to trace the path from gene to behavior one must find the true focus at which the gene acts in the developing organism. How? A good way to troubleshoot in an electronic system—a stereophonic set with two identical

© 1973 SCIENTIFIC AMERICAN, INC

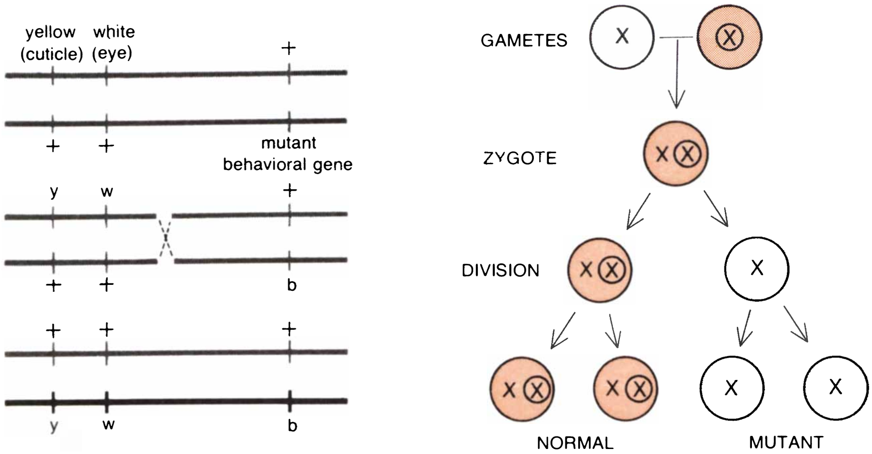
channels, for example—is to interchange corresponding parts. That is in effect what we do with *Drosophila*. Rather than surgically transplanting organs from one fly to another, however, we use a genetic technique: we make mosaic flies, composite individuals in which some tissues are mutant and some have a normal genotype. Then we look to see just which part has to be mutant in order to account for the abnormal behavior.

One method of generating mosaics depends on a strain of flies in which there is an unstable ring-shaped *X* chromosome. Flies, like humans, have *X* and *Y* sex chromosomes; if a fertilized egg has two *X* chromosomes in its nucleus, it will normally develop into a female fly; an *XY* egg yields a male. In *Drosophila* it is the presence of two *X* chromosomes that makes a fly female; if there is only one *X*,



COUNTERCURRENT APPARATUS developed by the author can "fractionate" a population of flies as if they were molecules of behavior. The device consists of two sets of plastic tubes arranged in a plastic frame. Flies are put in Tube *0*; the device is held vertically and tapped to knock the flies to the bottom of the tube, and then the frame is laid flat and placed before a light at the far end of the tubes (*a*). Flies showing the phototactic response move toward the light, whereas others stay behind (*b*). After 15 seconds the top row of tubes is shifted to the right (*c*) and the responders are tapped down again (*d*), falling into Tube *1*. The upper frame is returned to the left (*e*), the frame is laid flat and again the responders move toward the light. The procedure is repeated five times in all. By then the best responders are in Tube *5*, the next best in Tube *4* and so on (*f*). The curves (*bottom left*) show typical results. Phototactic flies show two very distinct peaks depending on whether the light was at the opposite end of the tubes from the starting point (*color*) or at the starting end (*black*). Nonphototactic flies, however, yield about the same curve (*light color or gray*) regardless of the position of the light. In order to distinguish variation in motor activity from phototaxis, the separation is carried out first toward light and then, processing the flies in each tube again, away from light, yielding a two-dimensional "chromatogram" (*bottom right*).

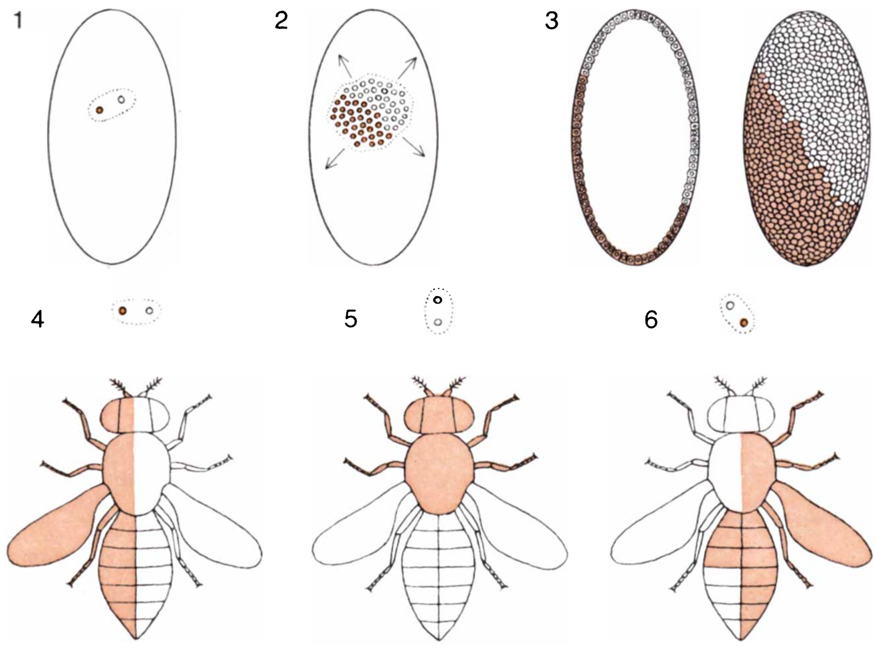
© 1973 SCIENTIFIC AMERICAN, INC



PREPARATION OF MOSAIC FLIES depends on the recombination on one *X* chromosome of genes for mutant "marker" traits and for a behavioral mutation. Recombination occurs through the crossing-over of segments of two homologous chromosomes, as shown at left. Males with an *X* chromosome carrying the desired recombination (*black*) are mated with females carrying an unstable ring-shaped *X* chromosome (*top row at right*). Among the resulting zygotes, or fertilized eggs, will be some carrying the mutation-loaded *X* and a ring *X*. In the course of nuclear division the ring *X* is sometimes lost. Tissues that stem from that nucleus are male, and mutant. In tissues that retain the ring *X*, however, the mutant genes are masked by the genes on the ring *X*, and these tissues are female and normal.

the fly will be male. The ring *X* chromosome has the property that it may get lost during nuclear division in the developing egg. If we start with female eggs that have one normal *X* and one ring *X*, in a certain fraction of the embryos some of the nuclei formed on division lose the ring *X* and therefore have only one *X* chromosome left, and will therefore produce male tissues. This loss of the ring *X*, when it occurs, tends to happen at a very early stage in such a way as to produce about equal numbers of *XX* and *X* nuclei. The nuclei divide a few times in a cluster and then migrate to the surface of the egg to form the early embryonic stage called a blastula: a single layer of cells surrounding the yolk [*see bottom illustration on this page*]. The nuclei tend to retain their proximity to their neighbors in the cluster, so that the female (*XX*) cells populate one part of the blastoderm (the surface of the blastula) and the male cells cover the rest. It is a feature of *Drosophila* that the axis of the crucial first nuclear division is oriented arbitrarily with respect to the axes of the egg. The dividing line between the *XX* and *X* cells can therefore cut the blastoderm in different ways. Once the blastoderm is formed the site occupied by a cell largely determines its fate in the developing embryo, and so the adult gynandromorph, a male-female mosaic, can have a wide variety of arrangements of male and female parts depending on how the dividing line falls in each particular embryo. The division of parts often follows the intersegmental boundaries and the longitudinal midline of the fly's exoskeleton. The reason is that the exoskeleton is an assembly of many parts, each of which was formed independently during metamorphosis from an imaginal disk in the larva that was in turn derived from a specific area of the blastoderm [*see illustrations on opposite page*].

The reader will perceive that a mosaic fly is a system in which the effects of normal and of mutant genes can be distinguished in one animal. We use this system by arranging things so that both a behavioral gene and "marker" genes that produce anatomical anomalies are combined on the same *X* chromosome. This is done through the random workings of the phenomenon of recombination, in which segments of two chromosomes (in this case the *X*) "cross over" and exchange places with each other during cell division in the formation of the egg. In this way we can, for example, produce a strain of flies that are *nonphototactic* and also have white eyes (instead of the normal red) and a yellow body color. Then we breed males of this strain with females of the ring *X* strain. Some of the resulting embryos will have one ring *X* chromosome and one mutation-loaded *X* chromosome. In a fraction of these embryos the ring *X* (carrying normal genes) will be lost at an early nuclear division. The *XX* body parts of the resulting adult fly will have one *X* chromosome with normal genes and one with mutations; because both the behavioral and the anatomical genes in question are recessive (their effect is masked by the presence of a single nor-



DEVELOPMENT OF A MOSAIC FLY proceeds from nuclear division (*shown in the illustration at top of page*), in which loss of the ring *X* occurs, producing an *XX* (*color*) nucleus and an *X* (*white*) nucleus (*1*). The nuclei divide a few times (*2*), then migrate to the surface of the egg and form a blastula: a single layer of cells, shown here in section and surface views (*3*). Note that female (*XX*) cells cover part of the surface and male (*X*) cells the other part. The arrangement of male (*white*) and female (*color*) parts in the adult fly depends on the way the boundary between the *XX* and *X* cells happened to cut the blastula, and that in turn depends on the orientation of the axis along which the original nucleus divides (*4–6*).

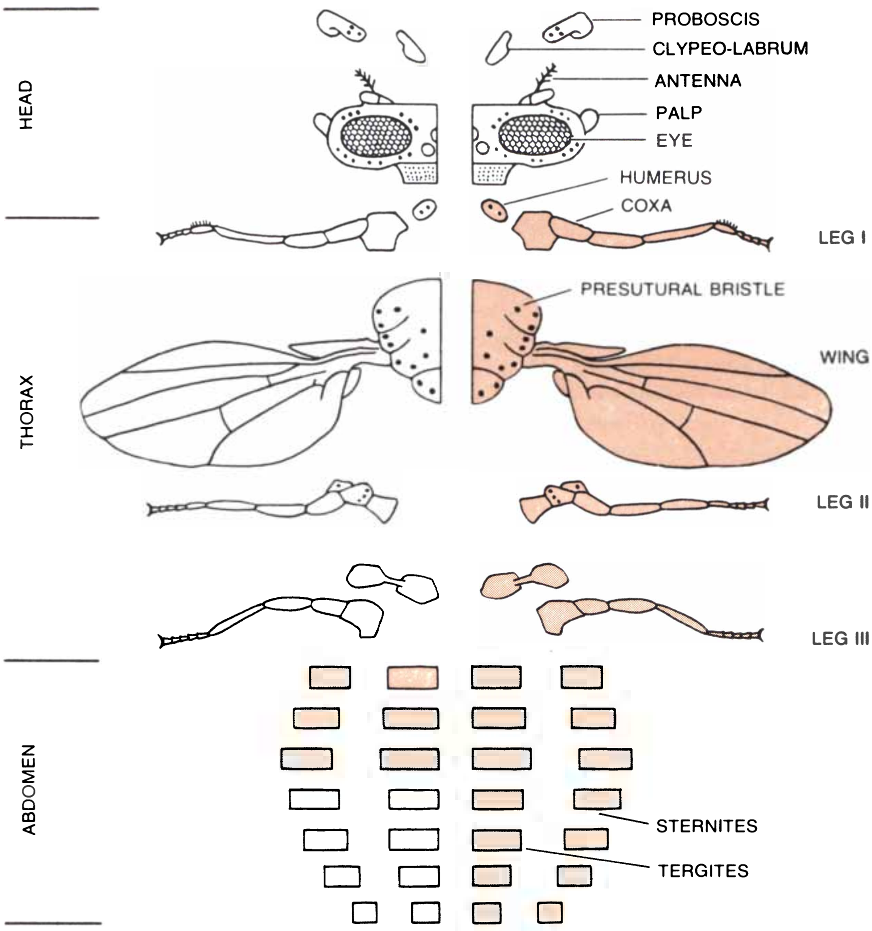
© 1973 SCIENTIFIC AMERICAN, INC

mal gene) the mutations will not be expressed in those parts. In the body parts having lost the ring *X*, however, the single *X* chromosome will be the one carrying the mutations. And because it is all alone the mutations will be expressed. Examination of the fly identifies the parts that have normal color and those in which the mutant genes have been uncovered. We can select from among the randomly divided gynandromorphs individuals in which the dividing line falls in various ways: a normal head on a mutant body, a mutant head on a normal body, a mutant eye and a normal one and so on. And then we can pose the question we originally had in mind: What parts must be mutant for the mutant behavior to be expressed?

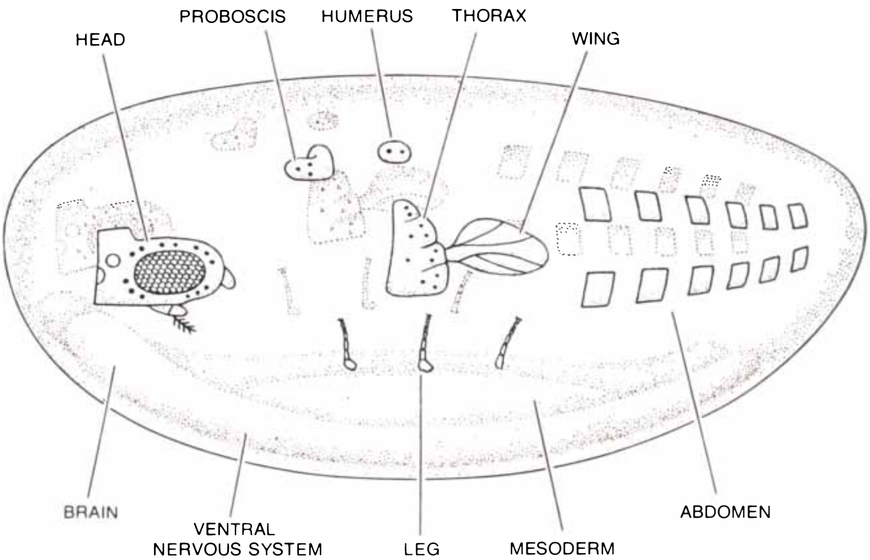
When Hotta and I did that with certain visually defective mutants, for instance ones that produce no receptor potential, we found that the electroretinogram of the mutant eye was always completely abnormal, whereas the normal eye functioned properly. Even in gynandromorphs in which everything was normal except for one eye, that eye showed a defective electroretinogram. This makes it clear that the defects in those mutants are not of the vitamin A type I mentioned above; the defect must be autonomous within the eye itself.

The behavior of flies with one good eye and one bad eye is quite striking. A normal fly placed in a vertical tube in the dark climbs more or less straight up, with gravity as its cue. If there is a light at the top of the tube, the fly still climbs straight up because phototaxis (which the fly achieves by moving so as to keep the light intensities on both eyes equal) is consistent in direction with the negative geotaxis. A mosaic fly with one good eye also climbs straight up in the dark, since its sense of gravity is unimpaired. If a light is turned on at the top, however, the fly tends to trace a helical path, turning its defective eye toward the light in a futile attempt to balance input signals. If the right eye is the bad one, the fly traces a right-handed helix; if the left eye is bad, the helix is left-handed. (Sometimes it is difficult to resist the temptation, out of nostalgia for the old molecular-biology days, to put in two flies and let them generate a double helix.)

In these mutants the primary focus of the *phototactic* defect is in the affected organ itself. More frequently, however, the focus is elsewhere. A good way to see how this situation is dealt with is to consider a *hyperkinetic* mutant that



ADULT FLY is an assembly of a large number of external body parts, each of which was formed independently from a primordial group of cells of the blastula. In a mosaic fly the boundary between male and female tissues tends to follow lines of division between discrete body parts. Here the main external parts are named; black dots are the major bristles.



FANCIFUL DRAWING of the blastula shows how each adult body part came from a specific site on the blastula: left-side and right-side parts (or left and right halves of parts such as the head) from the left and right sides of the blastula respectively. The nervous system and the mesoderm (which gives rise to the muscles) have also been shown by embryologists to originate in specified regions of the blastula. It is clear that the probability that any two parts will have a different genotype (that is, that they will be on different sides of the mosaic boundary that cuts across the blastula) will depend on how far they are from each other on the blastoderm, the blastula surface. Conversely, the probability that two parts are of different genotypes should be a measure of their distance apart on the blastoderm.

© 1973 SCIENTIFIC AMERICAN, INC

was studied by Kaplan and Kazuo Ikeda. When such a fly is anesthetized with ether, it does not lie still but rather shakes all six of its legs vigorously. Kaplan and Ikeda found that flies that are mosaics for the gene shake some of their legs but not others and that the shaking usually correlates well with the leg's surface genotype as revealed by markers—but not always. (Suzuki and his colleagues found the same to be true of flies mosaic for the *paralyzed* mutation.) The point is that the markers are on the outside of the fly. The genotype of the surface is not necessarily the same as that of the underlying tissues, which arise from different regions of the embryo. And one might well expect that leg function would be controlled by nervous elements somewhere inside the fly's body that could have a different genotype from the leg surface. The problem is to find a way of relating internal behavioral foci to external landmarks. Hotta and I developed a method of mapping this relation by extending to behavior the idea of a "fate map," which was originally conceived by A. H. Sturtevant of Cal Tech.

Sturtevant was the genius who had earlier shown how to map the sequence of genes on the chromosome by measuring the frequency of recombination among genes. He had seen that the probability of crossing over would be greater the farther apart the genes were on the chromosome. In 1929 he proposed that one might map the blastoderm in an analogous way: the frequency with which any two parts of adult mosaics turned out to be of different genotypes could be related to the distance apart on the blastoderm of the sites that gave rise to those parts. One could look at a large group of mosaics, score structure *A* and structure *B* and record how often one was normal whereas the other was mutant, and vice versa. That frequency would represent the relative distance between their sites of origin on the blastoderm, and with enough such measurements one could in principle construct a two-dimensional map of the blastoderm. Sturtevant scored 379 mosaics of *Drosophila simulans*, put his data in a drawer and went on to something else. At Cal Tech 40 years later Merriam and Antonio Garcia-Bellido inherited those 379 yellowed sheets of paper, computed the information and found they could indeed make a self-consistent map.

When Hotta and I undertook to map behavior in *D. melanogaster*, we began by preparing our own fate map of the adult external body parts based on the scores for 703 mosaic flies [*see upper illustration on these two pages*]. Distances on the map are in "sturts," a unit Merriam, Hotta and I have proposed in memory of Sturtevant. One sturt is equivalent to a probability of 1 percent that the two structures will be of different genotypes.

Now back to *hyperkinetic*. We produced 300 mosaic flies and scored each for a number of surface landmarks and for the coincidence of marker mutations at those landmarks with the shaking of each leg. We confirmed the observations of Ikeda and Kaplan that the behavior of each leg (whether it shakes or not) is independent of the behavior of the other legs and that the shaking behavior and the external genotype of a leg are frequently the same—but not always. The independent behavior of the legs indicated that each had a separate focus. For each leg we calculated the distance from the shaking focus to the leg itself and to a number of other landmarks [*see lower illustration on these two pages*] and thus determined a map location for each focus. They are near the corresponding legs but below them, in the region of the blastoderm that Donald F. Poulson of Yale University years ago identified by embryological studies as the origin of the ventral nervous system. This is consistent with electrophysiological evidence, obtained by Ikeda and Kaplan, that neurons in the thoracic ganglion of the ventral nervous system behave abnormally in these mutants.

Another degree of complexity is represented by a mutant we call *drop-dead*. These flies develop, walk, fly and otherwise behave normally for a day or two after eclosion. Suddenly, however, an individual fly becomes less active, walks in an uncoordinated manner, falls on its back and dies; the transition from apparently normal behavior to death takes only a few hours. The time of onset of the syndrome among a group of flies hatched together is quite variable; after the first two days the number of survivors in the group drops exponentially, with a half-life of about two days. It is as if some random event triggers a cataclysm. The gene has been identified as a recessive one on the *X* chromosome. Symptoms such as these could result from malfunction almost anywhere in the body of the fly, for example from a blockage of the gut, a general biochemical disturbance or a nerve disorder. In order to localize the focus we did an analysis of 403 mosaics in which the *XX* parts were normal and the *X* body parts expressed the *drop-dead* gene and surface-marker mutations, and we scored for *drop-dead* behavior and various landmarks.

Drop-dead behavior, unlike shaking behavior, which could be scored separately for each leg, is an all-or-none property of the entire fly. First we did a rough analysis to determine whether the behavior was most closely related to the head, thorax or abdomen, considering only flies in which the surface of each of these structures was either completely mutant or completely normal. Among mosaics in which the entire head surface was normal almost all behaved

COXA OF LEG I	ANTENNA: NORMAL	ANTENNA: MUTANT
NORMAL	35	12
MUTANT	13	40

$\frac{12+13}{100}$ = 25 PERCENT = 25 STURTS FROM ANTENNA TO COXA I

PRESUTURAL BRISTLE	COXA OF LEG I: NORMAL	COXA OF LEG I: MUTANT
NORMAL	45	8
MUTANT	6	41

$\frac{8+6}{100}$ = 14 PERCENT = 14 STURTS FROM COXA I TO PRESUTURAL BRISTLE

FATE MAP, a two-dimensional map of the blastoderm, is constructed by calculating the distances between the sites that gave rise to various parts. This is done by observing a large number of adult flies and recording the number of times each of two parts is mu-

SHAKING OF LEG I	COXA OF LEG I: NORMAL	COXA OF LEG I: MUTANT
NORMAL	277	51
MUTANT	33	224

$\frac{84}{600}$ = 14 STURTS FROM COXA I TO SHAKING FOCUS

SHAKING OF LEG I	ANTENNA: NORMAL	ANTENNA: MUTANT
NORMAL	253	82
MUTANT	85	180

$\frac{167}{600}$ = 28 STURTS FROM ANTENNA TO SHAKING FOCUS

BEHAVIORAL FOCI, the sites at which a mutant gene exerts its effect on behavior, are plotted in the same way. The behavior in this example (*left*) is abnormal shaking of

© 1973 SCIENTIFIC AMERICAN, INC

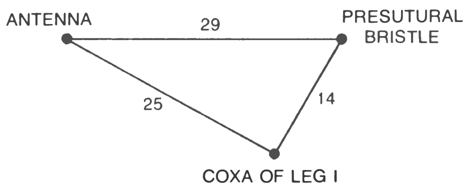
normally, but six flies out of 97 died in the *drop-dead* manner; in the reciprocal class eight flies of 80 with mutant head surfaces lived. In other words, the focus was shown to be close to, but distinct from, the blastoderm site of origin of the head surface. Comparable analysis showed that the focus was substantially farther away from the thorax and farther still from the abdomen. Next we considered individuals with mosaic heads. The reader will recall that in certain visual mutants the visual defect was always observed in the eye on the mutant side of the head; flies with half-normal heads had normal vision in one eye. For *drop-dead*, on the other hand, of mosaics in which half of the head surface was mutant only about 17 percent dropped dead. All the rest survived.

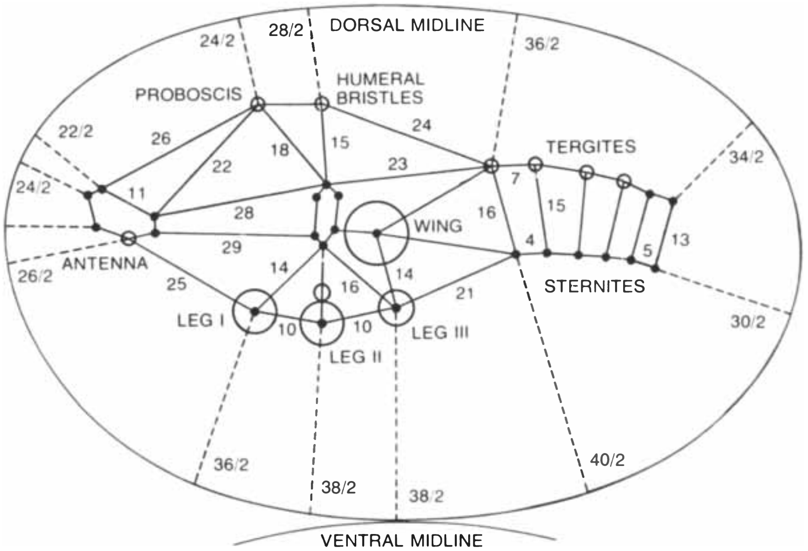
Now, a given internal part should occur in normal or mutant form with equal probability, as the external parts in these mosaics did. On that reasoning, if there were a single focus inside the head of the fly, half of the bilateral-mosaic flies should have dropped dead. We formed the hypothesis, therefore, that there must be two foci, one on each side, and that they must interact. Both of them must be mutant for the syndrome to appear. In other words, a mutant focus must be "submissive" to a normal one. In that case, if an individual exhibits *drop-dead* behavior, both foci must be mutant, and if a fly survives, one focus may be normal or both of them may be.

Mapping a bilateral pair of interacting foci calls for special analysis. By considering the various ways a mosaic dividing line could fall in relation to a pair of visible external landmarks (one on

ANTENNA	PRESUTURAL BRISTLE: NORMAL	PRESUTURAL BRISTLE: MUTANT
	34	13
MUTANT	16	37

$\frac{13 + 16}{100}$ = 29 PERCENT = 29 STURTS FROM PRESUTURAL BRISTLE TO ANTENNA

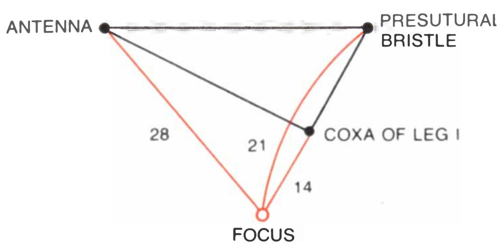


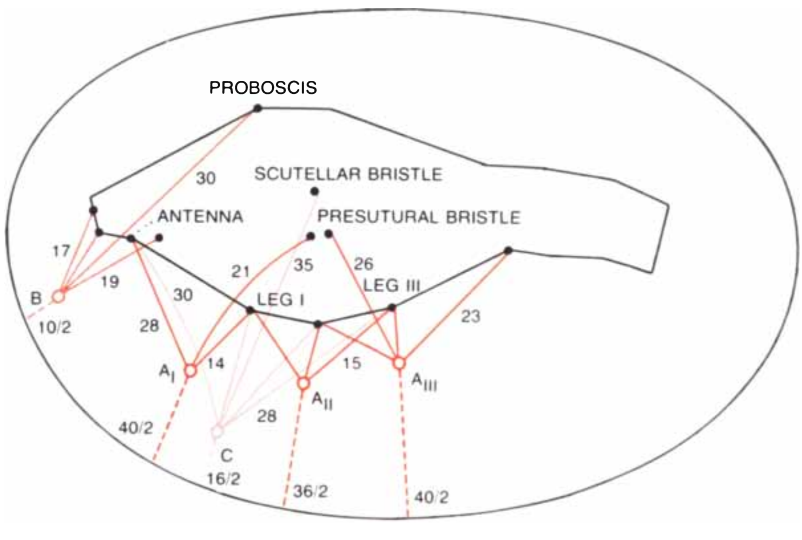


tant or normal. The numbers are entered in a matrix, as shown (*left*) for three pairs of parts. Instances in which one part is normal whereas the other part is mutant on the same fly (*colored boxes*) are totaled. That figure, divided by the total number of instances, gives the probability that the two parts are of different genotypes. And that probability is proportional to the distance between them, indicated in "sturts." Plotting the three distances triangulates the relative locations of the three sites. By thus scoring 703 mosaic flies for body parts, Yoshiki Hotta in the author's laboratory built up the fate map of external body parts (*right*). Broken lines represent distances to the blastula midlines, obtained by dividing by two the distances between homologous parts on opposite sides of the fly.

SHAKING OF LEG I	PRESUTURAL BRISTLE: NORMAL	PRESUTURAL BRISTLE: MUTANT
NORMAL	251	85
MUTANT	42	222

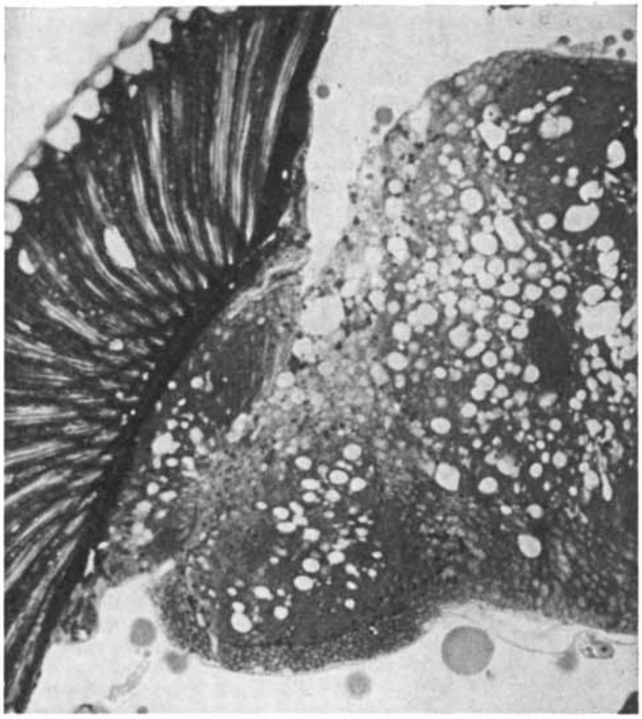
$\frac{127}{600}$ = 21 STURTS FROM PRESUTURAL BRISTLE TO SHAKING FOCUS

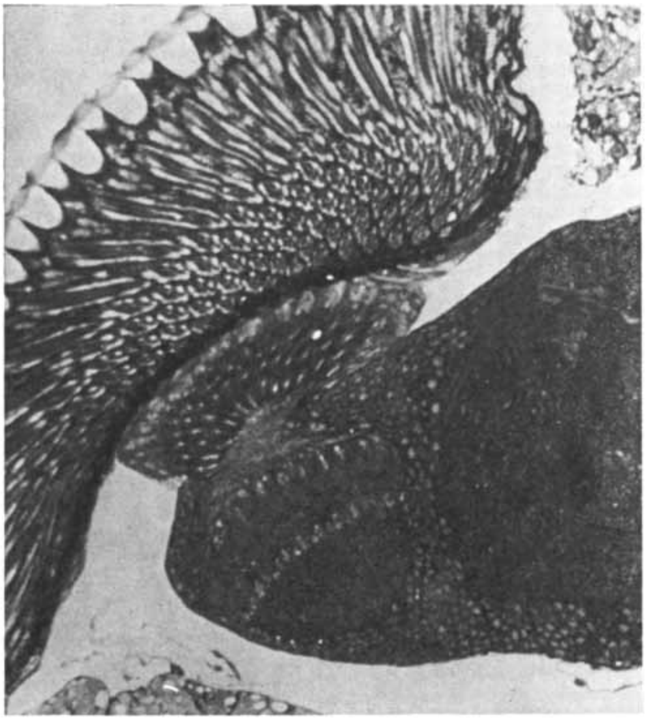




the legs under ether. The shaking is independent for each leg and here leg *I* has been scored for 300 flies—or 600 instances, since the data can be doubled to represent both sides of the fly. (The total of instances can be less than 600 because cases in which both the body part and the behavior are mosaic are eliminated.) Distances calculated (*colored lines*) triangulate the focus. In this way the foci for shaking behavior for each leg (*A*) are added to the map (*right*). Foci for *drop-dead* (*B*) and *wings-up* (*C*) behavior are also found.

© 1973 SCIENTIFIC AMERICAN, INC





BRAINS OF DROP-DEAD MUTANTS that have reached the symptomatic stage show striking degeneration, as shown by photomicrograph (*left*) of a section of such a fly's head enlarged 300 diameters. The brain and the optic ganglia are full of holes. Sections fixed before a mutant has shown any symptoms, on the other hand, show no more degeneration than a section of a normal brain does (*right*).

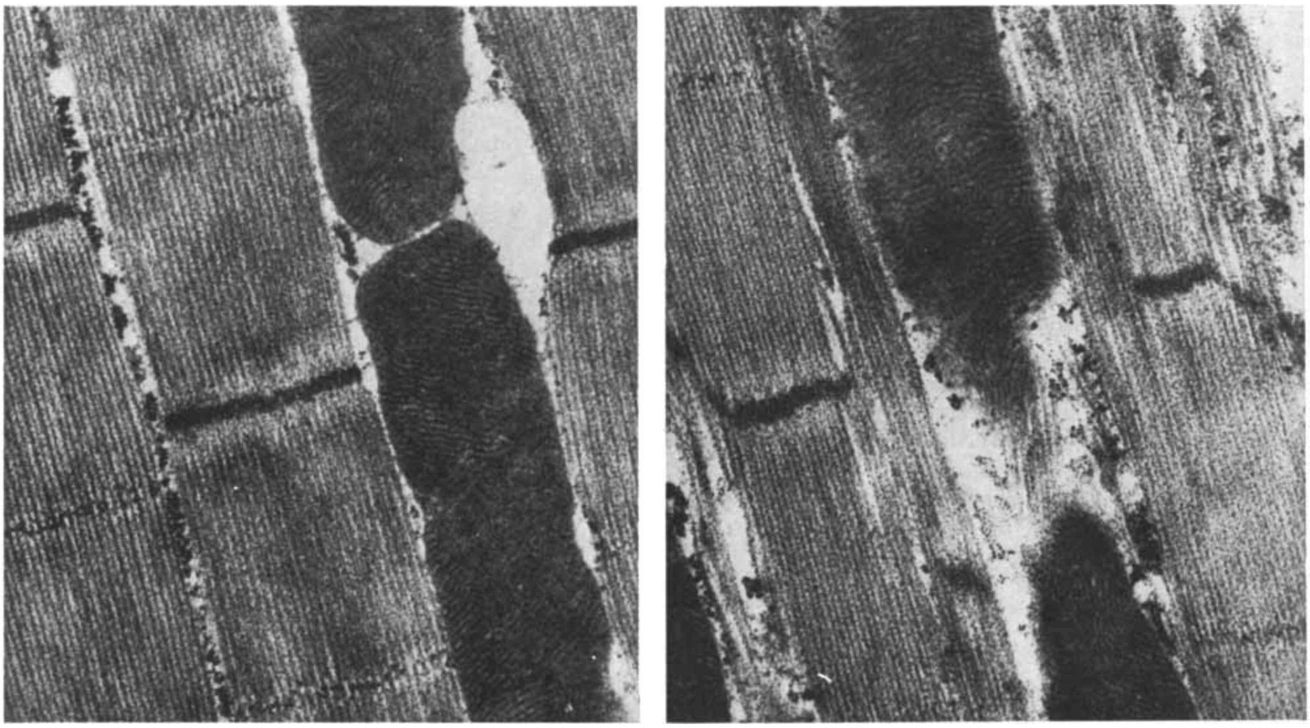
each side of the body) and a symmetrical pair of internal foci, one can set up equations based on the probability of each possible configuration. Using the observed data on how many mosaic flies showed the various combinations of mutant and normal external landmarks and mutant or normal behavior, it is possible to solve these equations for the map distance from each landmark to the corresponding focus and from one focus to the homologous focus on the other side of the embryo. The *drop-dead* foci turn out to be below the head-surface area of the blastoderm, in the area embryologists have assigned to the brain. Sure enough, when we examined the brain tissue of flies that had begun to exhibit the initial stages of *drop-dead* behavior, it showed striking signs of degeneration, whereas brain tissue fixed before the onset of symptoms appeared normal. As for mosaics whose head surfaces are half-normal, those that die show degeneration of the brain on both sides; the survivors' brains show no degeneration on either side, a finding consistent with the bilateral-submissive-focus hypothesis. It appears that the normal side of the brain supplies some factor that prevents the deterioration of the side with the mutant focus.

There is another kind of bilateral focus, "domineering" rather than submissive. An example is the mutant we call *wings-up*. There are two different genes, *wup A* and *wup B,* which produce very similar overt behavior: shortly after emergence each of these flies raises its wings straight up and keeps them there. It cannot fly, but otherwise it behaves normally. Is *wings-up* the result of a defect in the wing itself, in its articulation or in the muscles or neuromuscular junctions that control the wing, or of some "psychological quirk" in the central nervous system? The study of mosaic flies shows that the behavior is more often associated with a mutant thorax than with a mutant head or abdomen. The focus cannot be in the wings themselves or anywhere on the surface of the thorax, however, because in some mosaics the wings and the thorax surface are normal and yet the wings are held up and in other mosaics the wings and thorax display all the mutant markers and yet the fly flies. These observations suggest that some structure inside the thorax could be responsible.

Once again we look at the bilateral mosaics, those with one side of the thorax carrying mutant markers and the other side appearing normal. Unlike the *drop-dead* bilateral mosaics, most of which were normal, these bilaterals are primarily mutant; well over half of them hold both wings up. Both wings seem to act together; either both are held up or both are in the normal position. This suggests two interacting foci, one on each side, with the mutant focus domineering with respect to the normal one, that is, if either of the foci is mutant, or both are, then both wings will be up. Again we can set up equations based on the probability of the various mosaic configurations and solve to find the pertinent map distances. The focus comes out to be close to the ventral midline of the blastula. That is a region known to produce the mesoderm, the part of the developing embryo from which muscle tissue is derived, which suggested that a defect in the fly's thoracic muscle tissue could be responsible for *wings-up* behavior.

The abnormality became obvious when we dissected the thorax. In the fly the raising and lowering of the wings in normal flight is accomplished by changes in the shape of the thorax, changes brought about by the alternate action of sets of vertical and horizontal muscles. Under the phase-contrast microscope these indirect flight muscles are seen to be highly abnormal in both *wings-up* mutants. Developmental studies show that in *wup A* the muscles form properly at first, then degenerate after the fly emerges. In the *wup B* mutant, on the other hand, the myoblasts that normally produce the muscles fuse properly but the muscle fibrils fail to appear. In both mutants the other muscles, such as those of the leg, appear to be quite normal,

© 1973 SCIENTIFIC AMERICAN, INC



FLIGHT MUSCLE OF WINGS-UP MUTANTS shows degeneration that seems to account for their behavior. Normal flight muscle, enlarged 30,000 diameters in an electron micrograph, has bundles of filaments crossed by straight, dense bands: the *Z* lines (*left*). In the muscle of flies heterozygous for the gene *wup B*, which hold their wings normally but cannot fly, the *Z* lines are irregular (*right*).

and the flies walk and climb perfectly well. In flies that are heterozygous for *wup A* (nonmosaic flies with one mutated and one normal gene) the muscles and flight behavior are normal, that is, the gene is completely recessive. In *wup B* heterozygotes, on the other hand, the wings are held in the normal position but the flies cannot fly. Electron microscopy shows that even in these heterozygotes the indirect flight muscles are defective: the microscopic filaments that constitute each muscle fibril are arranged correctly, but the Z line, a dense region that should run straight across the fibril, is often crooked and forked. Examination of the muscles in bilateral mosaics confirmed the impression that the *wup* foci are domineering. In every mosaic that had shown *wings-up* behavior one or more muscle fibers were degenerated or missing; no fibers were seriously deficient in any flies that had displayed normal behavior. The natural shape of the thorax apparently corresponds to the *wings-up* position, and the presence of defective muscles on either side is enough to make it impossible to change the shape of the thorax, locking the wings in the vertical position.

The mutants so far mapped provide examples involving the main components of behavior: sensory receptors, the nervous system and the muscles. For some of the mutants microscopic examination has revealed a conspicuous lesion of some kind in tissue. The obvious question is whether or not fate mapping is necessary; why do we not just look directly for abnormal tissue? One answer is that for many mutants we do not know where to begin to look, and it is helpful to narrow down the relevant region. Furthermore, in many cases no lesion may be visible, even in the electron microscope. More important, and worth reiterating, is the fact that the site of a lesion is not necessarily the primary focus. For example, an anomaly of muscle tissue may result from a defect in the function of nerves supplying the muscle. This possibility has been a lively issue in the study of diseases such as muscular dystrophy. Recently, by taking nerve and muscle tissues from a dystrophic mutant of the mouse and from its normal counterpart and growing them in tissue culture in all four combinations, the British workers Belinda Gallup and V. Dubowitz were able to show that the nerves are indeed at fault.

The mosaic technique in effect does the same kind of experiment in the intact animal. In the case of the *wings-up* mutant the primary focus cannot be in the nerves, since if that were so the focus would map to the area of the blastoderm destined to produce the nervous system, not to the mesoderm, where muscle tissue is formed. The *wings-up* mutants clearly have defects that originate in the muscles themselves.

Another application of mosaics is in tagging cells with genetic labels to follow their development. The compound eye of *Drosophila* is a remarkable structure consisting of about 800 ommatidia: unit eyes containing eight receptor cells each. The arrangement of cells in an ommatidium is precise and repetitive; the eye is in effect a neurological crystal in which the unit cell contains eight neurons. Thomas E. Hanson, Donald F. Ready and I have been interested in how this structure is formed. Are the eight photoreceptor cells derived from one cell that undergoes three divisions to produce eight, or do cells come together to form the group irrespective of their lineage? This can be tested by examining the eyes of flies, mosaic for the *white* gene, in which the mosaic dividing line passes through the eye. By sectioning the eye and examining ommatidia near the border between white and red areas microscopically, it is possible to score the tiny pigment granules that are present in normal photoreceptor cells but absent in *white* mutant cells. The result is clear: A single ommatidium can contain a mixture of receptor cells of both genotypes. This proves that the eight cells cannot be derived from a single ancestral cell but have become associated in their special

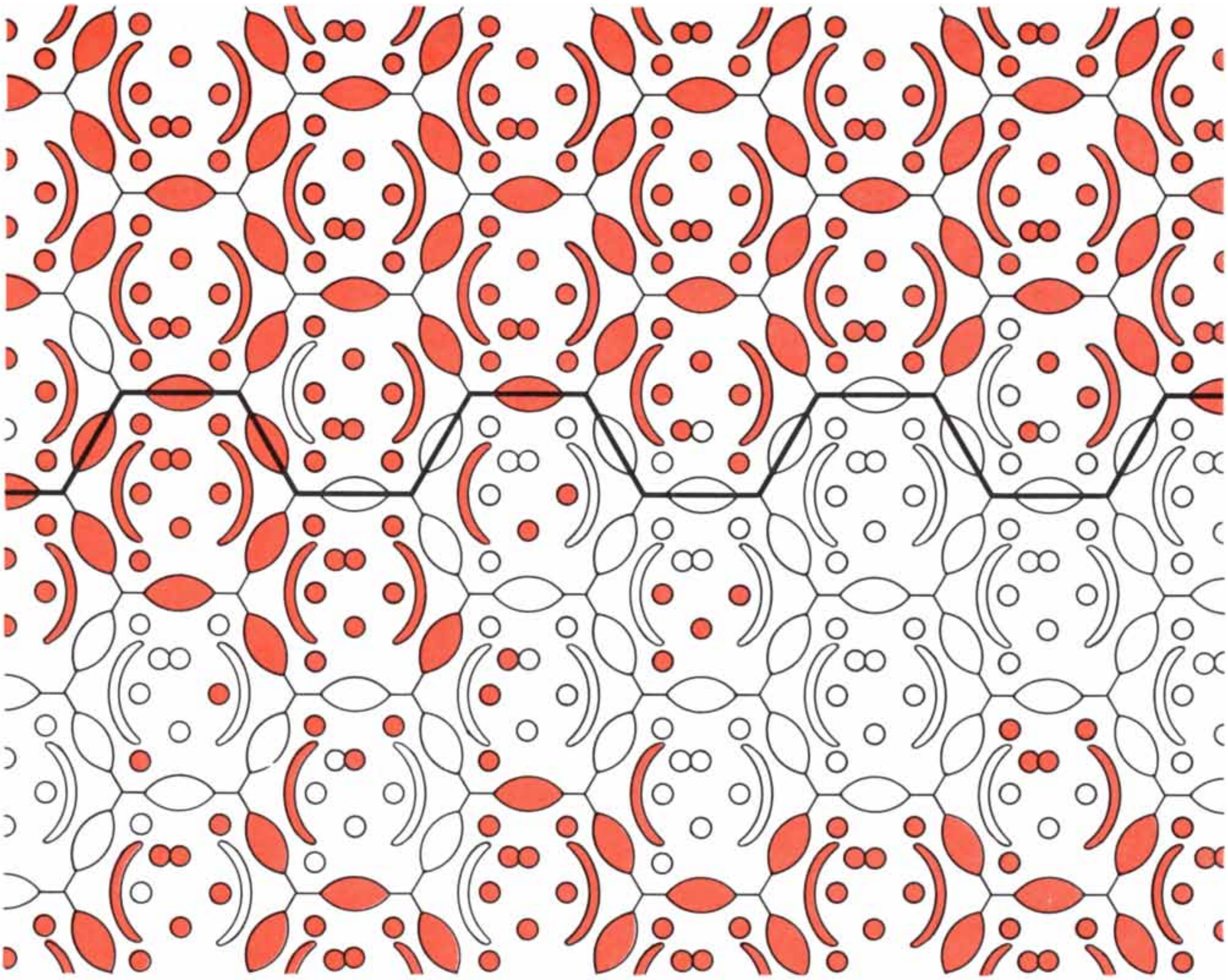
© 1973 SCIENTIFIC AMERICAN, INC

group of eight irrespective of lineage. The same conclusion applies to the other cells in each ommatidium, such as the normally heavily pigmented cells that surround the receptors.

Not all cells have such convenient pigment markers. It would obviously be valuable to have a way of labeling all the internal tissues as being either mutant or normal, much as yellow color labels a landmark on the surface. This can now be done for many tissues by utilizing mutants that lack a specific enzyme. If a recessive enzyme-deficient mutant gene is recombined on the *X* chromosome along with the *yellow, white* and behavioral genes and mosaics are produced in the usual way, the male tissues of the mosaic will lack the enzyme. By making a frozen section of the fly and staining it for enzyme activity one can identify normal and mutant cells.

In order to apply this method in the nervous system one needs to have an enzyme that is normally present there in a large enough concentration to show up in the staining procedure and a mutant that lacks the enzyme, and the lack should have a negligible effect on the behavior under study. Finally, the gene in question should be on the *X* chromosome. Douglas R. Kankel and Jeffrey Hall in our laboratory have developed several such mutants, including one with an acid-phosphatase-deficient gene found by Ross J. MacIntyre of Cornell University. By scoring the internal tissues they have constructed a fate map of the internal organs of the kind made earlier for surface structures. We are now adapting the staining method for electron microscopy in order to work at the level of the individual cell.

The staining procedure has demonstrated graphically that the photoreceptor cells of the eye come from a different area of the blastoderm than do the neurons of the lamina, to which they project. In the adult fly the two groups of cells are in close apposition, but the former arise in the eye whereas the latter come from the brain. The distance between them on the fate map, determined by Kankel, is about 12 sturts, so that a considerable number of mosaic flies have a normal retina and a mutant lamina or vice versa. This makes it possible to distinguish between presynaptic and postsynaptic defects in mutants with blocks in the visual pathway. In the nonphototactic mutants Hotta and I analyzed in mosaics, the defect in the electroretinogram was always associated with the eye. In contrast, a mutant with a similar electroretinogram abnormality that was studied by Linda Hall and Suzuki



MOSAIC EYE contains a patch of cells that carry the *white* gene and therefore lack the normal red pigment. The fly's compound eye is an array of hexagonal ommatidia, each containing eight photoreceptor cells (*circles*) and two primary pigment cells (*crescents*) and surrounded by six shared secondary pigment cells (*ovals*). The fact that a single ommatidium can have *white* and normal genotypes shows its cells are not necessarily descended from a common ancestral cell. Nor is the mirror-image symmetry about the equator (*heavy line*) the result of two cell lines: mutant cells appear on both sides. Drawing is based on observations by Donald Ready.

© 1973 SCIENTIFIC AMERICAN, INC

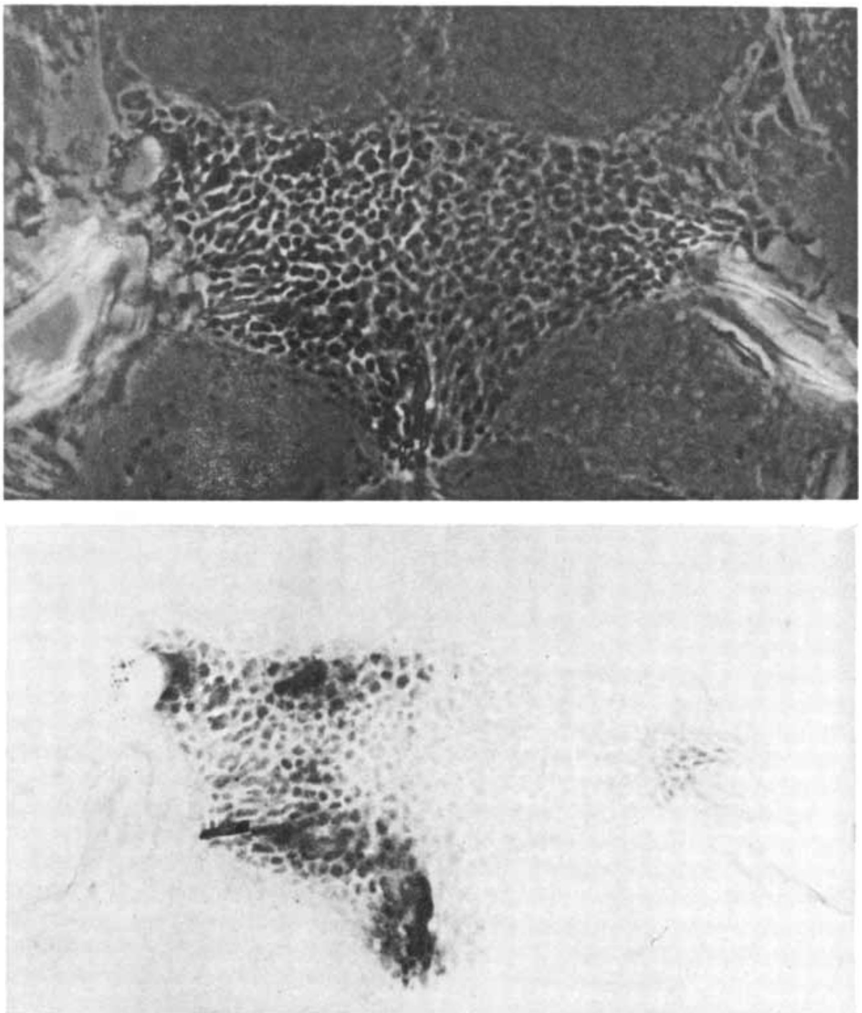
showed, in some mosaics, a normal trace for a mutant eye—and vice versa. Fate mapping placed the focus in precisely the region corresponding to the lamina. What appeared to be similar malfunctions in two mutants were thus shown to be different, due in one case to a presynaptic block and in the other case to a postsynaptic one.

Much of what has been done so far involves relatively simple aspects of behavior chosen to establish the general methodology of mutants and mosaic analysis. Can the methodology be applied to more elaborate and interesting behavior such as circadian rhythm, sexual courtship and learning? Some beginnings have been made on all of these. By making flies that are mutant for normal and mutant rhythms, Konopka has shown that the internal clock is most closely associated with the head. Looking at flies with mosaic heads, he found that some exhibited the normal rhythm and others the mutant rhythm but that a few flies exhibited a peculiar rhythm that appears to be a sum of the two, as if each side of the brain were producing its rhythm independently and the fly responded to both of them. By applying the available cell-staining techniques it may be possible to identify the cells that control the clock.

Sexual courtship is a higher form of behavior, since it consists of a series of fixed action patterns, each step of which makes the next step more likely. The sex mosaics we have generated lend themselves beautifully to the analysis of sexual behavior. A mosaic fly can be put with normal females and its ability to perform the typical male courtship steps can be observed. Hotta, Hall and I found that the first steps (orientation toward the female and vibrating of the wings) map to the brain. This is of particular interest because the wings are vibrated by motor-nerve impulses from the thoracic ganglion; even a female ganglion will produce the vibration "song" typical of the male if directed to do so by a male brain. It would appear that the thoracic ganglion in a female must "know" the male courtship song even though she does not normally emit it. This is consistent with recent experiments by Ronald Hoy and Robert Paul at the State University of New York at Stony Brook, in which they showed that hybrid cricket females responded better to the songs of hybrid males than to males of either of the two parental species.

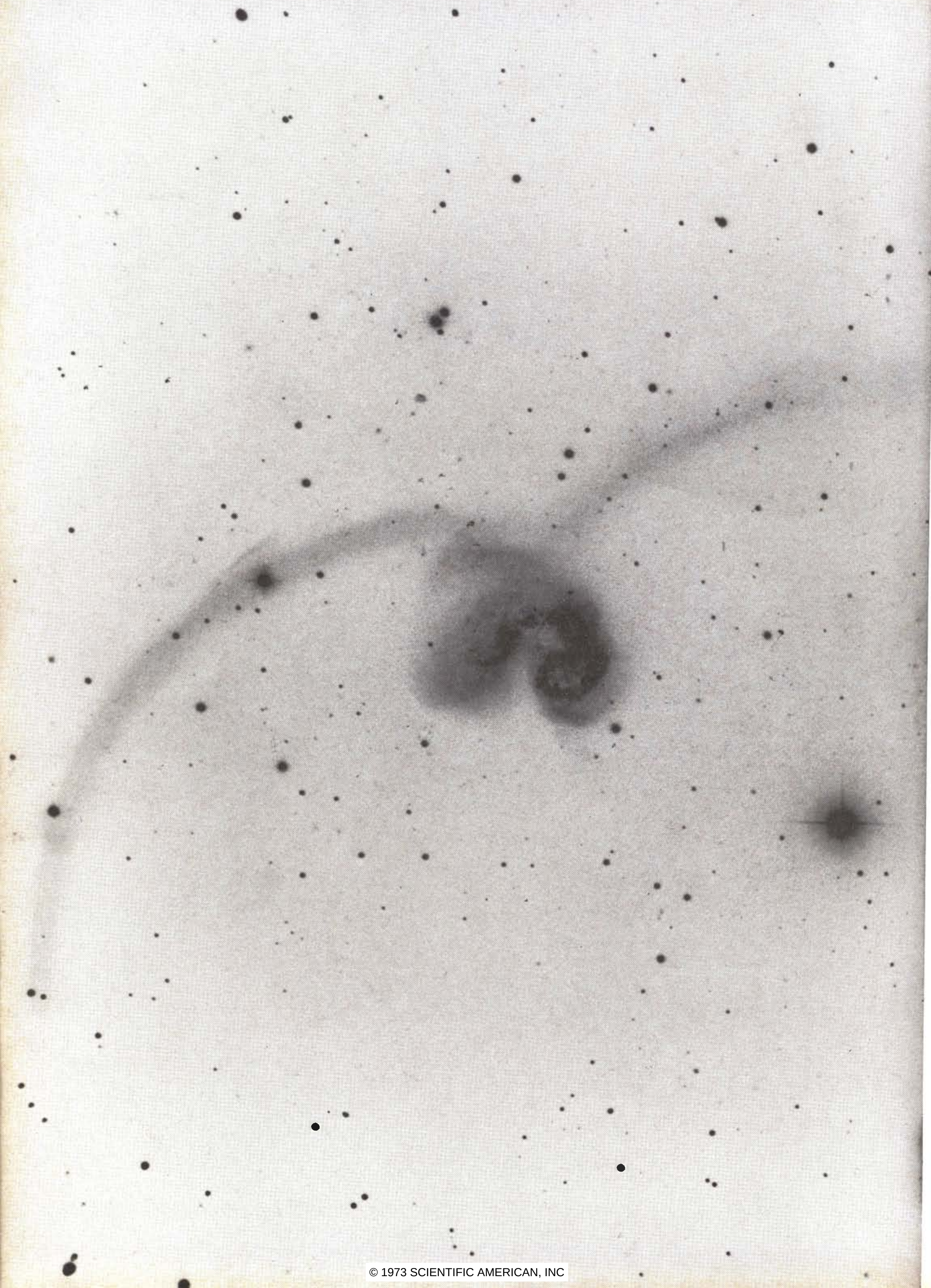
Sexual behavior in *Drosophila*, although complex, is a stereotyped series of instinctive actions that are performed correctly by a fly raised in isolation and without previous sexual experience. Other forms of behavior such as phototaxis also appear to be already programmed into the fly when it ecloses. Whether a fruit fly can learn has long been debated; various claims have been made and later shown to be incorrect. Recently William G. Quinn, Jr., and William A. Harris in our laboratory have shown in carefully controlled experiments that the fly can learn to avoid specific odors or colors of light that are associated with a negative reinforcement such as electric shock. This opens the door to genetic analysis of learning behavior through mutations that block it.

In tackling the complex problems of behavior the gene provides, in effect, a microsurgical tool with which to produce very specific blocks in a behavioral pathway. With temperature-dependent mutations the blocks can be turned on and off at will. Individual cells of the nervous system can be labeled genetically and their lineage can be followed during development. Genetic mosaics offer the equivalent of exquisitely fine grafting of normal and mutant parts, with the entire structure remaining intact. What we are doing in mosaic mapping is in effect "unrolling" the fantastically complex adult fly, in which sense organs, nerve cells and muscles are completely interwoven, backward in development, back in time to the blastoderm, a stage at which the different structures have not yet come together. Filling the gaps between the one-dimensional gene, the two-dimensional blastoderm, the three-dimensional organism and its multidimensional behavior is a challenge for the future.



DIRECT SCORING OF NORMAL AND MUTANT CELLS within the nervous system is possible with a staining method developed by Douglas Kankel and Jeffrey Hall in the author's laboratory. Mosaics are produced in which mutant cells are deficient in the enzyme acid phosphatase. When the proper stain is applied to a section of nerve tissue, normal cells stain brown and mutant cells are unstained. Here a section of the thoracic ganglion, thus stained, is shown in phase-contrast (*top*) and bright-field (*bottom*) photomicrographs. In the bottom picture normal cells are marked by the stain, delineating the mosaic boundary.

© 1973 SCIENTIFIC AMERICAN, INC



© 1973 SCIENTIFIC AMERICAN, INC

Violent Tides between Galaxies

The peculiar forms of certain galaxies could be a result of tidal distortions. This theory, out of favor for a decade, seems to be confirmed by experiments with computer models of galaxies

by Alar and Juri Toomre

Almost every crowd includes a few charming eccentrics or confounded exceptions. This is true of the "crowd" of galaxies. Most are objects of majestic regularity and symmetry and can be readily classified. One or 2 percent, however, do not conform. Because of their bizarre appearance or unusual spectra they are known to astronomers as "peculiar" galaxies.

Many of the galaxies that are peculiar in shape are members of multiple-galaxy systems, and it is only natural to suppose that their unusual and sometimes even grotesque forms may have resulted from the interaction of two or more galaxies. The nature of this interaction has been a matter of controversy, however. In the 1950's, when large numbers of galaxies with strange appendages were first discovered, it was immediately proposed that these morphological anomalies were the aftereffects of gravitational forces exerted during near collisions between galaxies. In the 1960's this idea fell into disrepute, although no alternative theory won general acceptance. In the 1970's computer experiments such as those described here have begun to reaffirm that gravitation may in fact be responsible for the appearance of some of the most peculiar galaxies.

One of the most strikingly peculiar galaxy pairs was discovered before it had been demonstrated that galaxies other than our own exist and can be seen from the earth. In 1917 C. O. Lampland noted that long, faint filaments were visible on improved photographic plates of a double nebulosity listed in the 1888 New General Catalogue (NGC) as entries 4038 and 4039. The objects were photographed again in 1921 with the newly completed 100-inch Hooker telescope on Mount Wilson. J. C. Duncan, who made the Mount Wilson photographs, was particularly impressed by "faint extensions of extraordinary appearance," rather "like antennae" [*see illustration on opposite page*].

The curving filaments do resemble the antennae of an insect, and the system has become known as the Antennae. It is about 50 million light-years from our galaxy, which among galaxies is not a very great distance. Only about 1,000 easily recognized galaxies lie closer to ours.

The only other notably peculiar object found in this era was discovered by Heber D. Curtis in 1918; he observed a small, luminous "jet" protruding from Messier 87, later identified as an elliptical galaxy at about the same distance as the Antennae. (The Messier catalogue was compiled by Charles-Joseph Messier of France about 1800.)

By 1924 Edwin P. Hubble had deduced that many of the objects then called nebulae were in fact galaxies. The following two decades were an important period of discovery for extragalactic astronomy, yet almost none of the many galaxies identified seemed as bizarre as the Antennae or M87. The only exception, perhaps, was the "faint but definite band of nebulosity" that Philip C. Keenan found to connect two rather widely separated galaxies, NGC 5216 and 5218 [*see top illustration on page 48*].

One reason that scant attention was paid to peculiar galaxies was that an intense effort was being made to understand "ordinary" galaxies. The diversity of forms was great even among those galaxies that clearly fitted Hubble's broad categories of elliptical, spiral and irregular galaxies. In addition, basic questions of the size, distance and velocity of the galaxies remained to be answered. Hubble himself knew of the Antennae and urged Duncan to take an interest in them, but he never systematically searched for similar galaxies.

There is another reason, however, that few peculiar galaxies were discovered in this period: the instruments in use were ill-suited to finding them. As we now know, the "links," "wisps," "plumes," "streamers," "filaments" or "extensions" exhibited by one or two galaxies in a hundred are usually quite faint; they are often little brighter than the night glow of the earth's atmosphere. Such dim, extended features are not easily detected with the type of telescope that was then available. Telescopes such as the 100-inch reflector on Mount Wilson, which has a focal ratio of $f/5$, are quite "slow," that is, they require long exposure times. To photograph the filaments of the Antennae, for example, would take an entire night. In addition, the field of view of such instruments is narrow: about a quarter of a degree, or half the apparent diameter of the moon. For the observation of the faint, extended features of galaxies a "faster" instrument with a wide field of view was needed. A suitable telescope was invented by Bernhard Schmidt in 1931; it provides a focal ratio of about $f/2$ for faster exposures.

A 48-inch Schmidt telescope went into

LONG, FAINT FILAMENTS **curve away from the pair of galaxies NGC 4038 and NGC 4039, also known as the Antennae. These two galaxies, whose "tails" extend across more than a third of a degree of arc in the sky, are almost certainly genuine companions and not merely objects superimposed in our line of sight. The photograph was taken in 1956 by Fritz Zwicky with the 200-inch Hale reflecting telescope on Palomar Mountain. It is printed as a negative rather than in the conventional white on black to accentuate the faint features.**

© 1973 SCIENTIFIC AMERICAN, INC

operation on Palomar Mountain in 1949 as a major partner to the just installed 200-inch Hale telescope. For the next seven years this large Schmidt telescope was used to photograph all the northernmost three-quarters of the sky visible from California in a pattern of almost 900 overlapping square fields, each seven degrees on a side. This was the Palomar Sky Survey; when it was complete, the number of known peculiar galaxies had grown from a few to an untidy and baffling multitude.

By 1956 Fritz Zwicky of the California Institute of Technology wrote that "a surprisingly large number of rather widely separated galaxies appear connected by luminous intergalactic formations." In addition, particularly among close pairs and other multiple galaxies, "many were found to possess long extensions not previously known." Zwicky had somewhat anticipated these discoveries through his work with an 18-inch Schmidt, and he went on to make detailed photographs of many of the galaxies with the 200-inch telescope.

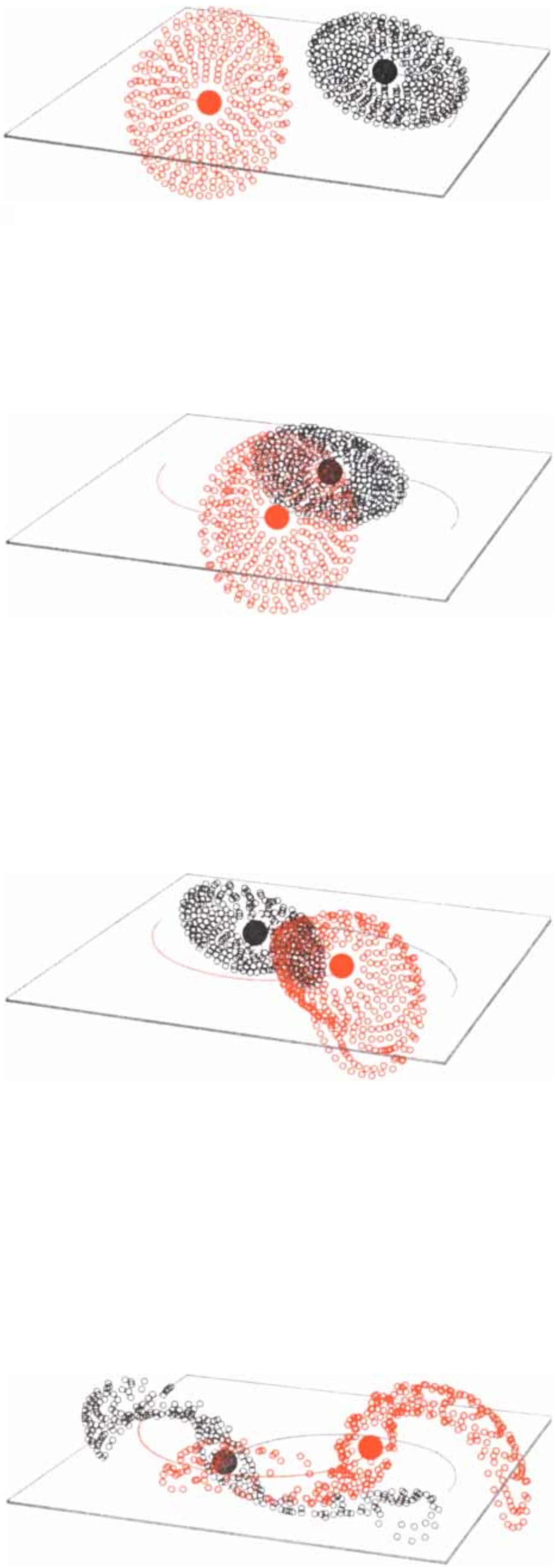
By 1959 the Russian astronomer B. A. Vorontsov-Velyaminov compiled an illustrated catalogue of 355 "interacting" galaxies based on the Sky Survey. Others discovered still more, rephotographed the known ones to larger scale and studied them spectroscopically [see "Peculiar Galaxies," by Margaret and Geoffrey Burbidge; Scientific American, February, 1961]. Today a particularly fine collection of more than 300 photographs

1

2

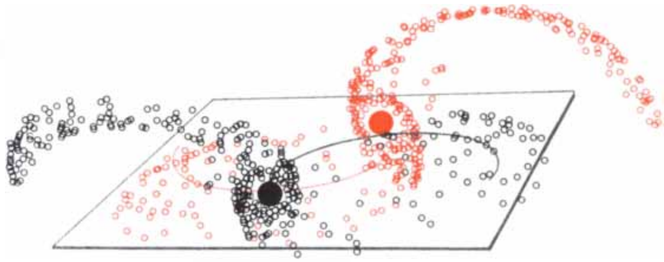
3

4

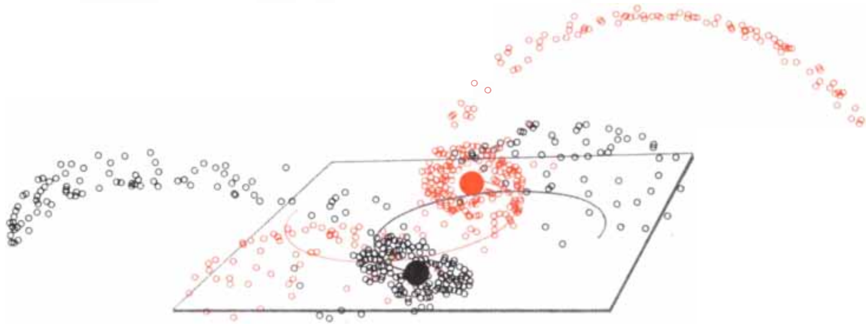


SEQUENCE OF DRAWINGS by computer shows the very close passage of two identical model galaxies and demonstrates how the encounter between them can produce two tidal tails similar to the tails in the photograph of the Antennae (*see illustration on page 38*). In the computer sequence the mass and gravitational force of each galaxy are concentrated at its center (*large central dot*). Around this central mass rotates a disk of some 350 massless test particles. The two central masses approach each other in elliptical orbits in one plane (*1 and 2*), bringing their disks of particles with them. Even before they reach the instant of closest approach (*3*) they feel a severe pull from the other central mass. Soon the effects due to tidal forces are dominant (*4*), and as more time passes, the material from the far side of each former disk stretches into an ever lengthening tail of debris (*5–7*). The two narrow, arching tails would appear to be crossed, and the bodies of the galaxies would almost overlap if the end product of the encounter (*8*) were viewed from the direction of the arrow. Successive frames are separated by an interval of 100 million years.

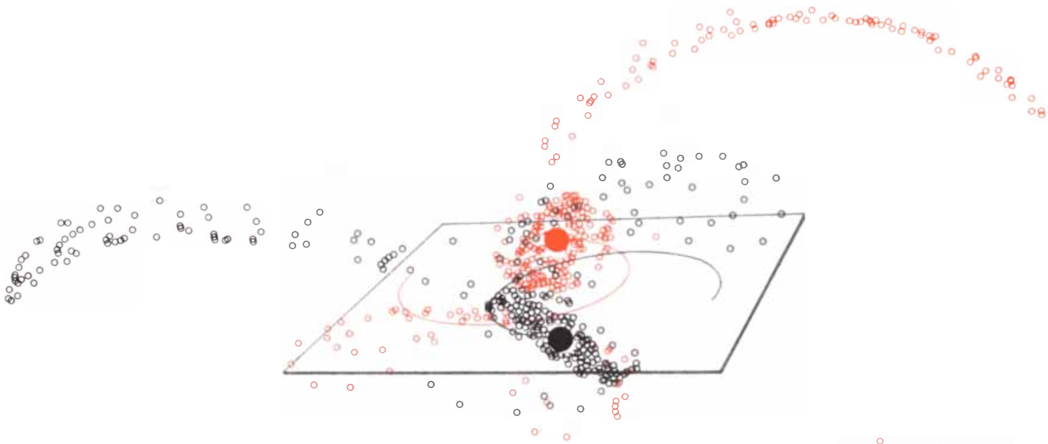
© 1973 SCIENTIFIC AMERICAN, INC



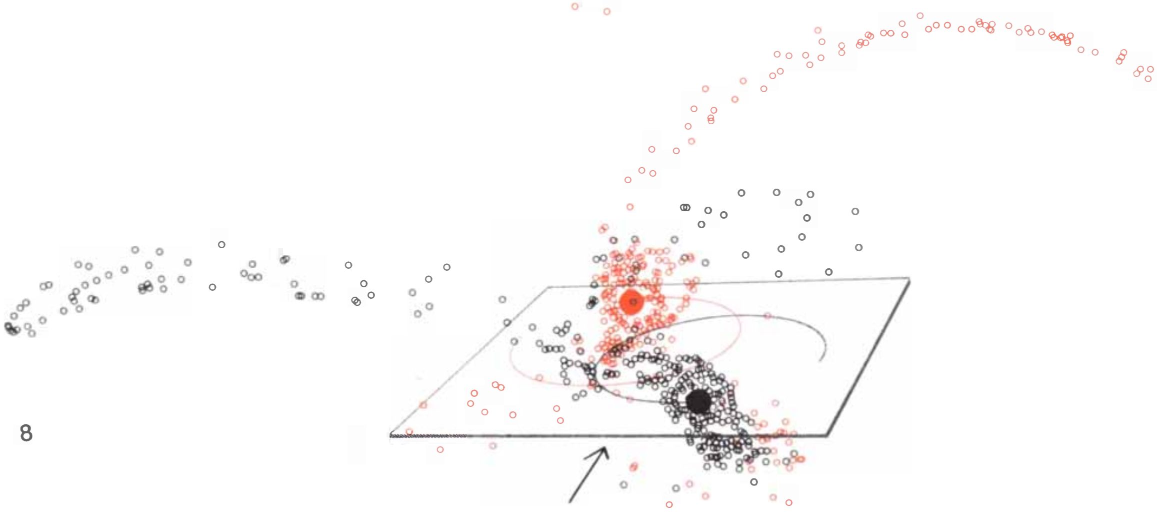
5



6

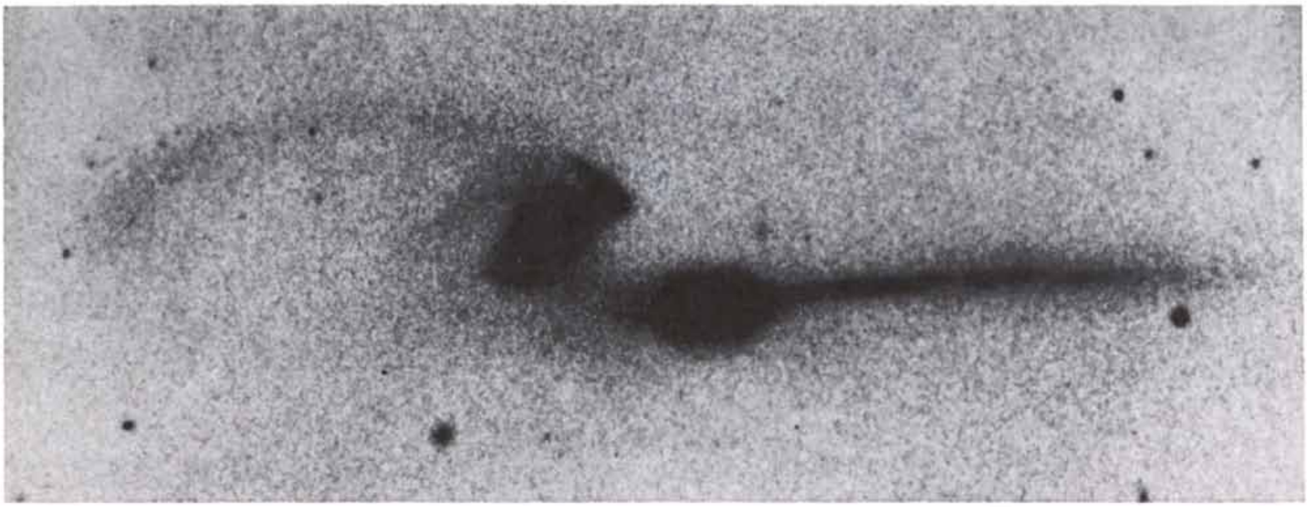


7

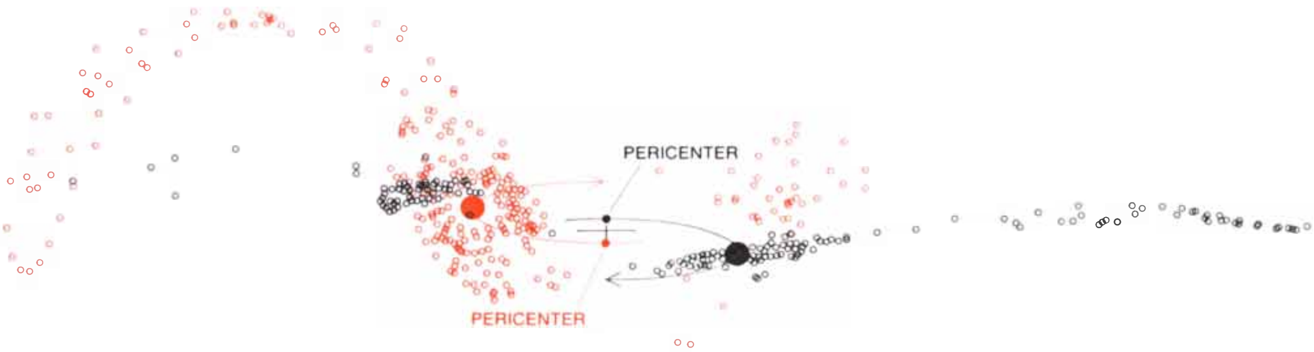


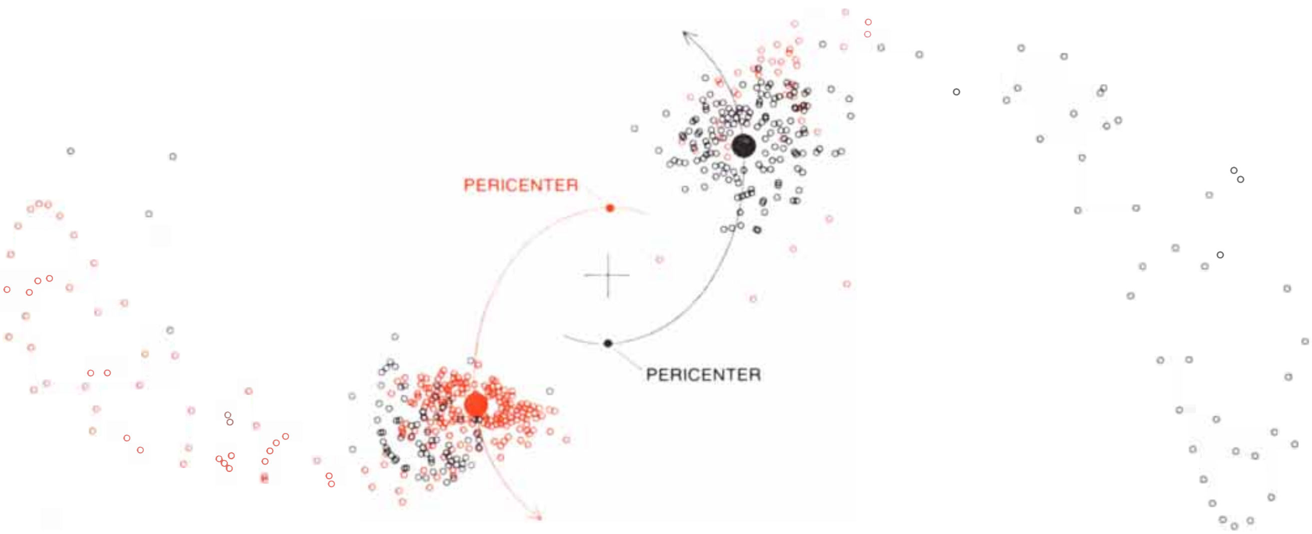
8

© 1973 SCIENTIFIC AMERICAN, INC



ANOTHER PAIR OF TAILS dominates the pair of galaxies NGC 4676A (*right*) and NGC 4676B (*left*), nicknamed "the Mice." The long tail from NGC 4676A is intense, narrow and almost straight; the one from NGC 4676B appears fainter, more diffuse and much more curved in this photograph made by Halton C. Arp with the 200-inch telescope. The Mice seem roughly one-quarter the angular size of the Antennae yet they are also four times more distant. Hence the true dimensions of the two systems are comparable.





COMPUTER-SIMULATED CLOSE PASSAGE of two identical galaxies yielded the long tails of tidal debris viewed from two separate directions. The top diagram models the actual view of the Mice in the photograph at the top of the page; the bottom diagram repeats the scene as if it were viewed from a direction nearly at right angles. The pericenter is point of closest approach. The central cross marks the center of mass of the system for reference. Long before the encounter each galaxy was again taken to be a circular disk of test particles revolving around a central mass. The two disks grazed each other in elliptical orbits. The tails and surviving bodies of the galaxies appear dissimilar only because each disk was tilted at a different angle with respect to the plane of its orbit around the other. The less tilted disk on the right spilled the material from its far side into a nearly flat tail that lies almost in its orbital plane; the more tilted disk on the left produced the tail that arches high above the plane in the top view.

© 1973 SCIENTIFIC AMERICAN, INC

of these objects exists in the *Atlas of Peculiar Galaxies* published in 1966 by Halton C. Arp of the Hale Observatories.

None of these later discoveries closely resemble the Antennae, but a number do exhibit luminous arcs extending far into space from at least one galaxy in a group. All such curving filaments have come to be known as "tails"; two are evident in NGC 4676, a pair of galaxies named the Mice [*see illustrations on opposite page*].

The connecting filaments, or "bridges," also assume many forms. One type is represented by the narrow link discovered by Keenan in 1935; Arp's *Atlas* shows many others. One class of bridges seems particularly distinctive. It consists of galactic systems in which a much elongated spiral arm seems almost to grope for a neighboring galaxy. In many cases another limb projects from the opposite side of the deformed galaxy.

Whatever gave rise to these intergalactic bridges and such formations as the Mice and the Antennae? The answer is not yet certain. It appears, however, that the intuitions of the observers of the 1950's may have been for the most part correct.

The obvious clue available to workers such as Zwicky was that most of the distorted galaxies come in pairs. It was also evident from the shapes and rotational motions of many normally formed galaxies that gravitation remains significant even on a galactic scale, over distances of tens of thousands of light-years. Hence it was natural to wonder if the bizarre forms might represent damage that adjacent galaxies had inflicted on one another by their mere presence and gravity. In other words, could we be viewing colossal tides?

Zwicky believed that tides could in fact explain the tails and bridges. He considered as being particularly good evidence the far-side features, or "counterarms," that usually accompany intergalactic bridges. These offered a crude two-sided symmetry analogous to that of more familiar tides, such as those induced in the terrestrial oceans chiefly by the moon. On the earth high tide comes every 12 hours rather than every 24 because the water level is raised not only at the moving point closest to the moon but also at the point diametrically opposite [see "Tides and the Earth-Moon System," by Peter Goldreich; SCIENTIFIC AMERICAN, April, 1972].

Unlike the orbit of the earth and moon, however, the orbits of most galactic partners probably are not almost circular. For a few years in the 1950's it was widely supposed that many such pairs were not even true satellites or companions. They were believed instead to be mere passersby that had almost collided in their separate courses through space.

One reason this close-approach hypothesis became popular was that only grazing passages seemed capable of producing tides of sufficient magnitude: the tide-raising force varies approximately as the inverse of the cube of the separation of the two bodies, and so it decreases with distance even more rapidly than gravity itself. A second and more enticing reason, however, was that actual collisions between galaxies gave promise of explaining the powerful sources of radio-frequency signals, such as Cygnus A, that had recently been discovered [see "Colliding Galaxies," by Rudolph Minkowski; SCIENTIFIC AMERICAN, September, 1956].

Cygnus A was the first discrete source of radio waves detected outside the solar system, and it remains the most powerful extragalactic radio source perceived here. It was identified with a visible object by Walter Baade and Rudolph Minkowski in 1951. They found that it is at an enormous distance, by modern estimates about a billion light-years, and that it must therefore radiate prodigious quantities of radio energy. Its optical spectrum was also found to be unusual; it suggests gases in a high state of excitation.

Photographs made with the 200-inch telescope showed two large galaxies that appeared to be almost overlapping. Baade and Minkowski reasoned that the observed radio and optical emissions could be produced if the galaxies were interpenetrating at high speed. In such a collision the probability that the stars of the galaxies will collide is nil, since even within galaxies the distance between stars is vast. Interstellar gases would interact, however, causing mechanical commotion and, it was presumed, copious radiation of the wavelengths detected.

For a few years this explanation of extragalactic radio sources seemed nearly confirmed by observations of two nearer radio sources approximately coincident with the galaxies NGC 1275 and 5128. Both of these sources are very peculiar elliptical galaxies rich in dispersed gases and dust. It was thought once again that their curious features represented other galaxies in transit through them. One can thus understand why Zwicky keenly noted in 1956 that even the Antennae are "a weak radio source and therefore probably a system of two galaxies in the process of a close collision." Minkowski agreed.

Nevertheless, by 1960 the colliding-galaxies theory of radio sources had all but expired. For one thing, the theory proved unable to account for numerous newly discovered sources whose appearance and internal motions gave no hint of any collision. It was also found that the radio emissions of several of the distant bodies come not from the observed galaxies but from regions on each side of them, many thousands of light-years beyond the areas where the impact of gas clouds would be most vigorous. Finally, the radio static was recognized as a type of emission known as synchrotron radiation (because it resembles the radiation produced by the particle accelerators called synchrotrons). This radiation is emitted by charged particles moving in a magnetic field at speeds close to the speed of light; there is no known mechanism by which the collision of galaxies could yield such particle speeds.

When the collision theory of radio galaxies thus became discredited, tidal effects between galaxies were obviously deprived of an important ally. Left to fend for themselves, they met a barrage of postponed criticism.

It was pointed out, for example, that encounters between unrelated galaxies might be common enough to account for the rare radio sources, but that the space between galaxies is too vast for 1 or 2 percent to have grazed another in a chance meeting. It was also noted that tails emanate from some galaxies that appear to be isolated from their neighbors. Moreover, even if the occurrence of many near collisions could be explained, it was remembered that no one had demonstrated that such encounters could produce the narrow filaments seen in the Antennae, the Mice and certain other distorted galaxies.

In fact, tides seemed plain wrong on two counts. First, Vorontsov-Velyaminov noted that in double galaxies tails are more common than bridges. How can this be reconciled, he asked, with the two-sided symmetry of all known tides? Or even if that symmetry were imperfect, why should the distortion of the far side be greater than that of the side most exposed to the external gravitational field during an encounter? The other and even more worrisome point was that some bridges and tails are strikingly narrow. This seemed very odd, since known tides raise masses over wide areas. Zwicky himself was troubled by this objection; it seemed to demand that the galaxies behave almost like taffy.

It was not only such intrinsic weak-

© 1973 SCIENTIFIC AMERICAN, INC

nesses of the tidal theory, however, that caused its widespread abandonment. Also involved was a change of scientific mood or fashion. Even before the first quasars were discovered in the early 1960's, astronomers had developed respect for some highly energetic and even explosive phenomena in galaxies. Supernovae and radio galaxies are but two of many examples. Another is the jet of M87, which, as we have noted, had been known about as long as the Antennae; the discovery in the mid-1950's that even its visible light is synchrotron radiation startled many astronomers. Although poorly understood, all these processes seem to have little to do with gravity. Hence there was much open-mindedness toward invoking other forces, such as electromagnetism, in efforts to interpret various puzzling phenomena.

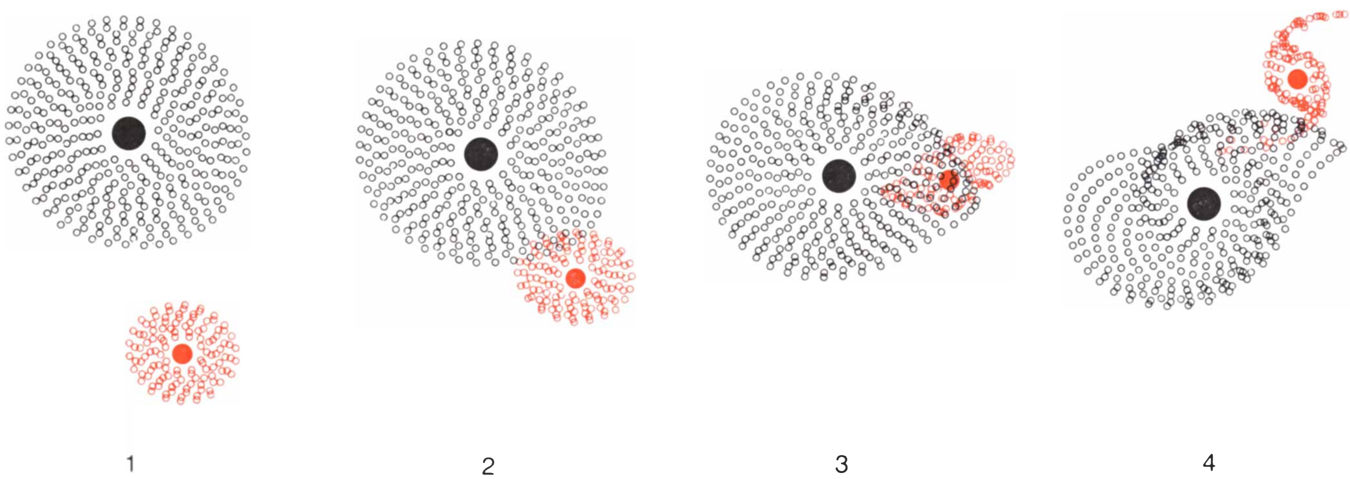
In this intellectual climate Geoffrey and Margaret Burbidge speculated that the "tubular forms" of such galaxies as the Mice might belong to systems still in the process of formation, probably in the presence of magnetic fields. Vorontsov-Velyaminov wondered if the strange shapes might have resulted from some novel "force of repulsion." More recently it has been suggested that the jet of M87 and some unusual features of other galaxies may have exploded from galactic nuclei. Arp has gone on to ask whether such ejecta might not include some of the small galaxies that seem to be connected to larger ones by bridges.

None of these alternatives of the 1960's were presented as full-fledged theories. They were only hopes or suspicions, no doubt nourished in large part by despair of accounting for objects such as the Mice and the Antennae primarily by gravitation. In this despair were echoes of older remarks, such as "a tidal perturbation can alter the shape of a galaxy but cannot draw out a long narrow filament." Such sentiments had one flaw: it had never been established that gravity could not do it.

Theoretical work since about 1970 has shown that tides can in fact account for some very peculiar structures. As our computer models illustrate, it seems possible after all for a slow near collision to rip the outer parts of a disk into thin and taillike ribbons by gravity alone. It also appears to be possible for other such tides to evolve into remarkably slender bridges and counterarms.

These conclusions are mostly our own, based on extensive experiments we have conducted during the past four years with mathematical models of some double-galaxy systems using the computer and graphic displays of the Goddard Institute for Space Studies in New York. To be sure, like many other overdue ideas, the need for such calculations dawned on several workers more or less simultaneously. Seven workers have recently reported results at least vaguely like ours. One, the Russian physicist N. Tashpulatov, definitely preceded us. Yet the roots of this work go all the way back to an inspired but long forgotten study made by the German astronomer Jorg Pfleiderer about 1960, at a time when chance flybys of galaxies still retained some promise.

Pfleiderer's models, like ours, were intended only as efficient caricatures of the loose confederations of orbiting stars, dust and gas that are the real galaxies. Pfleiderer was no less aware than we are that the mass of an actual galaxy is dis-



FLYBY OF A SMALL GALAXY produces the striking, if transient, spiral structure seen in this sequence of eight time frames of equal intervals from another computer simulation. Here the body at the center of the larger disk (*black*) is four times more massive than the one at the center of the smaller disk (*color*). Both disks are viewed face on and spin counterclockwise; they encounter each other in parabolic orbits. The plane of their orbits is inclined 45 degrees from the vertical and the disks do not actually interpene-

© 1973 SCIENTIFIC AMERICAN, INC

persed over its disk; yet all our models pretend boldly that the matter in their disks is of such small mass that the entire inverse-square gravitational field derives from a single point at each center.

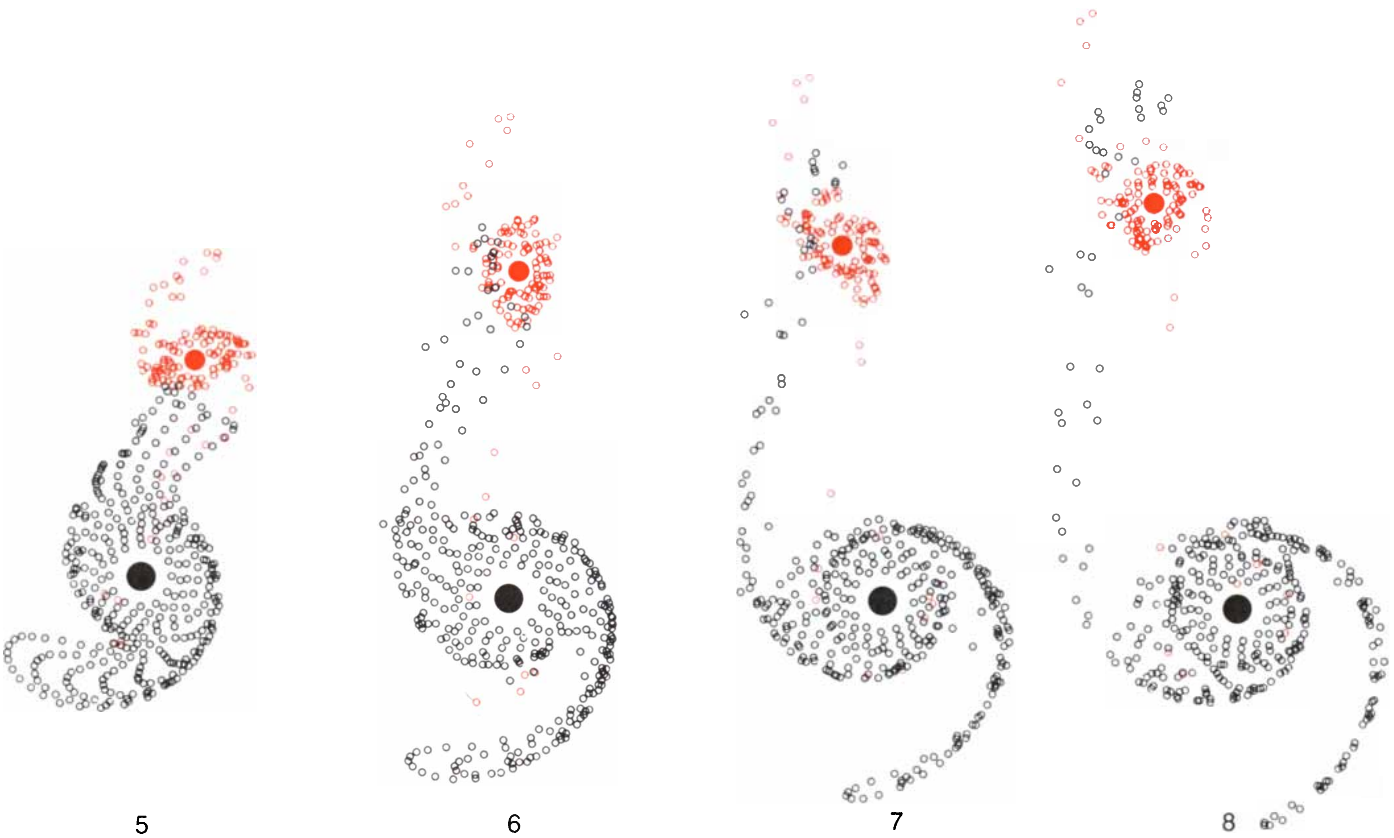
The rationale for using such highly idealized models is twofold. Pfleiderer reasoned that tidal effects should be much the strongest in the exposed and relatively slowly rotating outer parts of the galactic disks. Out there, at least, the mass is small and its self-gravity must be weak. The models should thus remain basically valid even if the peripheral mass is neglected entirely.

Second, as Pfleiderer was particularly conscious in those early days of electronic computers, the idealization of mass as a single point greatly simplifies the computational task of predicting the successive shapes of a disk composed of many particles. For a model galaxy consisting of n particles these numerical economies are roughly n-fold. In the most realistic models possible every particle in a collision of two equal galaxies would be influenced directly by $2n - 1$ other particles; in the simple models the motion of each particle is influenced by only the postulated central masses of the two disks. As it is, the motions of the $2n$ test particles constitute a set of $2n$ distinct "restricted three-body problems"; such three-body equations have no known analytic solutions of practical value, but they are easily solved in tandem by computer. One can gauge the efficiency of this process by noting, for instance, that our entire simulation of the Antennae (with $n = 350$) could be rerun in less than five minutes on any fast modern computer.

Incidentally, because the test particles are without mass it makes no difference to the motions of one galaxy whether the other arrives with or without its own retinue of massless points. Each of our simulations is thus an anthology of two stories, calculated separately but in the diagrams superposed.

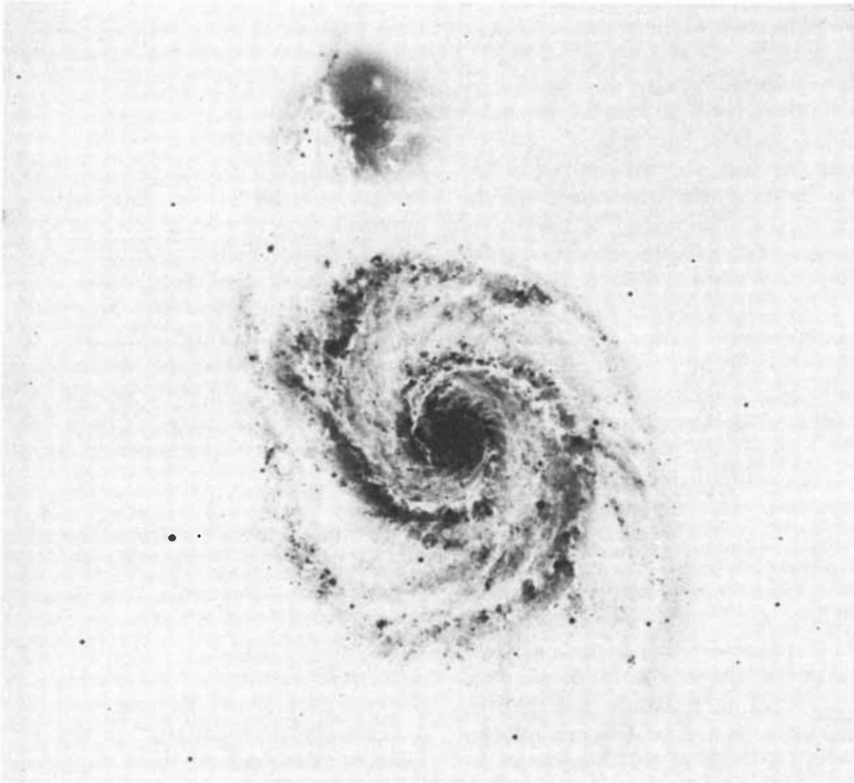
One might well ask why, if these calculations were so inexpensive, we did not adopt more elaborate mathematical models taking some account of self-gravity. The reason is mainly that the construction of even these few examples required hundreds of trial encounters for the purpose of gaining an understanding of the effects of various mass ratios, orbital parameters and times and directions of viewing. These fairly systematic searches revealed that the results are insensitive to changes in certain of the parameters. Yet three conditions seem consistently vital. To produce narrow bridges and tails (1) the galaxies must approach in parabolic orbits or in even slower, elliptical orbits; (2) they must penetrate each other, but not too deeply; (3) the approach of the "attacking" galaxy must be in roughly the same direction as that in which the "victim" disk rotates. Bridges result if the passing galaxy is of fairly small mass, whereas tails require that the two galaxies be nearly equal.

The above may be the crucial ingredients for making bridges and tails, but why do tides assume such forms at all? One reason is that the galaxies themselves are already spinning; the other and less obvious reason is that they experience the intense tidal force only over a relatively short interval. If the sequences portrayed in these computer models actually occurred, they would

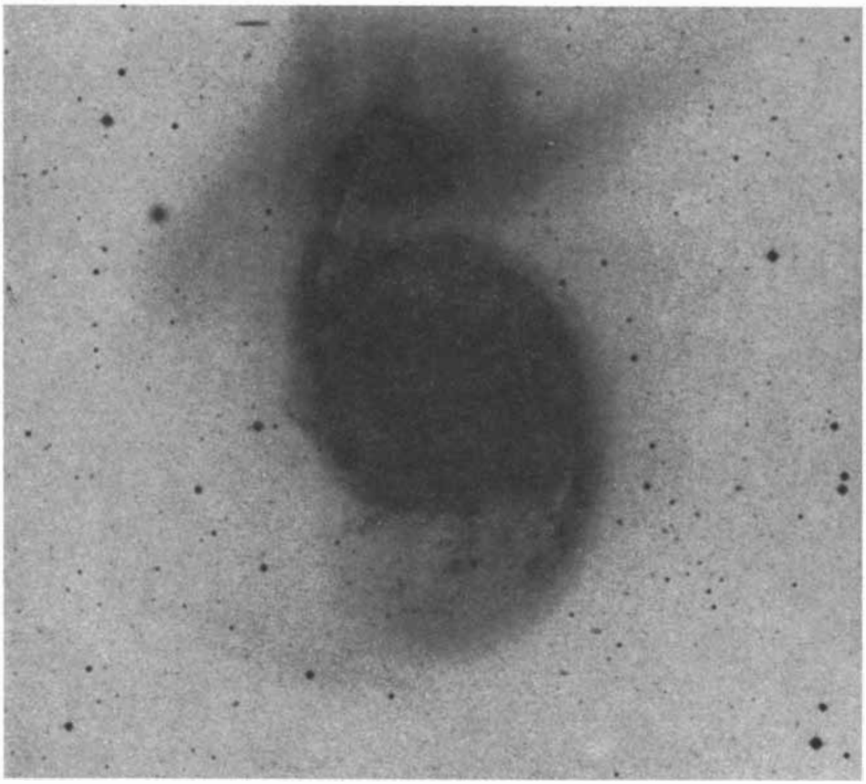


trate. In time frames *1* and *2* the barely distorted small galaxy is still rising toward the viewer. At its closest approach to the larger galaxy (*3*) it passes as much in front of it as to the right of it. The tidal effects in both disks (*4*) are distinctly two-sided. As the smaller galaxy recedes (*5–7*) the tide it raised on the side of the larger disk closer to it evolves into a narrow bridge connecting the two galaxies. The similar bulge that it caused on the far side wraps into a fine counterarm that will become sparse and eventually disappear.

© 1973 SCIENTIFIC AMERICAN, INC



NORMAL PHOTOGRAPH OF THE WHIRLPOOL NEBULA in the constellation Canes Venatici, also known as Messier 51, exemplifies the interior spiral pattern of the stars, dust and gas. The smaller, irregular galaxy appears to be a genuine companion to the larger one.



OVEREXPOSED PHOTOGRAPH OF THE WHIRLPOOL NEBULA, taken in 1969 by Sidney van den Bergh with the 48-inch Schmidt telescope on Palomar Mountain, reveals the confusion of faint material that surrounds the smaller galaxy and the two long streamers that extend from it in the directions of two o'clock and eight o'clock. The broad lower arm of the spiral galaxy, prominent in this photograph, is almost invisible in most others.

have required hundreds of millions of years; to the galaxies involved, however, these encounters would have seemed fairly sudden.

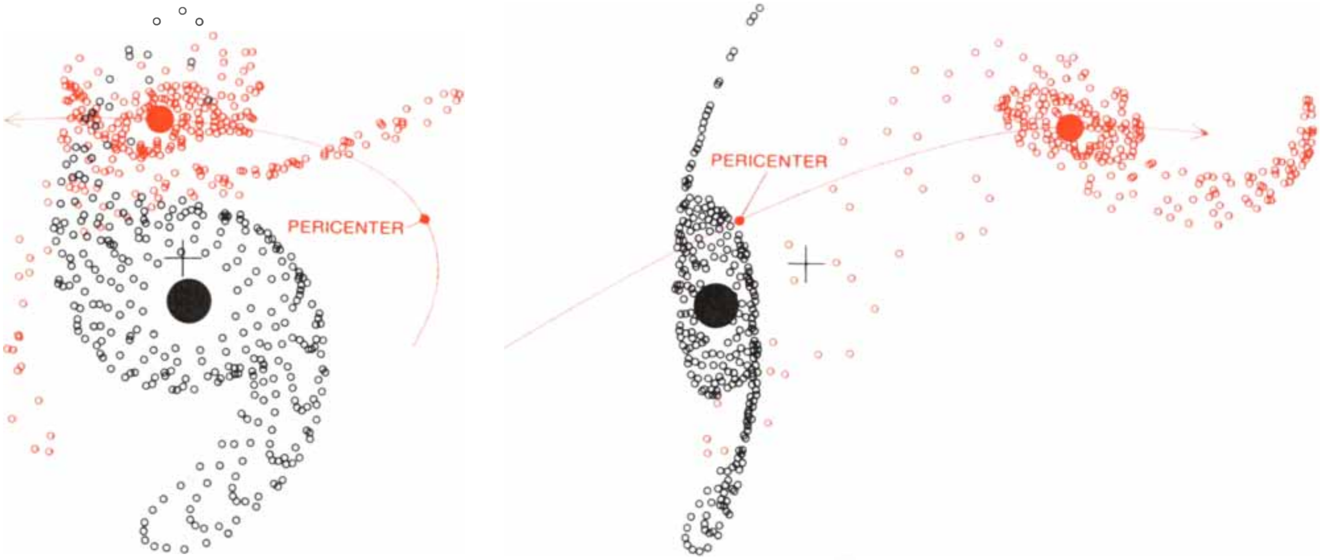
The distorting force is not the gravitational field itself but the difference between the fields perceived in the near and far parts of the galaxy. This is in fact the tidal force; as we have noted, it varies inversely not as the square of the distance but as the cube, and therefore it does not become significant until the galaxies are really close. In these computer models it is strong only during the three time frames that bracket the instant of pericenter.

Because of this "hit and run" nature of the tidal force, by the time the tidal damage looks impressive the model galaxies have almost ceased to interact. Their further evolution is merely kinematic; they drift on independently, like two armadas of spacecraft coasting after a brief, simultaneous firing of engines. Hence the spiral forms (and even the tails) develop not because the imposed gravitational field had a spiral structure but because particles assigned "low" orbits always tend to overtake those in "high" orbits. Those nearer the galactic nucleus simply shear more and more out of alignment with those farther away.

This qualitative reasoning goes a long way toward explaining the rather two-sided bridge and counterarm that become evident in our computer simulation of the passage of the small companion. The question remains, however, of why the tidal damage in the simulation of the Antennae should have become so much more pronounced on the far side of each galaxy. Part of the answer is that such equal partners obviously damage each other more than the ones in the bridge-building sequence. In fact the near-side tidal forces in that encounter are so great that the material pulled out of one galaxy, rather than forming a bridge, falls in an avalanche into an amorphous mass in the general vicinity of the other. At the same time the far-side material is "launched" vigorously, if indirectly, by having its parent mass practically yanked out from under it. Much of this debris eventually escapes from the influence of both galaxies, resulting in counterarms that grow ever more grotesque and soon dominate the appearance of the galaxy pair. Evidently they are the tails that puzzled Vorontsov-Velyaminov and others.

The reason the orbits must be parabolic or slower is that otherwise the bridges would not connect, nor would there be any avalanching. These failings, if they can be called that, were illustrat-

© 1973 SCIENTIFIC AMERICAN, INC



COMPUTER MODEL OF THE WHIRLPOOL NEBULA explores in two views the probable geometry of the encounter that seems to have deformed at least the outer parts of both galaxies. The first view (*left*) shows that the deflected particles from two distinct disks whose central masses are in the ratio of three to one can indeed mimic several of the faint outer features visible in the overexposed photograph at the bottom of the opposite page. The computer model shows both an open-spiral structure in the nearly face-on larger disk and long tidal streamers drawn out from the smaller companion. Second view (*right*) is at right angles to the first and can be thought of as being edge on to the sky; it shows that the arm of the larger galaxy is not a true bridge to the companion.

ed by Pfleiderer's calculations with fast but massive passersby. He obtained some fine transient spirals but no bridges or tails.

Since life is too short to watch galaxies move, one cannot be sure that real galaxy pairs orbit each other in the parabolas or elongated ellipses demanded by our models. It should be noted, however, that the statistical objections previously voiced against chance hyperbolic encounters do not apply here. Galaxy pairs in highly eccentric elliptical orbits would necessarily spend a large fraction of their orbital period near maximum separation and would descend only occasionally, like comets, for brief but spectacular displays. At any given moment we would expect to see most such partners well separated from each other, and, unless we knew otherwise, we might never suspect that they were destined to come close. There are in fact many such loose double systems in the sky.

In this discussion devoted to the bizarre it may seem odd to mention M51, a pair of galaxies dominated by the well-known Whirlpool. On most photographs the form and regularity of the Whirlpool show it to be an almost idealized specimen of the spiral galaxy [*see top illustration on opposite page*]. It has probably appeared in more textbooks, articles and even advertisements than any other galaxy. Indeed, it was the first galaxy in which a spiral structure was detected (by the Earl of Rosse in 1845).

In spite of the magnificence of its inner spiral structure, the Whirlpool is a peculiar galaxy. The evidence is abundant in a recent photograph made by Sidney van den Bergh; it shows the faint outer features of both members of the M51 pair about as well as they can be recorded with the telescopes and photographic emulsions available today [*see bottom illustration on opposite page*].

Two anomalies of the outer structure revealed by the photograph have been known for some time. They are the "horns" above the companion galaxy and the arm of the Whirlpool that seem to link the two objects. These clues have long suggested tidal damage, but they are inconclusive. Much more significant are the two "plumes" that seem to emanate from the companion. Their importance was first recognized by van den Bergh, although they had been noted two decades ago by Zwicky. Also very interesting is the broad lower extremity of the Whirlpool. This feature, almost invisible in the standard photograph, is most likely a counterarm still in the process of development.

We have calculated the geometry of an encounter between the Whirlpool and its companion that seems qualitatively to explain all those observed outer shapes and yet is consistent with the substantial known speed of recession of the companion [*see illustration above*]. If this hypothetical encounter is realistic, one fact is clear: the connection between the galaxies is an illusion; the apparent bridge and the more distant companion merely lie in the same line of sight.

Like the vast majority of spiral galaxies, the Whirlpool probably developed most of its fine spiral structure through processes that are intrinsic and have little to do with tides. Yet one wonders: Were the presumed tidal effects such as the outermost arms only superposed on that preexisting structure, or was even the interior of the galaxy somehow rendered more photogenic by the violent tides? These questions remain largely unanswered.

As we have seen, tidal models promise to explain some strange features of galaxies, but they by no means account for all. Of the original threesome of the Antennae, the jet of M87 and Keenan's system that were known to Hubble, only the first now seems to have been plausibly explained by tides. The second appears to be far more esoteric, and as for Keenan's system, no one as yet seems to have any inkling of whether its origin was mundane or exotic.

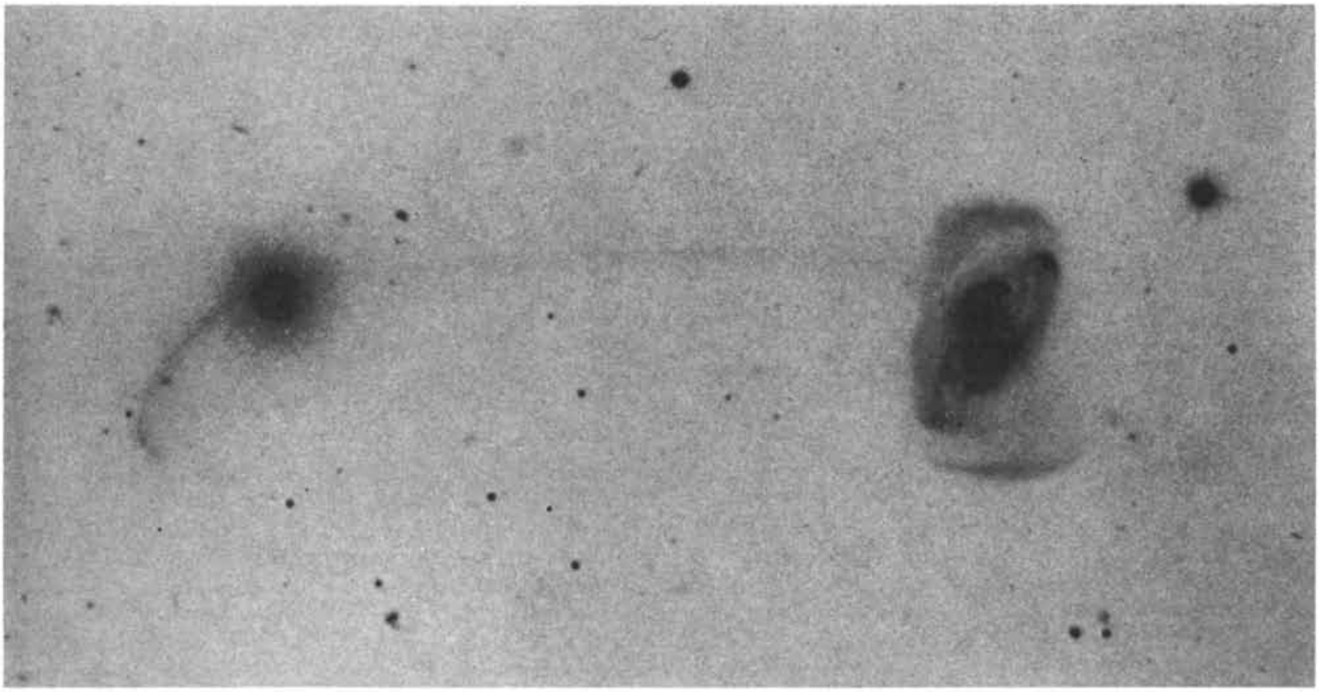
Many other geometrically peculiar galaxies also remain to be explained. One particularly baffling object is NGC 3921, a galaxy with multiple streamers somewhat like the tails formed in our models [*see bottom illustration on next page*]. Its deformities are large, yet no second galaxy has been detected anywhere in the vicinity. The hypothesis that we are seeing two galaxies with streamers in the same line of sight might explain this particular object if it were unique, but there are at least five other NGC galaxies in Arp's *Atlas* known to have multiple tails.

© 1973 SCIENTIFIC AMERICAN, INC

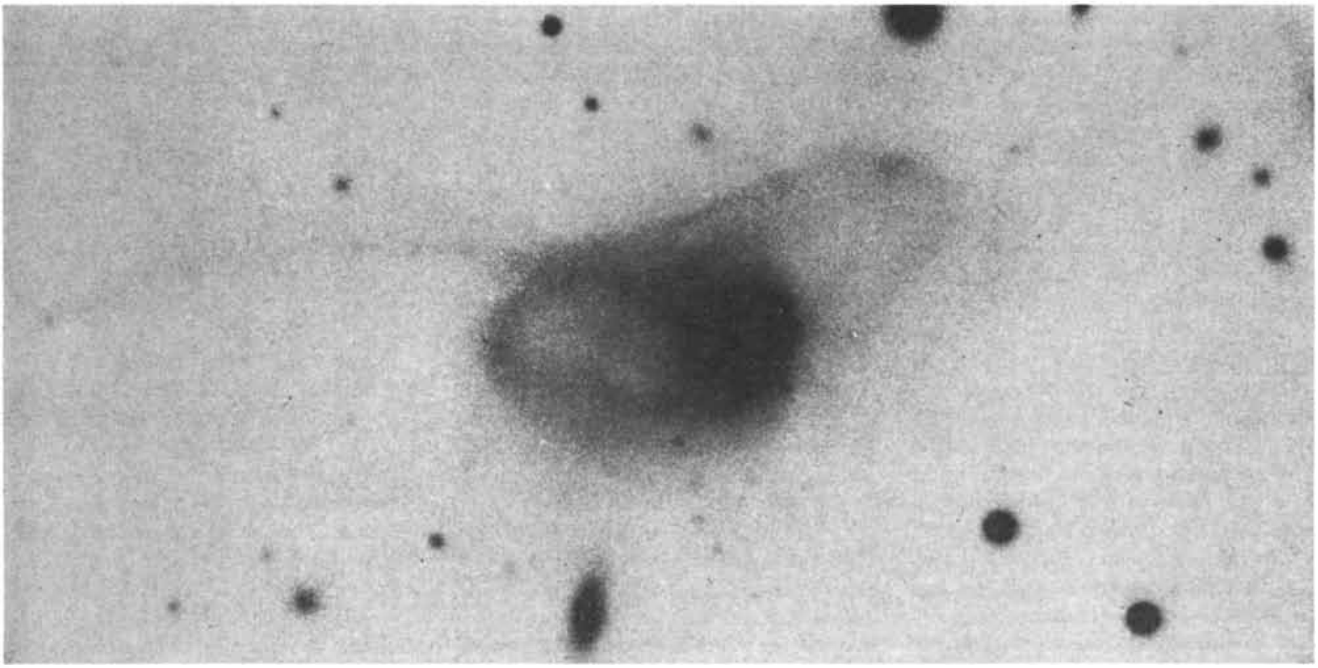
Even the existence of a "black hole" nearby would not suffice; it might well cause tides, but there is no known way it could cause multiple streamers.

Yet an explanation even of NGC 3921 may not be outside the realm of gravitational dynamics. In our models collisions were assumed to be perfectly elastic; in reality, as the Swedish astronomer Erik B. Holmberg pointed out in the 1930's, collisions between galaxies would involve some frictional forces. It simply costs orbital energy to raise all those violent tides. In the same spirit we suspect that in NGC 3921 and similar objects one is witnessing the vigorous tumbling together or merger of what until recently were two quite separate galaxies.

If this merger hypothesis is confirmed, it will raise the possibility of similar recent goings-on in those peculiar elliptical galaxies that now exhibit either double nuclei or strange interspersed material. It may also provide further impetus to the study of sudden "refuelings" of the very centers of galaxies with fresh interstellar matter.



INTERGALACTIC BRIDGE not only connects these two galaxies but also seems to extend through and beyond the one at left. The galaxies, NGC 5216 (*left*) and 5218, are known as Keenan's system after Philip C. Keenan, who discovered the filament in 1935.



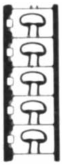
MULTIPLE STREAMERS extend from the object designated NGC 3921. One extends well to the left; another starts in about the same direction but soon turns sharply and seems to end in the faintly luminous region on the right. Authors speculate that two galaxies may here be permanently merging. Both this photograph and the one above were made by Halton C. Arp of the Hale Observatories.

© 1973 SCIENTIFIC AMERICAN, INC

For the gifting season, family Talkies.
Professional use permitted.

KODAK EKTASOUND Movie Cameras are now available for less than $190, which is an unprofessional price.* Sights and sounds the camera records stay together on the super 8 film in synch during processing. Spoken comment can be added to the magnetic stripe during projection.

For professional communications without loss of regard for fiscal prudence,** it joins in significance certain other developments that have preceded it in the marketplace. Others will follow soon. Here's a rundown:



The very idea of super 8. In an image this size, photographic technology today delivers definition and color quality that once asked too much even of 35mm. Scaling everything down in proportion permits great proliferation of super 8 films. Individual communication needs then are met by intercutting original footage with what's suitable and already available.

Shooting by available light. First offered in this KODAK XL Movie Camera and now in the new Ektasound cameras. No need for movie lights if showing what the eye would see when coming upon the scene is acceptable.

Viewing in room light. That's a KODAK EKTALITE Projection Screen up front. There is more to it than you'd think when you unwrap it. It rejects stray light originating outside the projection area. Keeping the audience in the dark may or may not be good. Now there is a choice. Note the low profile of the KODAK SUPERMATIC 60 Sound Projector.

Table for one. To convert the Supermatic projector for use like a book, flip a lever. With the Supermatic 70 projector, she could add her own comments on the sound track, like marginal notes one writes in a book. An interlock can forestall marginal notes when used for instruction of the young.

No fumbling with film. Just insert a cassette in the projector. Film comes out, does its stuff, retreats back in. KODAK SUPERMATIC Cassettes come in four sizes, providing anywhere from 15 seconds to 29 minutes of uninterrupted story. Cassettes on any number of subjects are now obtainable. Whatever the number, you can add to it. What author quits because the world already has enough books?

Videoplayer. The cassette doesn't tie you down to movie projectors. Any ordinary TV set will be fine for both picture and sound. Much of the population has been conditioning itself to TV since infancy. Just slip any size Supermatic cassette into a KODAK SUPERMATIC Film Videoplayer connected to the set or a building full of monitors. First shipments of the videoplayer in a few months.

Immediate high-quality processing of super 8 film by anybody around. Mid-'74 will see the advent of the KODAK SUPERMATIC 8 Processor for operation by non-experts. It will contain a little computer and certain other ingenious means to replace personal expertise.

If you want our advice on how to fit any or all of this to your communications plans, write Joerg Agin, Kodak, Rochester, N.Y. 14650.

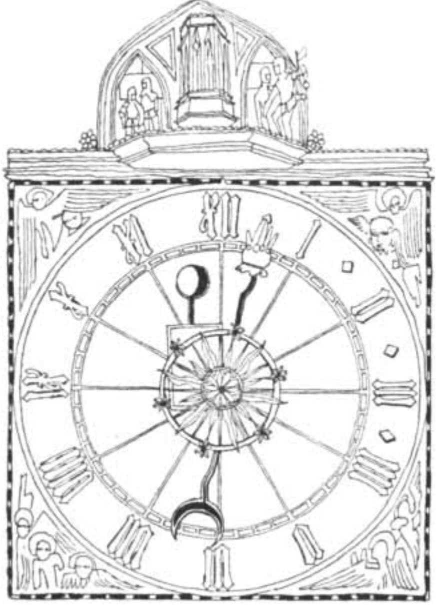
Kodak

*Though subject to change without notice.

**This is a circumlocution. It means that in science and technology Ockham's razor might just possibly shave as well in administration as in reasoning.

© 1973 SCIENTIFIC AMERICAN, INC

SCIENCE AND THE CITIZEN



The Nobel Prizes

The 1973 Nobel prize in physiology or medicine was awarded to Karl von Frisch, Konrad Lorenz and Nikolaas Tinbergen for their "discoveries concerning organization and elicitation of individual and social behavior patterns." The prize in chemistry went to Ernst Otto Fischer and Geoffrey Wilkinson "for their pioneering work performed independently on the chemistry of the organometallic so-called sandwich compounds." The prize in physics was awarded to Leo Esaki and Ivar Giaever "for their experimental discoveries regarding tunneling phenomena in semiconductors and superconductors respectively" and to Brian Josephson "for his theoretical predictions of the properties of a supercurrent through a tunnel barrier." The prize in economic science was given to Wassily Leontief "for the development of the input-output method and for its application to important economic problems."

Von Frisch, 87, was director of the Zoological Institute of the University of Munich until his retirement in 1958. He is best known for discovering in the early 1920's that foraging honeybees that have located a source of food communicate to their hive-mates its approximate direction and distance by performing stereotyped dances. If the food is nearby, a simple "round dance" suffices: the bee turns in circles alternately to the left and right. The other bees soon fly off seeking the scent they have detected on the dancer. For sources more distant than about 85 meters the returning bee uses a tail-wagging dance: it makes repeated short runs in a straight line, returning in a semicircle to the starting point by alternating directions while wagging its abdomen from side to side. If the dance is performed on a horizontal surface, the direction of the straight run corresponds to the direction of the food source; distance is indicated by the tempo of the dance. If the dance is performed on a vertical surface inside the hive, a run straight up the wall means the food source is in line with the sun; if the source is either to the left or to the right of that line, the angle of deviation is translated into a corresponding angle to the left or right of the vertical during the dance. Von Frisch concluded that such dances could not be learned but must consist of "innate patterns, impressed on the nervous system of the insects over the immense reaches of time of their phylogenetic development" (see "Dialects in the Language of the Bees," by Karl von Frisch; SCIENTIFIC AMERICAN, August, 1962).

Lorenz and Tinbergen studied the innate behavior of higher animals, establishing the discipline now called ethology. Lorenz, who received a degree in medicine and a Ph.D. in zoology from the University of Vienna, works at the Max Planck Institute for Behavioral Physiology at Seewiesen in West Germany. In collaboration with his teacher Oskar Heinroth, he discovered the phenomenon of "imprinting" in animals. They observed that at a critical age a gosling or duckling will follow the first moving object it sees. Normally, of course, the object is the bird's mother, but if she is not present, it can be almost any other moving object, animate or inanimate. A central concept of imprinting is the "innate release mechanism." This mechanism, which is believed to be genetically determined, predisposes an animal to be especially responsive to particular stimuli at a specific stage of its development (see "The Evolution of Behavior," by Konrad Z. Lorenz; SCIENTIFIC AMERICAN, December, 1958).

Tinbergen received his doctorate in zoology at the University of Leiden, briefly worked with Lorenz in the 1930's and accepted his present post at the University of Oxford in 1949. He has studied the behavior of the snow bunting, the phalarope, the small fish known as the stickleback and most notably the herring gull. He has paid particular attention to the ritualistic movements that gulls and other animals use to communicate their "state of mind" to animals of the same species. He was able to show that a basic vocabulary of signaling gestures exists among species belonging to the same family. He refers to these cross-species behavioral studies as comparative ethology, which he describes as "a powerful method for reconstructing the evolutionary history of species and for elucidating the relationships among them" (see "The Evolution of Behavior in Gulls," by N. Tinbergen; SCIENTIFIC AMERICAN, December, 1960). Tinbergen's older brother Jan shared the first Nobel prize in economics, which was awarded in 1969.

Fischer and Wilkinson, who won the chemistry prize for their studies of organometallic compounds, work respectively at the Technical University of Munich and the Imperial College of Science and Technology. The first chemical compound in which a metal atom (zinc) was joined to a carbon-containing group was synthesized in 1849 by the British chemist Sir Edward Frankland. In 1912 Victor Grignard of France won the Nobel prize in chemistry for showing how organometallic compounds can be used to synthesize a wide variety of organic compounds.

In 1951 T. J. Kealy and P. L. Pauson attempted to use a standard Grignard procedure to prepare an elusive compound called fulvalene, in which two five-member carbon rings are joined side by side. One reactant contained iron in the form of ferric chloride; the other contained the five-member rings as magnesium halides. To the surprise of Kealy and Pauson, the resulting compound contained in addition to the two five-member rings an atom of iron. They concluded that the iron held the two rings together by forming a single bond to one carbon atom in each ring, yielding a compound with the empirical formula $C_5H_5FeC_5H_5$.

Not only had such a compound never been seen before but also there were strong theoretical reasons to believe that it should be highly unstable, which it was not. The account of the new compound in *Nature* caught the eye of Wilkinson, who was just changing his field

© 1973 SCIENTIFIC AMERICAN, INC

A report on equal opportunity employment policies and practices at General Motors.

In General Motors we have coupled our commitment to equal opportunity with extensive programs of training and development. Their purpose is to enable our employes—minorities, women and others—to take better advantage of the opportunities which await them in our organization.

One of our difficulties in recruiting more minority employes and women is that many of GM's white-collar jobs require some engineering and technical training. Traditionally, however, few minorities or women have studied engineering. So, even as we recruit intensively at institutions with engineering and technical curricula, including predominantly black and women's colleges, we must take other, more direct, steps to qualify more minorities and women for engineering jobs.

For example: General Motors maintains and operates a five-year cooperative engineering college: the General Motors Institute in Flint, where today 3,000 students are earning degrees, most of them in engineering and industrial administration. They alternate periods of study at the Institute with paid work assignments at GM divisions. One of the great advantages of the GMI system is that its graduates are assured good management or professional jobs and an opportunity to progress at General Motors. The entrance requirements at GMI are stiff. They compare with those at the best engineering schools in the country. A pre-freshman program has been established to qualify applicants who were not able to receive adequate preparation for engineering studies in high school. Currently, 88 minority students and 31 women are in this program. This is paying off in the number of minority and women students at GMI. Eight

© 1973 SCIENTIFIC AMERICAN, INC

years ago we had only 13 minority students at GMI. Two years ago we had 167. This year we have 412.

There are relatively few women graduate engineers. Last year, for example, in the entire United States only 493 bachelor degrees in engineering were conferred upon women. They represented 1.1% of the total bachelor degrees earned in engineering during 1972.

Last year 112 women were enrolled at GMI. This fall, there are 247 women, 8.3% of the total GMI enrollment.

We expect—indeed we know—that these young men and women will be among the managers of General Motors in the years to come. All that is needed is their continued efforts, our continued resolve, and time.

Several programs have been established throughout the Corporation to assist employes who may wish to continue their formal education. GM has a Tuition Refund Plan and a Graduate Fellowship Plan which last year refunded $2.9 million to employes who completed courses in recognized educational institutions. And we place special emphasis on increasing the number of minority and women employes in skilled trades. Pre-apprentice training programs at many GM plants develop the technical skills of prospective candidates for skilled-trade apprenticeships.

By such efforts, we are making long strides in short time. We are bringing minorities and women into General Motors, placing them in the mainstream of opportunity, and training, educating, and preparing them for higher positions. Our goal is nothing short of full equality of opportunity throughout our organization—and we are moving toward this goal.

Several years ago we made a significant shift in our thinking. We had always been against discrimination, but we decided then that just to be *against* was no longer enough. We chose a more positive, more affirmative role. We committed the Corporation to work not only to prevent discrimination, but to promote equal opportunity in employment. Then, and since then, we have made it very plain that it is the continuing policy of General Motors to provide equal opportunity for every American in every area of our business.

We are convinced that this policy—positive rather than negative, active rather than passive—is the right one. It is right because it not only fulfills the let-

© 1973 SCIENTIFIC AMERICAN, INC

ter of the law, but reaches to the spirit of our American commitment to equality.

Our record at General Motors has a special quality enhanced by GM's tradition of success. General Motors is successful because it applies rigid standards for advancement to all employes. The rewards and incentives are high, and so are the standards of performance necessary to achieve them. When an employe progresses in General Motors, he or she can be sure that recognition has been earned. Everyone who knows General Motors knows this is so.

Here are a few figures. The percentage of minority employment in GM grew from 11.2% of our U.S. work force in 1965 to 16.7% by the end of 1972. And since then, the 16.7% has climbed to over 17%.

This is progress, and significantly the gains of minorities in white-collar jobs have been more rapid. Minority Americans in these jobs increased from 1.7% in 1965 to about 4.7% in 1971. Just a year later, the 4.7% became 7.1%, and today the percentage of minority employes with white-collar jobs in General Motors is over 8.4%.

In 1965, women accounted for 12.9% of our work force. By December 1972, the number had increased to 13.9%, and today the percentage of women in the GM work force is 15.1%. Of the managers, technicians and professionals at GM in 1965, eleven hundred were women. By the end of 1971, the number had increased to 1600, and as of the end of last year the number was 2800. And since then, it has climbed to 3900.

Percentages and numbers are cold, but these represent in General Motors 113,000 minority Americans and 97,000 women earning for themselves and their families the employment opportunity they deserve. They are more than numbers—they are real human stories—over 210,000 of them. And the number is growing every day.

And every job in General Motors, white-collar or blue-collar, is a good job. The average hourly employe who works in our plants earns more than $12,500. Their wages alone—not counting fringes—place these employes in at least the upper one-fourth income bracket in the United States.

We know that equal opportunity in employment is not up to the employe alone. The person who does the hiring and the promoting is crucial. So we train not only employes, but we train mana-

© 1973 SCIENTIFIC AMERICAN, INC

gers as well. We teach them how to take positive action to speed upward mobility throughout the Corporation.

In January 1972, this message was given to our Personnel Directors: "As you are all aware, the policy of General Motors Corporation is that everyone will be given an equal opportunity in employment without regard to his or her race, religion, or national origin. This is the policy of General Motors, and every member of management must implement this policy.

"Now, there may be many personal prejudices in connection with this problem. These are being expressed in different ways throughout the country, and each person is entitled to his own opinion. However, the position of GM in these matters is unmistakably clear: there is no room for prejudice in General Motors—and we mean just that. If we have any person at management level in any GM facility who cannot function within this policy, or is not giving it full attention, then he will simply no longer be able to work for General Motors."

We are making progress, but the effort is hard. Progress does not come easily. It requires hard work and dogged dedication—day after day. But it is worth the effort. Minorities and women in General Motors are earning their way to economic equality, gaining—day by difficult day. They are getting there—surely. A number of minorities and women are now in top positions. Hundreds more are just below them, and thousands more a level down, and throughout the Corporation there are more than a hundred and thirteen thousand minority Americans and ninety-seven thousand women—all working, all earning opportunity.

No one can doubt the commitment of General Motors to full employment equality. Neither should anyone doubt the certainty of its eventual achievement.

GM cares about cars. GM cares about people too.

★ ★ ★ ★ ★

General Motors

© 1973 SCIENTIFIC AMERICAN, INC

of interest from nuclear chemistry to the organic chemistry of transition metals (such as iron), and Fischer, who was completing his Ph.D. under Walter Heiber, a world authority on organometallic chemistry. Wilkinson and Fischer independently guessed that the compound's stability required more than a simple carbon-iron-carbon bond. With three colleagues at Harvard University, Wilkinson concluded from various physical studies that the iron atom was sandwiched symmetrically between the two rings and was thus bonded in an unusual way to all 10 carbon atoms. Using X-ray-diffraction techniques, Fischer confirmed that such was the case. The compound, since named ferrocene, opened an exciting new field of organic chemistry based on the unusual bonding properties of the transition metals. Practical applications include new kinds of homogeneous catalysts for preparing drugs and synthetic polymers.

Esaki is the third Japanese to win a Nobel prize in science and Giaever (now a U.S. citizen) is the third Norwegian. The quantum-mechanical concept of tunneling, on which their prizewinning work was done, was first described in 1928 by J. Robert Oppenheimer, R. H. Fowler and Lothar Nordheim. The concept explains how particles that, according to classical theory, lack the energy needed to surmount a barrier of electric charge can nonetheless tunnel through the barrier. Tunneling occurs because particles have the properties of waves; such waves do not stop abruptly at a barrier but penetrate some tiny but measurable distance.

Apart from explaining such phenomena as the emission of alpha particles in radioactive decay, tunneling received little attention from physicists until 1957. In that year Esaki, then a graduate student working at the Sony Corporation research laboratory, demonstrated the tunneling process in germanium and showed how it could be used in an electronic switching device named a tunnel diode. Esaki received his Ph.D. from the University of Tokyo in 1959 and the next year came to the U.S. to work for the International Business Machines Corporation.

Giaever received a degree in mechanical engineering in 1952 from the Norwegian Institute of Technology. In 1955 he was hired by the General Electric Company in Canada, and the following year he moved to General Electric in Schenectady, where he worked at first as an applied mathematician. He soon asked if he could apprentice himself as a physicist and was assigned to work in a solid-state group under John Fisher. Simultaneously he began studying physics at Rensselaer Polytechnic Institute.

Asked to investigate the electrical properties of ultrathin films, Giaever proved to be a resourceful experimentalist. When a course at Rensselaer introduced him to the theory of superconductivity, he learned of the energy-gap concept. According to that theory, if one tried to inject electrons of certain "forbidden" energies into a metal in a superconducting state, they would be rejected. In other words, only electrons of certain energies would be allowed to tunnel across a barrier into a superconductor. When Giaever asked his more experienced colleagues if they thought the effect of the energy gap on tunneling could be observed, they were doubtful. They nevertheless encouraged him to look for the effect. After a few initial failures Giaever confirmed the effect in 1960 and was able to measure the energy gap in a direct and simple way. Previous evidence for the energy gap had involved difficult infrared measurements. Giaever's experiments did much to establish the theory of superconductivity for which John Bardeen, Leon Cooper and J. Robert Schrieffer received last year's Nobel prize in physics.

According to the Royal Swedish Academy of Sciences, "the discoveries of Giaever left some very important theoretical questions open and this fact inspired the young physicist Brian Josephson, then a graduate student at Cambridge, to make a deep analysis leading to a new calculation of the current flowing through the barrier. This work published in 1962 predicted completely new and unexpected phenomena in superconductors and in particular the phenomena which are generally called the Josephson effects." Josephson predicted that a supercurrent can flow through a thin barrier between two superconducting metals even when there is no applied voltage across the barrier. He also predicted that if a fixed applied voltage were applied across the barrier, it would cause a high-frequency alternating current to flow through the barrier with a frequency in the microwave range (see "The Josephson Effects," by Donald N. Langenberg, Douglas J. Scalapino and Barry N. Taylor; SCIENTIFIC AMERICAN, May, 1966). The Josephson effects have allowed extremely accurate determinations of physical constants involving voltages and currents. It is a remarkable fact that all three of the 1973 recipients of the physics award did their prizewinning work before they had received their doctorate.

Leontief, the winner of the economics prize, was born in Russia in 1906, received his Ph.D in economics from the University of Berlin in 1928 and came to the U.S. in 1931 after spending two years as an adviser to the Chinese government. His lifework has been the development of the input-output technique for economic analysis. The technique anchors forecasting and planning in the stable relations, determined largely by technology, governing the interindustry flow of goods and services. In the U.S., for example, the data for the inputs to each plant from its supplier-industries and for the outputs from each plant to its customer-industries are now gathered by the triennial Census of Manufactures conducted by the Department of Commerce. Aggregated to some 500 industrial and business sectors, the data are published in a matrix that displays the input-output coefficients (the ratio of each input to the output to which it contributes) and constitutes a numerical model of the U.S. industrial and business system. Worked by matrix algebra and a sufficiently capacitous computer, such an input-output table (the current U.S. table is for the year 1967) makes it possible to relate analysis of the macrosystem to the microlevel of industry and firm. Thus changes in the dimension and composition of the gross national product can be traced, in a single solution of the table, to their direct and indirect impacts on the outputs of each and every industry.

The technology of input-output analysis is now incorporated in the bookkeeping of more than 50 national states. Members of the Common Market coordinate their bookkeeping and pool their data to produce periodic input-output tables for the European economic community. In the U.S. industrial firms are experimenting with intracompany tables. The movement begins to respond to Leontief's stricture: "The task of filling the 'empty boxes of economic theory' with relevant empirical content becomes every day more urgent and challenging" (see "Input-Output Economics," by Wassily W. Leontief; SCIENTIFIC AMERICAN, October, 1951).

After MIRV, MARV

The most sophisticated of the warheads now in the U.S. arsenal is the multiple independently targeted reentry vehicle (MIRV), which by 1975 will be deployed on about two-thirds of all U.S. missiles (see "Multiple-Warhead Missiles," by Herbert F. York; SCIENTIFIC AMERICAN, November, 1973). A suc-

© 1973 SCIENTIFIC AMERICAN, INC

cessor to MIRV is now planned; it is called the maneuverable reentry vehicle (MARV).

MIRV warheads are launched into space aboard a post-boost control system, or "bus"; once released by the bus, they cannot change their direction but follow ballistic trajectories, courses determined entirely by their position and velocity at the moment of launching. MARV warheads would also be carried aloft by a bus; once they reentered the atmosphere, however, they would be able to change course repeatedly to avoid interception.

At least two MARV mechanisms are being considered by the Department of Defense. One, being developed by the McDonnell Douglas Corporation for the advanced ballistic reentry systems (ABRES) program, uses movable flaps, like the control surfaces of an airplane, to achieve maneuverability. The second system, designed by the General Electric Company for the Navy, achieves aerodynamic control through the use of a "bent" nose on the warhead. According to *Aviation Week & Space Technology*, the General Electric device could be fitted to the Trident submarine-launched missile scheduled to be deployed by 1978. The McDonnell Douglas system is in an earlier stage of development and apparently could not be adapted directly to any existing or proposed missiles.

In addition to the maneuvering mechanism itself a MARV warhead would require a guidance system capable of assuming control of the weapon's trajectory after it had left the bus. The Kearfott Division of the Singer Company has been awarded a contract by the ABRES program for such an inertial-guidance device. (MIRV warheads require no guidance system.)

The Garbage Sickness

Most people know that pork should be well cooked in order to avoid trichinosis but it comes as a surprise to learn that infection with the larva of *Trichinella spiralis* is more common in the U.S. than in most parts of the world. A survey of tissue samples by the National Institutes of Health, completed in 1941, concluded that 12 percent of the U.S. population, or 15.8 million individuals, harbored trichina worm larvae; in 1947 a leading parasitologist estimated that 20 million Americans might be infected, or three times as many people as in the rest of the world. The situation is better now, but the U.S. rate is still one of the highest in the world. In 1970, according to a comprehensive study whose results have recently been reported, 2.2 percent of the U.S. population was infected, or some 4.4 million people.

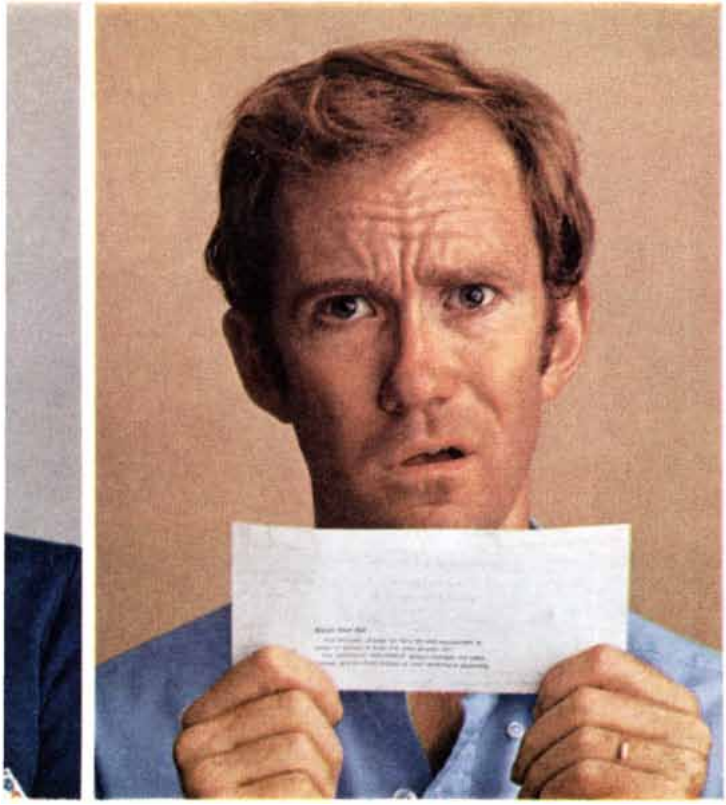
The trichina worm most commonly infests hogs, and its cycle is perpetuated by the feeding of raw garbage (including pork scraps) to swine. The worms enter the human digestive tract as larvae coiled inside cysts in pork; the larvae mature and copulate in the human intestine and the new embryos migrate in the blood and lymph to muscle cells, where they grow to about a millimeter long, coil up and become encysted among the muscle fibers. A serious infection is marked by fever, muscular pain and blood disorders and can cause death, usually by interfering with breathing. Since trichinae are killed by a temperature of 131 degrees Fahrenheit, thorough cooking provides complete protection. The danger is primarily from sausages that are eaten uncooked.

Between 1966 and 1970 the Veterinary Medical Research Institute of Iowa State University examined more than 8,000 specimens of human diaphragms obtained at autopsy, submitted by hospitals in 73 cities in 48 states. Trichina larvae or cysts were found in 335 samples, or 4.2 percent of them (as compared with 16.1 percent in the 1941 study), according to an account of the study in *Health Services Reports* by W. J. Zimmermann of Iowa State, J. H. Steele of the University of Texas and I. G. Kagan of the U.S. Center for Disease Control. Correction for the age bias inherent in a study based on autopsies produced the estimate of 2.2 percent infection for the U.S. population as a whole. In most cases the trichinae were dead, suggesting that the infections were old ones; only a few samples had enough trichinae to have caused definite symptoms and none of the individuals from whom the samples were taken was recorded as having died of the disease. Epidemiological statistics show that the number of reported cases has declined from more than 400 a year in the late 1940's to 113 a year between 1966 and 1970. Trichinosis (or trichiniasis, as it is sometimes called) is obviously a common infection but a rare disease, the authors note.

Nevertheless, it persists in humans and also, of course, in swine that are fed commercial garbage or "unofficial" garbage on farms. It could be eradicated, the authors write, if all garbage fed to pigs were first cooked or—preferably—if the feeding of garbage were prohibited by law and if pork were subjected to microscopic examination at slaughter, as it is in most European countries.

Wrong number?

© 1973 SCIENTIFIC AMERICAN, INC



Error on your phone bill? We'll take care of it.

If you reach a wrong number when you're dialing a toll call, let the operator know about it as soon as it happens. We'll help you get the charge removed.

If the call does turn up on your bill, or if you are charged for a call you didn't make, just call your local Bell business office.

We know mistakes can happen. A service representative will be happy to correct any that turn up on your bill.

At AT&T and your local Bell Company, we agree: you shouldn't have to pay for calls you didn't make.

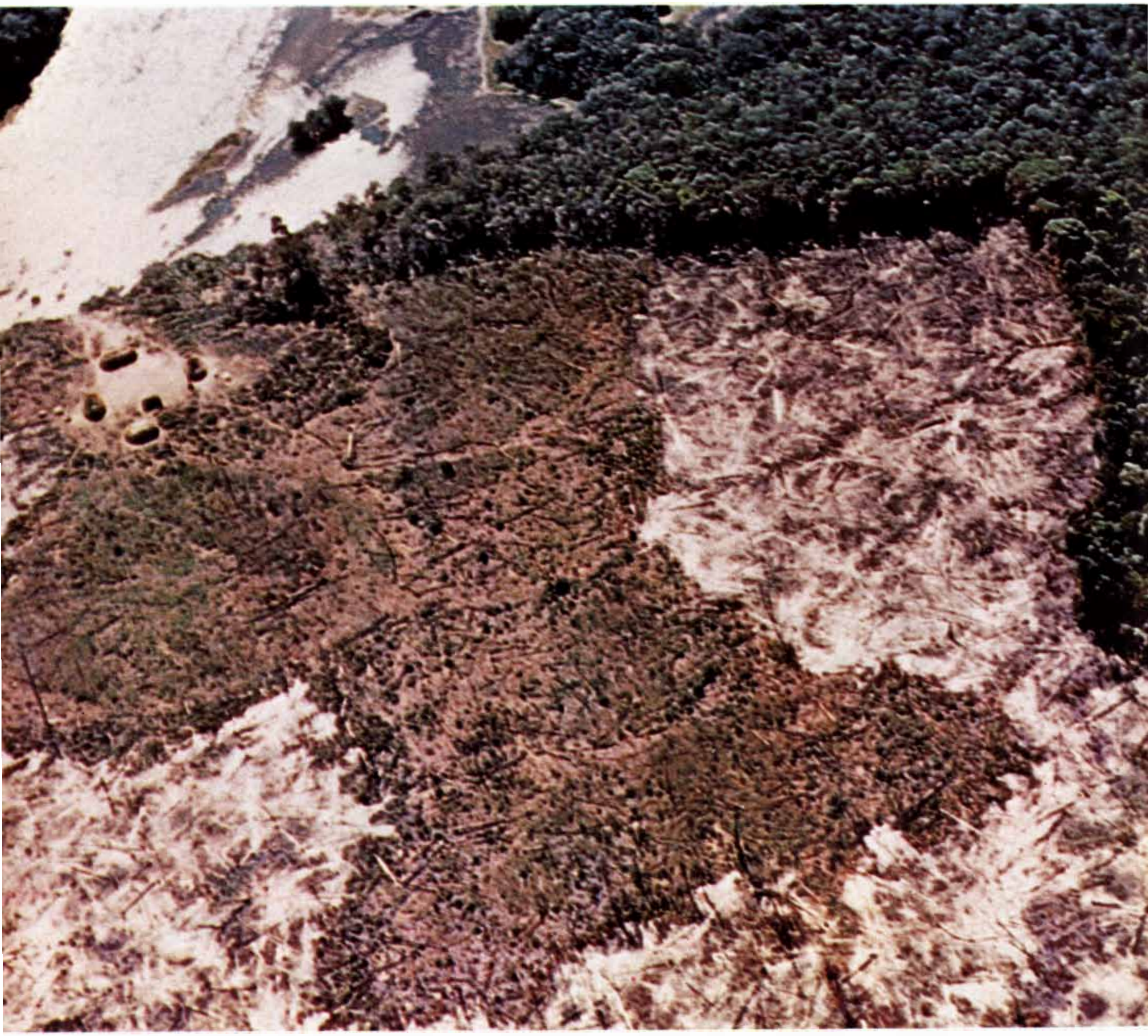
We hear you.

© 1973 SCIENTIFIC AMERICAN, INC

THE TROPICAL RAIN FOREST

One of the oldest ecosystems and a reservoir of genetic diversity, the wet evergreen tropical forest is threatened by the activities of man and may virtually disappear by the end of the 20th century

by Paul W. Richards



© 1973 SCIENTIFIC AMERICAN, INC

If it had been possible to photograph the earth from a satellite 150 or 200 years ago, one of the conspicuous features of the planet would have been a belt of green extending 10 degrees or more north and south of the Equator. This green zone was the wet evergreen tropical forest, more commonly known as the tropical rain forest. Two centuries ago it stretched almost unbroken over the lowlands of the humid Tropics of Central and South America, Africa, Southeast Asia and the islands of Indonesia.

If such photographs had been made 1,000 or even several million years earlier, this part of the world would probably have looked much the same, because the tropical rain forest is one of the most ancient ecosystems. Fossil evidence in Malaysia and elsewhere suggests that it has existed continuously since the Cretaceous period, which ended more than 60 million years ago. It has shrunk in some periods and expanded in others, and the plants and animals of which it consists have changed in the course of evolution, but even in the remote past its general appearance and characteristics may well have been much as they are now.

Today, however, the rain forest, like most other natural ecosystems, is rapidly changing. Satellite photographs made recently show that it is no longer a continuous belt but is fragmented and much reduced in area. In the past two decades huge expanses have been felled for timber or replaced by plantations of oil palms, bananas, rubber, cocoa and other crops. Still larger areas have been cleared for "slash and burn" farming, a system of agriculture that demands a perpetual supply of uncultivated land. Sizable areas of rain forest still stand in Amazonia, Africa, Borneo and New Guinea, but even in these regions, as everywhere else, the rain forest is retreating. It is likely that by the end of this century very little will remain.

The destruction in modern times of a forest that is millions of years old is a major event in the earth's history. It is larger in scale than the clearing of the forests of temperate Eurasia and America, and it will be accomplished in a much shorter time.

Should the destruction of the tropical rain forests be noted as merely another landmark in man's conquest of nature? Or could some of its consequences be unwelcome or even dangerous? I shall consider here what these consequences are likely to be, both for man and for the biosphere as a whole. First, however, it is necessary to describe some of the characteristics of the rain forest, the ways in which it resembles other ecosystems and the ways in which it differs from them.

The Rain Forest Ecosystem

The tropical rain forest has been described frequently, although not always correctly, in travel books and magazine articles. The features most often mentioned are the monotonous green of the foliage; the scarcity of large, brightly colored flowers; the vines and epiphytes in the forest canopy; the tall, straight, disproportionately slender tree trunks, often buttressed at the base; the apparent scarcity of animal life except for occasional birds and the omnipresent ants, termites and other insects. Often misrepresented is the density of the undergrowth; actually the vegetation near the ground is not very dense or difficult to penetrate, except where the forest has been disturbed and at the edges of rivers and roads where light is admitted below the canopy. It is also often stated that the forest floor is littered with dead leaves and "rotting vegetation"; actually, because of the high temperature and humidity, decomposition is rapid and there is less dead organic material on and in the soil than there is in a temperate forest.

The tropical rain forest is the most complex ecosystem on the earth. It can nevertheless be described in the same way as other self-supporting ecosystems: as an association of producing, consuming and decomposing organisms, all ultimately deriving their energy from sunlight. The producers are the trees and other green plants; the consumers are the animals, some of which (the carnivores) prey on other animals; the third class of organisms, the decomposers, consists of bacteria, fungi and certain small animals such as termites, worms and mites, which break down dead organic material so that the carbon, nitrogen and minerals it contains can be recycled.

The most important of the producers are woody plants ranging in size from giant trees to miniature "treelets" no larger than shrubs but like trees in form. Also in this group are the woody-stemmed vines. In size the trees of the rain forest do not rival the redwoods or the Australian eucalypts, but the largest of them commonly grow to more than 150 feet, and sometimes (in Malaysia and occasionally in West Africa) they exceed 200 feet. The total leaf area of the trees, and hence the amount of chlorophyll available for photosynthesis, is roughly proportional to their height. Large trees are much less numerous than smaller ones, but no precise relation between the height of the trees and their numbers has been found.

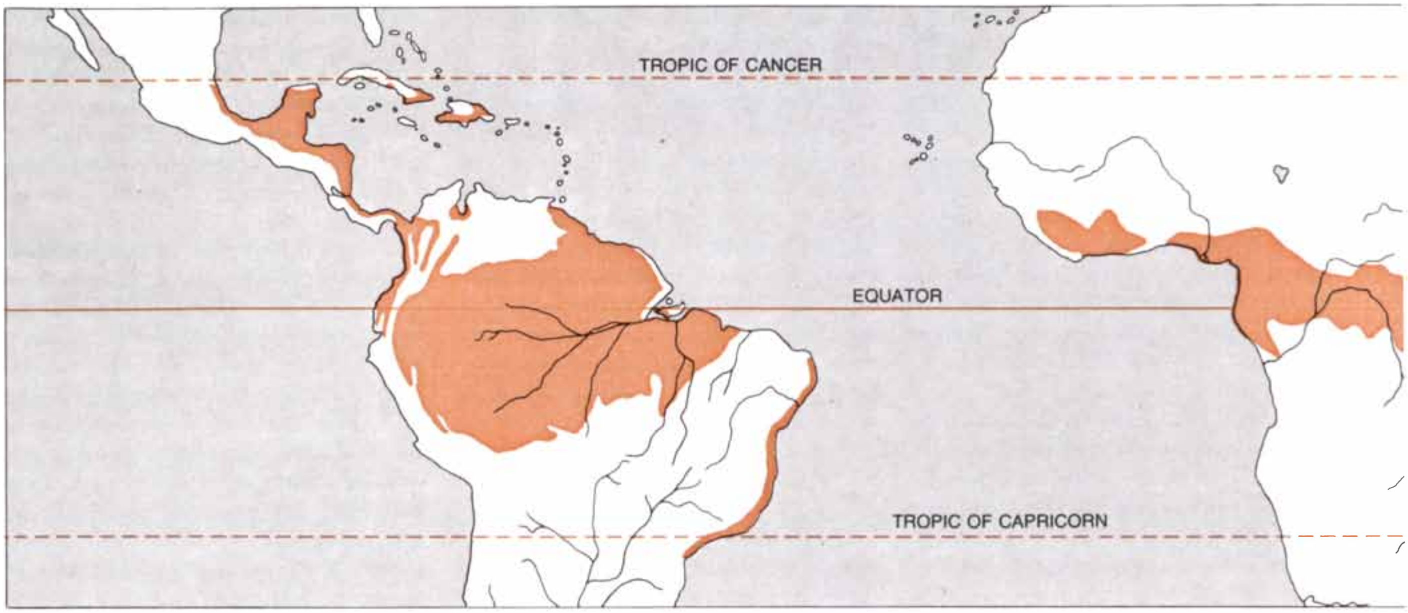
The crowns and foliage of the rain forest trees form several strata, or stories [*see illustration on page 62*]. The stratification cannot be readily observed from the ground, and it is rarely well defined. In fact, it is often claimed that this structure does not actually exist, that it is imposed on the forest by the observer. Whether or not this is so, the presence of trees of many different heights subdivides the living space for animals and smaller plants. In the three or four horizontal layers that can be distinguished environmental conditions vary widely.

A major division is between the canopy, which is exposed to almost full sunlight, and the undergrowth, which is much less brightly illuminated, although flecks of sunlight penetrate even to the ground. The leaves, twigs and branches of the trees are barriers to the movement of air, to heat and to other forms of radiation as well as to visible light; there is therefore a strong contrast between the microclimate of the canopy and that of the strata closer to the ground, with intermediate microclimates at middle levels. In the canopy there is more air movement and a greater range of temperature and atmospheric humidity than there is in the undergrowth, which is one of the most constant of terrestrial environments. Insulated by the canopy from the effects of diurnal change, the forest floor rivals a cave or a laboratory growth room in uniformity of conditions.

The great vertical range of environ-

SLASH-AND-BURN FARMING, the prevailing system of subsistence agriculture in the humid Tropics, requires that tracts of rain forest be periodically cut down. In this aerial photograph of an Indian village near the Xingu River in Brazil, the bright area is recently burned forest (the gray material is wood ash); the central area was cut and burned a year or two earlier and bears a crop of manioc. The huts of the village are near the riverbank left of center. Two or three crops can be produced on the land before the nutrients of the soil are exhausted. The field will then lie fallow and a new section of forest will be cleared.

© 1973 SCIENTIFIC AMERICAN, INC



EXTENSIVE AREAS OF RAIN FOREST survive in three regions: the Amazon River basin in South America, the Congo River basin in equatorial Africa and the Malay Archipelago in Southeast Asia. Smaller forests are found in Central America, along the coast

ments in the rain forest is of fundamental importance to the organisms of which it is composed. Conditions for photosynthesis, transpiration and other plant functions in the crown of a large tree are quite unlike those for a treelet living in the shaded undergrowth. A large tree, during its development from seedling to maturity, must adapt successively to the entire range of light and other conditions.

For animals the variety of environments is equally important. In the various strata the available foods, the opportunities for concealment and the possible modes of locomotion are quite different. For example, animals living in the treetops can readily obtain large quantities of vegetable foods such as flowers, fruits and leaves but must have limbs adapted to climbing or running along branches and to swinging, jumping, gliding or flying from tree to tree. In contrast, the ground mammals (which include such large and ungainly creatures as the elephant and the rhinoceros) have little or no climbing ability and depend for food largely on fruits and other plant materials that drop from above, much as deep-sea animals depend on the rain of dead plankton that falls from the illuminated surface layers of the ocean.

For birds, reptiles and insects too, the opportunities for feeding and the other conditions of life are different in the various strata. Many of the butterflies, birds and frogs of the treetops rarely come down to ground level. The mosquitoes of the canopy are for the most part different from those of the undergrowth, and are normally limited to their upper-level habitat. The restriction of certain mosquito species to the treetops is of great importance to the epidemiology of malaria, yellow fever and other insect-borne diseases, which, it seems, did not develop on a catastrophic scale until tree-felling became extensive enough to bring the treetop mosquitoes into close contact with large human populations.

Species Richness

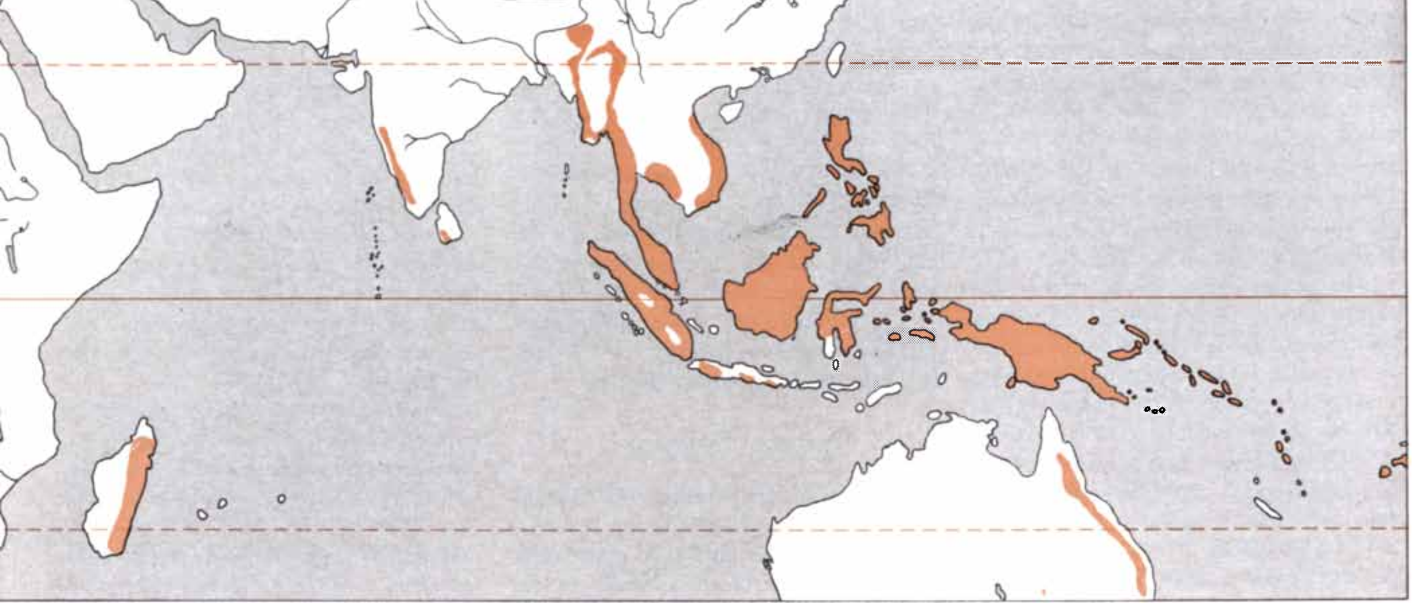
The most distinctive characteristic of the tropical rain forest is probably its great species richness; no other major ecological community has so many kinds of plants and animals. A two-hectare (about five-acre) sample of lowland rain forest often contains more than 100 species of trees a foot or more in diameter. In the richest areas, such as the (now almost vanished) lowland forest of the Malay Peninsula, more than 200 tree species have been recorded in a two-hectare plot. In a New England forest perhaps 10 species would be found in a comparable area, and even in the exceptionally species-rich "cove" forests of Tennessee and South Carolina there would be only about 25.

Large trees are of course only a part of the complement of plants. In the undergrowth there are (in addition to the smaller trees and treelets) herbaceous plants, including ferns; many vines, and often large numbers of orchids, bromeliads and other plants that grow epiphytically (nonparasitically) on the trunks and branches of trees. Less complex plants are also present, including mosses, liverworts, algae, fungi and lichens.

The composition of the animal population is more difficult to characterize because few groups of animals other than birds and mammals have been adequately studied and a vast number of species remain undescribed and unnamed. For those groups of animals that are well known, however, the number of species has been found to be very large. In Panama and Costa Rica, Edward O. Wilson and the late Robert H. MacArthur found that a 300-mile square of rain forest harbored from 500 to 600 resident species of birds, more than four times as many as are found in the broad-leaved temperate forests of eastern North America. Thomas W. Schoener and Daniel H. Janzen captured 500 species of insects in 2,000 sweeps of a net in the undergrowth of a Central American forest, and the number of insect species in the canopy and middle layers is certainly much higher. In the other animal groups too it is believed the number of species in the rain forest is large compared with the populations of other ecosystems.

Just as there is a great variety of plants and animals within a small sample area, there is diversity from hectare to hectare, from district to district and from continent to continent. The rain forests of the Old World and the New World are similar in general appearance and structure, yet they have almost no animal species and very few plant species in common. Entire groups of orga-

© 1973 SCIENTIFIC AMERICAN, INC



of the Gulf of Guinea in West Africa and in humid areas of India, Ceylon and Australia. In these latter regions much of the tropical rain forest has been cleared for agriculture, animal husbandry and habitation. Only isolated blocks and patches of forest remain.

nisms common in one hemisphere are lacking or extremely rare in the other. For example, the hummingbirds of the Americas are absent in Asia and Africa, and the bromeliads, characteristic of the tropical forests of the New World, are represented in the Old by only one species. (Even this plant is rare and is found not in the forest but on rocky hills in one small region of West Africa.)

Within a particular forest it is common to find that some species are dispersed unevenly. MacArthur reported that patchy distributions that cannot easily be related to differences of climate or other environmental factors are apparently common among the ants and the birds of the rain forest. A comparable lack of uniformity has been found in the distribution of tree species in Borneo and parts of South America and probably exists elsewhere in the Tropics.

One result of the large number of species in the rain forest is that most species are widely scattered and have a very low population density. Alfred Russel Wallace wrote long ago (in *Tropical Nature,* 1878): "If the traveller notices a particular species [of tree] and wishes to find more like it, he may often turn his eyes in vain in every direction. Trees of varied forms, dimensions and colour are around him, but he rarely sees any one of them repeated. Time after time he goes towards a tree which looks like the one he seeks, but a closer examination proves it to be distinct. He may at length, perhaps, meet with a second specimen half a mile off, or may fail altogether, till on another occasion he stumbles on one by accident." In a sample plot of a few acres most tree species are usually represented by a single individual; only a very few species contribute large numbers of specimens to the population. Sparse distribution is also characteristic of many animal groups, although here there are important exceptions, notably among the social insects such as ants and termites, which live in nests that consist of enormous numbers of individuals.

This pattern of many species and few individuals is characteristic of tropical rain forests and to some extent of tropical biota generally. Several explanations for it have been proposed, but no one by itself seems sufficient.

One factor that is almost certainly important is the great age of the rain forest ecosystem. In the humid Tropics plant and animal species have evolved over an extremely long period. Although many have no doubt been eliminated by natural selection, many others have survived and thus the number of species has grown simply by accumulation. Another factor may be the constancy of the environment, the lack of seasonal changes. Because severe cold and drought are unknown, and because plant and animal reproduction can continue throughout the year, the various processes that contribute to speciation can proceed without interruption [*see illustration on page 66*].

The scattered distribution common to tropical trees may be imposed on them by the damage done by herbivores. The seeds, fruits and seedlings of tropical trees form the chief source of food for a horde of mammals, birds, insects and other animals, many of which seem to be "host specific," that is, they feed exclusively on a single tree species or on a small group of species. It is common for the entire seed crop of a large tree to be destroyed by these animals.

The pressure of herbivores is greatest close to the parent tree and the number of herbivores falls off roughly in proportion to distance. The number of seeds too decreases with distance from the parent tree, and Janzen has suggested that there must be an optimum distance at which the curve for the number of seeds available crosses that for the number of herbivores eating them. This distance will vary from species to species, but if the herbivores are host-specific, natural selection will always tend to produce diffuse rather than aggregated tree populations.

The relentless pressure of consumers of all kinds should favor the evolution of protective mechanisms in trees and other producer plants. In fact one of the most widespread and successful families of tropical trees, the Leguminosae, has seeds that often contain poisonous or intensely bitter substances that deter insect larvae and other animals. It is significant that in certain exceptional types of tropical rain forest in which a single species is dominant (as in the oak and beech forests of temperate climates) the dominant tree is usually a member of this family.

Recent research is showing that a number of features of rain forest vegeta-

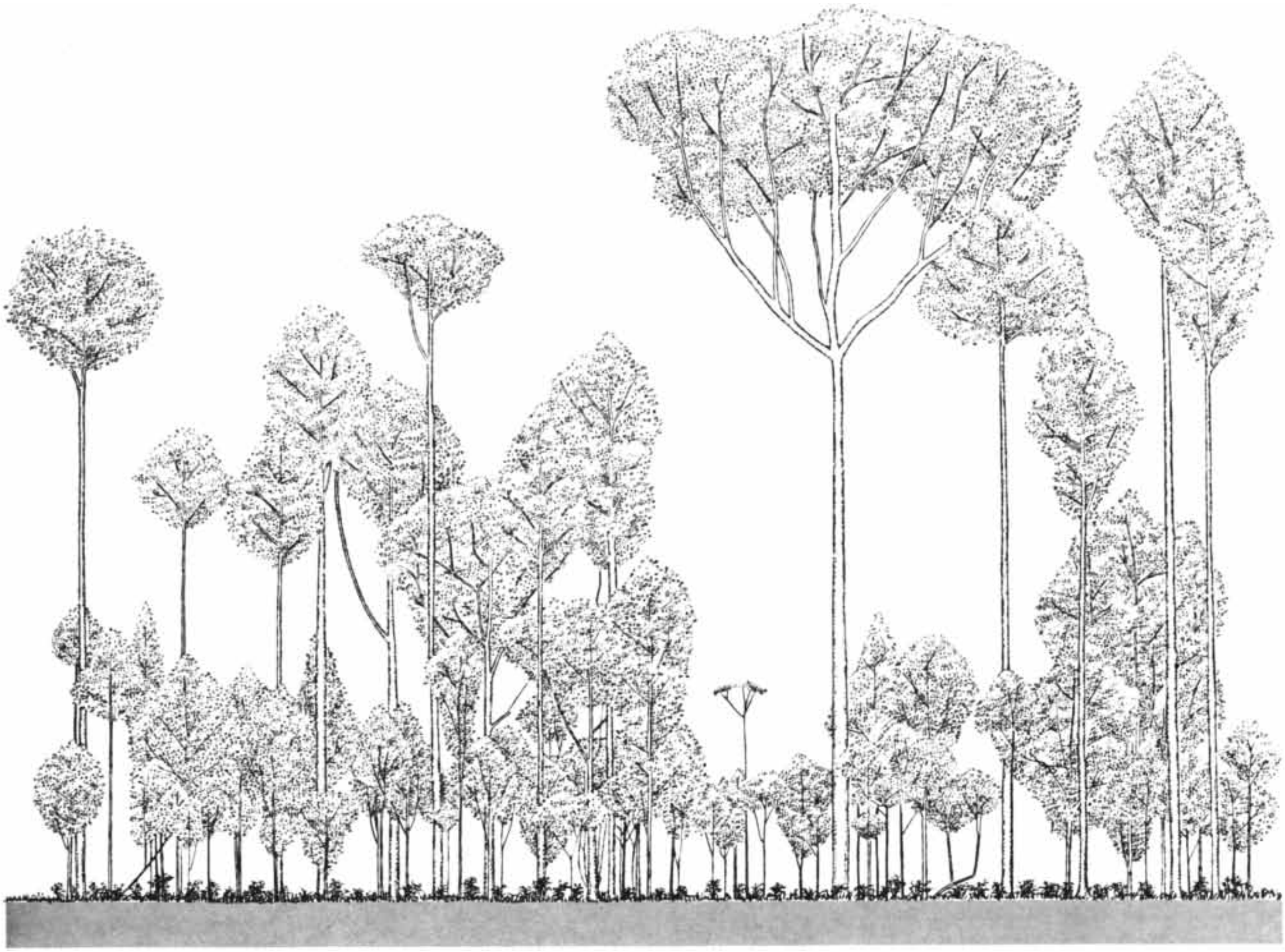
© 1973 SCIENTIFIC AMERICAN, INC

tion that were previously difficult to understand can probably be interpreted as defenses against insects and other herbivores. Among these are the frequency of myrmecophytes, or "ant plants," in which colonies of ants occupy hollow stems or special organs, and the abundance in the leaves of plants of distasteful and toxic compounds such as alkaloids and polyphenols. The degree to which plants have succeeded in this competition is perhaps indicated by the surprisingly low total mass of animal life in the rain forest compared with the mass of vegetation. E. J. Fittkau and H. Klinge recently calculated that the mass of the living plants in a hectare of Amazon rain forest is more than 900 metric tons and that the animals in the same area weigh about .2 ton. Only about 7 percent of the animals (by weight) feed on living plant material such as leaves. About 19 percent eat living or dead wood, and about 50 percent feed mostly on litter and other decaying material. The low ratio of animal to plant life (when measured as weight) confirms a suspicion, derived from other observations, that there is a shortage of edible plants in the rain forest. For man too the rain forest is a poor place to live off the land. The scarcity of plant and animal food is the main reason that jungle peoples dependent on hunting have always had very low population densities.

Scarcity of Nutrients

It is one of the paradoxes of tropical ecology that however luxuriant rain forest vegetation may appear its presence is not an indication of great fertility in the soil. This is a fact of which politicians eager to "develop" the humid Tropics are insufficiently aware. The rain forest exists on a very small nutrient budget, and it survives only by maintaining an almost closed nutrient cycle. When the land is cleared and converted to agricultural use, the results are usually disappointing; profitable yields can be maintained only by heavy application of fertilizer (which often proves uneconomical). What fertility the land possesses often vanishes rapidly after the first harvest.

Native cultivators have learned to cope with the limitations of the soil by the seemingly inefficient system of slash-and-burn, shifting, or "swidden" agriculture. They fell the forest, burn the trees and gather a few harvests. Often after only two or three crops the land is left



VERTICAL STRUCTURE of the rain forest divides it into several stories or strata, each of which has a different microclimate. The diagram above is drawn from measurements of the size and position of trees in a strip of forest 25 feet wide in West Africa. The topmost stratum consists of very tall trees whose crowns are fully exposed to sunlight; neighboring crowns are not usually in contact, so that the trees do not form a continuous canopy. Below this stratum is a layer of trees with narrower crowns, more closely packed than those of the first story and often bound together by lianas growing from tree to tree. Still lower is a dense stratum of small trees, seldom more than 10 meters high, and, below this, the undergrowth of treelets, saplings and herbaceous plants. Near the ground there is less air movement and more sunlight, temperature is lower, humidity is higher and all conditions tend to be more constant than they are in the treetops or in a clearing. Because of these differences of environment each story of the forest has its own assemblage of insects and other animals. The stratification of the forest is not always distinct, and it varies from place to place.

© 1973 SCIENTIFIC AMERICAN, INC

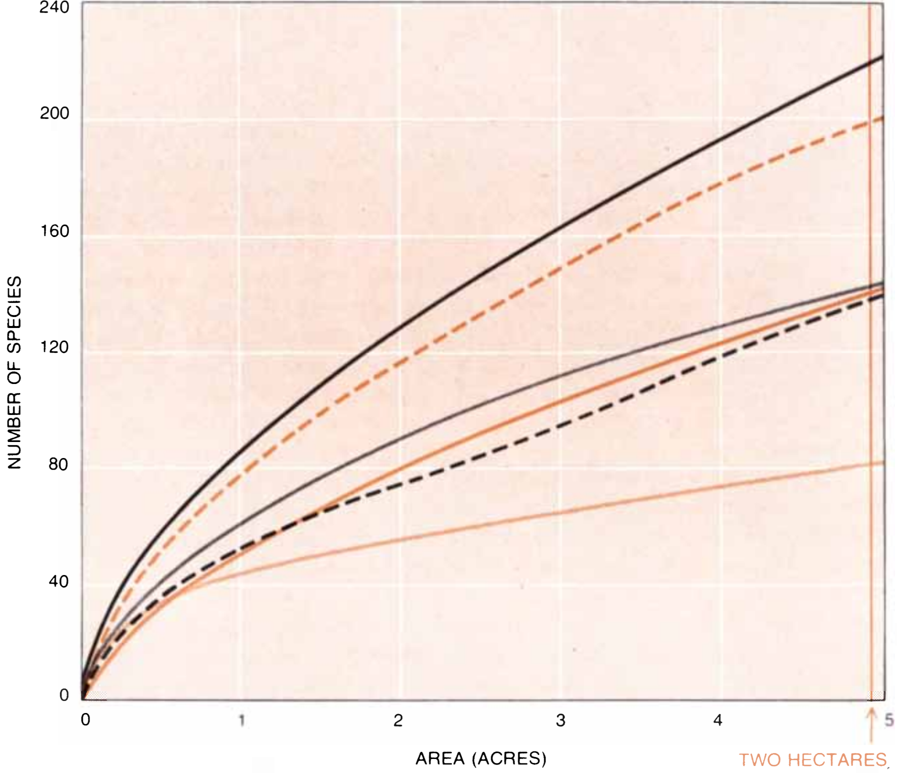
fallow and a new patch of forest is cleared as a "field." Where land is plentiful and the pressure of population is not great a fresh plot is cleared every year. If old fields are reused, it is not until they have lain fallow long enough for the fertility to have been at least partially restored.

For native farmers under existing economic conditions, cultivation systems that incorporate a long period of "forest fallow" are the only ones practicable for the growing of food crops. The most successful permanent crops in the Tropics are those, such as rubber and cocoa, that make relatively small demands on the soil because the amount of nutrients removed from the ecosystem in harvesting is not large.

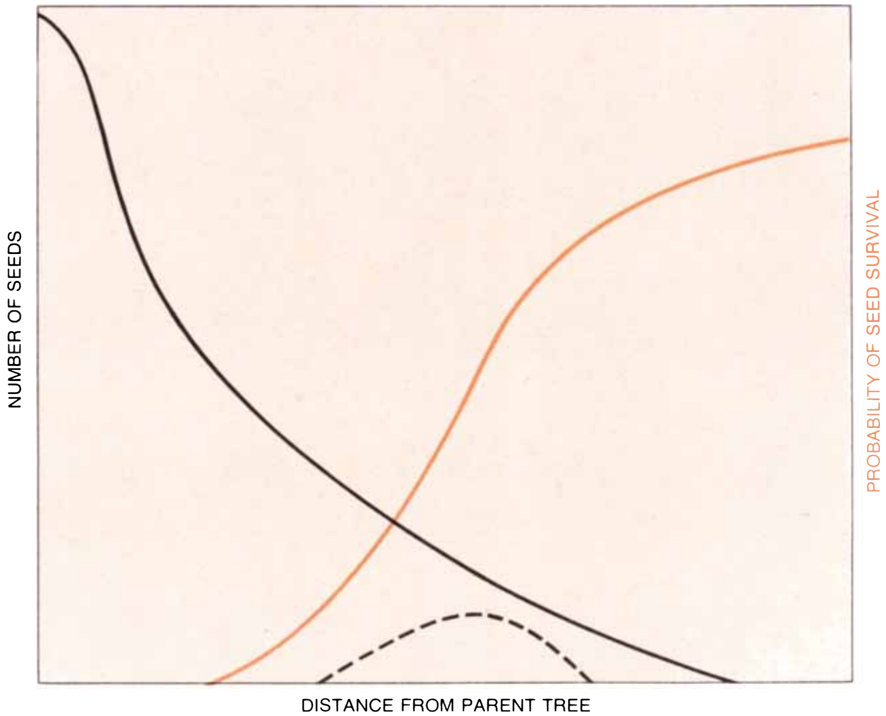
The factors that ordinarily limit growth in the temperate region—low temperatures, lack of water and a short growing season—are of little importance in the humid Tropics. Except on alluvial land and in areas where the soil is frequently enriched by volcanic dust, however, the stock of available mineral nutrients is quite small. The rain forest is able to flourish under these conditions because a large fraction of the available nitrogen, calcium, phosphorus, potassium and other minerals is held in the vegetation itself. The nutrients contained in dead wood and leaves and in the excretions and dead bodies of animals are quickly released by the activities of the decomposer organisms. Once the dead material has been broken down the minerals do not remain in the soil but are almost immediately taken up by the roots of the trees and other plants. Thus, although the total stock of nutrients is not large, recycling is rapid. It is also efficient; very little is lost from the system.

The roots of tropical trees are generally shallow; most are within the top three or four feet of soil and the greatest concentration of fine roots (which are the most active in the absorption of nutrients) are found in or just below the thin layer of litter at the soil surface. Fungal hyphae branch everywhere in the litter and surface soil and are in intimate contact with both the decomposing organic matter and the active plant roots. The fungi play an essential role in the process of decay. According to Frits W. Went and Nellie M. Stark, they carry the nutrients "door to door" from the decomposing material to the living root, so that almost nothing escapes.

Even if the mineral-transport system were slightly less efficient and small quantities of nutrients were carried away in drainage water, the losses could



SPECIES RICHNESS of the rain forest is indicated by counts of tree species at six sites in the trust territory of Brunei on the island of Borneo. The data were collected by P. S. Ashton and include all trees exceeding 12 inches in girth. The solid black line represents the species found in a valley bottom in the Andulau Forest Reserve; 220 species were recorded in the five-acre plot. The other graphs are for a ridge at Andulau (*broken colored line*), a forest near the town of Badas (*gray line*) and three plots in the Belalong forest: a lower hillside (*dark colored line*), a ridge 550 meters high (*broken black line*) and a ridge 700 meters high (*light colored line*). A sample of temperate forest might contain 10 species.



SPARSE DISTRIBUTION of most rain forest trees may be a result of the destruction of seeds and seedlings by herbivores. The number of seeds decreases with distance from the parent tree. Because herbivores are also concentrated near the parent, however, the chances of a seedling's surviving increase with distance, so that a new tree is most likely to grow where the two curves intersect. The product of the curves is shown as a broken line.

© 1973 SCIENTIFIC AMERICAN, INC

be compensated for by the decomposition of rock, although in the Tropics the weathering of rock usually occurs at a considerable depth below the soil surface, so that the products are often not readily available to the plants. Nutrients are added by rainwater in relatively large quantities, however. Near Manaus in the center of the Amazon basin Edmund Altherr has recently found that a year's rainfall contains an average of about .3 kilogram of phosphorus per hectare, two kilograms of iron, 10 kilograms of nitrogen (in the form of ammonia and nitrates) and 3.6 kilograms of calcium per hectare.

The great efficiency of the forest mineral cycle is indicated by the low concentration of mineral ions in the waters of the Amazon and other rivers that drain rain forest areas. Near Manaus the litter falling to the forest floor contains about 18.4 kilograms of calcium per hectare, yet in the streams of the same area the concentration of calcium is too small to be detected.

The modest nutrient budget of the rain forest is mainly a consequence of heavy precipitation. The annual rainfall is seldom less than 80 inches and in some areas, such as the Chocó of Colombia, it is more than 300 inches. The rain constantly leaches nutrients from the soil, removing all soluble materials. In its long history the rain forest has adapted to these conditions by evolving mechanisms that provide a rapid and almost leak-free mineral cycle.

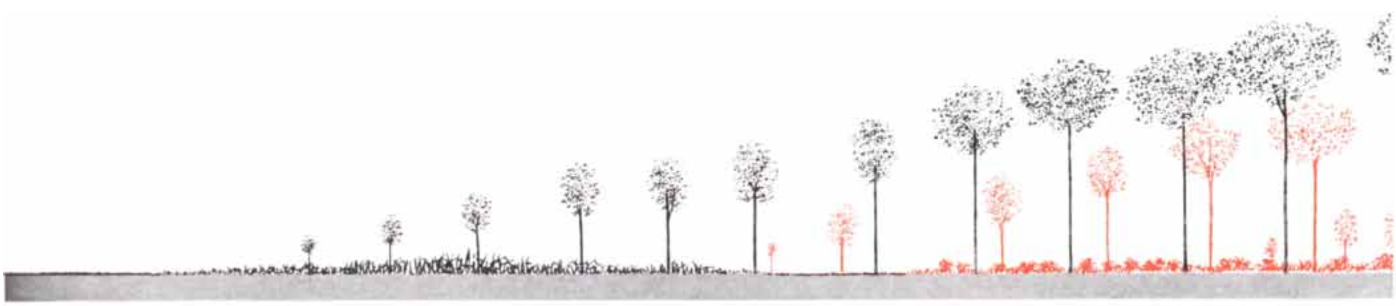
Some special types of rain forest are able to survive on an even more restricted supply of nutrients. In the Río Negro region of Amazonia, in the Guianas, in parts of Borneo and elsewhere extensive forests grow on podzolic sand, an extremely infertile soil that is white because even the iron oxides have been leached out. ("Podzol" is derived from the Russian *zola,* ashes.) Yet on these nutrient-poor acidic soils there are dense forests of trees growing to a height of more than 100 feet. Such vegetation probably receives almost no nutrients from the weathering of the soil. Apart from the activities of microorganisms that fix atmospheric nitrogen, the only input is from rainfall.

Where the shortage of nutrients is so severe that the replacement of leaves destroyed by animals represents a burden on the organism, adaptations that appear to be defense mechanisms against herbivores are common. Many of these plants produce large quantities of tannins and other phenolic compounds. In the "white-sand forests" of Borneo some plants even eke out their meager ration of nitrogen and phosphorus by preying on animal life. In these forests the insect-eating pitcher plants (*Nepenthes*) are common. The tropical podzols are useless even for shifting agriculture; the Dayak peoples of Borneo call them *kerangas:* "land on which one cannot grow rice."

The rain forest is well adapted to existence in a hot, humid, unvarying environment and to growing in relatively infertile soils. Frost and drought are rare, and the ability to endure such hazards is less important to survival than success in the competition between species and between individuals.

As in all ecosystems relations of dependence between organisms are important. Alfred North Whitehead wrote in *Science and the Modern World* that "a forest is the triumph of the organization of mutually dependent species." This is true of any forest, but it applies most forcibly to the tropical rain forest, where the number of species is large and where many strange and subtle interrelations are found.

One expression of the rain forest's degree of organization and integration consists of homeostatic mechanisms that repel invaders and maintain the stability of the system. Weeds and other nonnative organisms are almost never found in the rain forest except in man-made clearings and along paths. Epidemics of fungal diseases, plagues of caterpillars and other pest infestations, which are a menace to most tropical crops, do not seem to occur in the undisturbed forest. (One apparent exception is a curious caterpillar, or *ulat bulu,* plague in the swamp forests of Borneo, which has



SECONDARY SUCCESSION, the process that leads from cleared land to a stable, or climax, community, is illustrated schematically. The first invaders are weeds, tall grasses, vines and seedling trees. All these form a dense ground cover but the trees soon begin to overtop the other vegetation. The first trees are species that colonize clearings quickly because their seeds are dispersed more efficiently than those of the permanent forest trees. They thrive in full sunlight and are intolerant of shade. Most of them reach maturity

© 1973 SCIENTIFIC AMERICAN, INC

killed off trees in patches of a few acres. The forest affected is not a typical rain forest, however, but a specialized type dominated by a single tree species.)

Substitute Forests

In its natural condition the rain forest is clearly a very stable system; through natural selection it has acquired the ability to survive all the risks it has encountered in its history of many millions of years. It could not have acquired resistance to risks it has never experienced, however, such as those that have arisen in the past two centuries. These modern hazards result from the impact of civilized man. He has entered the forest in numbers and at a technical and cultural level far higher than those of the small groups of hunters and food-gatherers who previously were the only human inhabitants. Confronted by modern man, with his armory of power saws, bulldozers and herbicides, the rain forest is for the first time retreating and is in danger of disappearing altogether.

To say that the rain forest is retreating, or that it may eventually vanish, does not mean that bare ground will be left in its place. Because of the infertility of the soil, however, it is unlikely that more than a small part of the former forest area will ever become permanently productive farmland.

A clearing in a tropical forest, unless kept under continuous cultivation, soon becomes covered with a dense mass of weeds, shrubs, vines and young trees. Even many of the most heavily defoliated forest areas of Vietnam have sprouted green, seemingly healthy, vegetation. The tangle that springs up where the forest has been felled is the first stage in the growth of a "substitute forest." In more formal terms it is an early stage in the development of a "secondary forest," which will replace the cleared "primary forest."

The growth of a secondary forest can be most readily studied on the sites of native shifting agriculture. When a field has been exhausted and is left fallow, it becomes covered with vegetation, growing partly from seeds carried by the wind, by birds or by other animals, partly from seeds that have lain dormant in the soil and partly from roots that were not killed when the field was cleared for cultivation.

The first phase of the succession is dominated by weeds, including grasses, herbaceous dicotyledons, vines and shrubs, that grow to a height of from five to 10 feet. Trees soon take over and in a short time become quite tall; after about three years they produce enough shade to suppress many of the light-demanding plants of the first phase. These trees differ in several ways from those that dominate the primary forest. They are soft-wooded, fast-growing and short-lived; probably they seldom reach an age of 20 years, whereas the trees of the primary forest have a life-span of several hundred years.

Most trees of the secondary forest have light seeds easily carried by the wind, or edible fruits attractive to birds or fruit bats. They are thus "opportunists," able to colonize gaps and clearings quickly. The seeds and fruits of primary forest trees are usually much heavier, have less efficient dispersal mechanisms and therefore have a smaller dispersal range. Most of the smaller plants and probably many of the animals are also different in the secondary forest.

When the first generation of secondary forest trees reaches the end of its life, another group, still different from those of the primary forest, takes its place. These are somewhat slower-growing and more long-lived than the pioneers. Successional changes continue, but at a lower rate, until eventually a climax community is established, similar to the forest that originally occupied the site. The time from the clearing of the field to the reestablishment of the primary forest is probably measured in centuries, but the period required is not accurately known because long-term records of tropical successions have not been kept and because the absence of annual growth rings makes it difficult to determine the age of rain forest trees.

Such a progressive succession, leading

and die in 15 to 20 years; often only a single generation grows because the trees are unable to regenerate in their own shade. Growing below the pioneer trees, and eventually replacing them, are more long-lived and more varied species (*color*), which establish a community that in time begins to resemble the primary forest. A disproportionate number of light-demanding trees remain for many years, however; these are replaced only very slowly by trees more tolerant of shade. The succession may take centuries to complete.

© 1973 SCIENTIFIC AMERICAN, INC

to the restoration of the climax forest, is possible only if enough primary forest remains to restock the cleared areas. One reason for disquiet about the clearing of the forests of Indonesia, Brazil and other regions is that almost no refuge for the flora and fauna of the primary forest may be left.

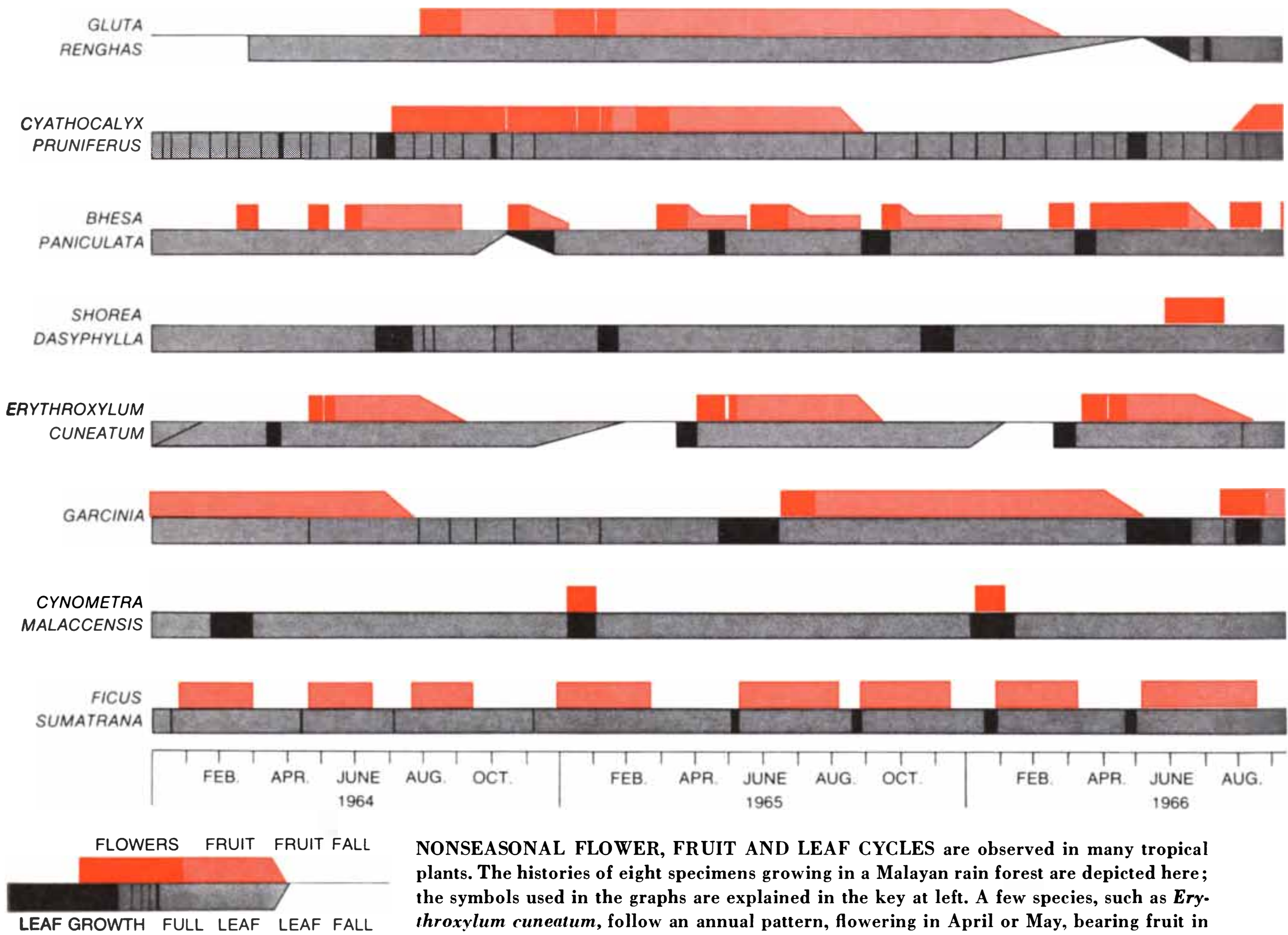
For a progressive succession it is also necessary that the secondary forest be allowed to develop undisturbed. Unfortunately with increasing population such land is often used as a source of firewood and timber and after a few years may be cleared again for cultivation. When that is done, the soil becomes increasingly impoverished and eventually becomes incapable of supporting even a secondary forest. It is then given over to savannas of coarse, nonnutritious grasses, bamboo thickets and stands of bracken and other ferns. Such vegetation tends to become inflammable in dry weather and is regularly burned, so that the reestablishment of the forest is indefinitely postponed.

It appears likely that all the world's tropical rain forests, with the exception of a few small, conserved relics, will be destroyed in the next 20 to 30 years. This destruction will inevitably have important consequences for life on the earth, although the nature and magnitude of these consequences cannot be foreseen with precision.

One effect that is certain, and probably already irreversible, is that man's impact on the tropical forest will permanently alter the course of plant and animal evolution. Biologists are generally agreed that much of the existing flora and fauna of the world, perhaps including man himself, originated in the humid Tropics. The rain forest has for millions of years served as a factory and storehouse of evolutionary diversity from which plants and animals able to adapt to more rigorous environments have migrated to populate the subtropical, temperate and colder regions. This role the tropical rain forest can play no longer; the destruction of forests and other ecosystems has already cut the lines of communication and made these migrations impossible. Even if the present, very reduced areas of rain forest were to be conserved, they could hardly play the same role as the much more extensive forest did earlier. Man has diverted the process of evolution permanently.

It is sometimes asserted that the clearance of large areas of tropical rain forest has had, or will have, important effects on the global environment, outside as well as in the Tropics. Although the existing data are not adequate to measure or predict such effects, it seems unlikely that they will be as important as is sometimes suggested.

For example, it has been claimed that the destruction of the Amazon forest might have a large effect on the world's supply of oxygen. Forest trees, like other green plants, absorb carbon dioxide and during daylight release large quantities of oxygen. Calculations based on measurements of the rate of organic production in forests indicate that the amount of oxygen produced by all the world's forests, tropical and temperate, is about 55,490 × 10^6 metric tons per year, or an average of about 16.9 tons per hectare. The contribution of the tropical rain forests is estimated to be about 15,300 × 10^6 tons, or 28 tons per hectare per year. These numbers seem very large, but actually they represent only a small frac-



NONSEASONAL FLOWER, FRUIT AND LEAF CYCLES are observed in many tropical plants. The histories of eight specimens growing in a Malayan rain forest are depicted here; the symbols used in the graphs are explained in the key at left. A few species, such as *Erythroxylum cuneatum*, follow an annual pattern, flowering in April or May, bearing fruit in

© 1973 SCIENTIFIC AMERICAN, INC

tion of the oxygen in the earth's atmosphere. The oxygen produced by forests probably does not account for more than that consumed by the small organisms that decompose dead organic matter.

Possible effects on climate have also been mentioned. Forests obviously modify environmental conditions near the surface on which they are growing. Under a stand of trees the soil temperature is more constant, and in hot climates it is lower, than in the air above the trees. In a tropical rain forest the temperature of the soil surface is typically about 26 degrees Celsius, with a variation during the year of less than two degrees. At a depth of 60 centimeters the temperature hardly varies at all. On bare soil or under other types of plant covering, such as grassland, temperatures are higher and the fluctuations are much larger.

Forests also affect the water regime by regulating the runoff of excess rainfall and by maintaining layers of humid air near the ground. To what extent forests affect the amount of rain falling over any large area, however, is a matter on which climatologists are not agreed.

It is thus uncertain whether or not the removal of all the world's rain forests would have any significant consequences for the global climate, even if they were replaced by bare rock and soil. As we have seen, the primary forests will probably be replaced by systems of impermanent cultivation, by artificial forests of much simpler ecological structure, and by secondary forests, scrub and savanna. This vegetation will also contribute oxygen to the atmosphere and will modify the microclimates at and near the surface, although the effects produced may be somewhat smaller than those produced by the original forest.

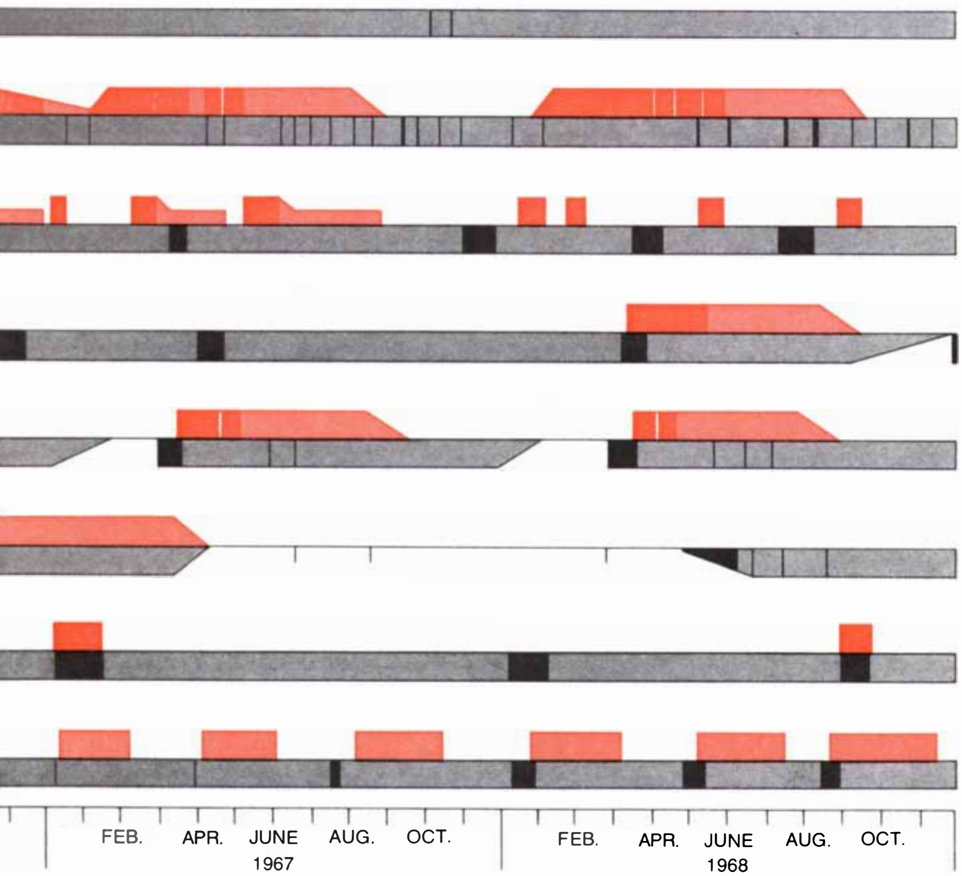
Consequences of Destruction

The real causes for concern are quite different. The tropical rain forest is a unique and rich community of plant and animal species that includes many of the most beautiful and bizarre forms of life. Only here are found such insects as the brilliant blue morpho butterfly of tropical America, countless striking and lovely birds, mammals such as the orangutan, the sloths and the scaly anteater, as well as magnificent orchids and trees. Tropical biota are so diverse and abundant, and they have received such limited scientific attention, that even among those species that have been named and described we know virtually nothing about the biological characteristics of a large majority. Much of the plant and animal life of the Tropics may thus become extinct before we have even begun to explore it. If we believe that all living creatures should be a source of wonder, enjoyment and instruction to man, a vast realm of potential human experience may disappear before there is even a bare record of its existence.

The tropical rain forest can be regarded as one of the world's great outdoor laboratories. Not only does it contain enormous wealth and variety of organisms, but also in its long history intricate and subtle relations have developed between organism and organism and between the organisms and the physical environment. In the past the tropical forest has been an important source of knowledge about nature and the human environment; Charles Darwin, Alfred Russel Wallace, Henry Walter Bates and Alexander von Humboldt are only four of many great investigators whose contributions to science depended largely on their experience of the rain forest. Today the rain forests of Costa Rica, Brazil, Panama, New Guinea and West and Central Africa are contributing much of fundamental importance to biology; if it were not for frustrating political and financial obstacles, they could contribute much more.

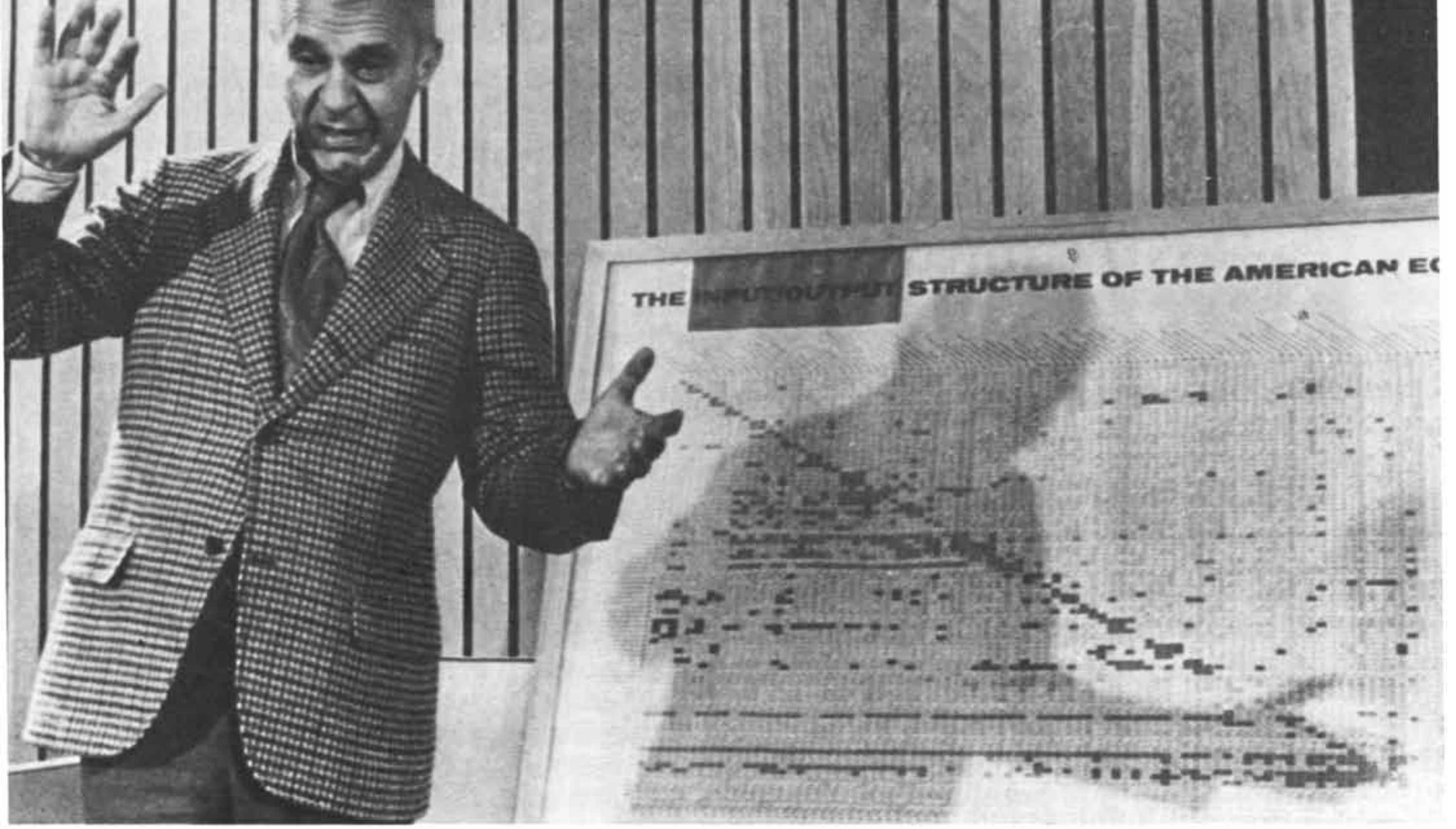
There is good reason to believe the tropical rain forest could yield at least as much knowledge in the future as it has in the past. If it is to do so, however, nature reserves, national parks and other conservation areas must be provided on a much more generous scale than they have been up to now.

It is generally agreed that ancient buildings and other monuments of the human past should be preserved; the efforts made to save them are often a source of national pride. Although the cost of preservation is sometimes high, it is considered to be justified by the insight such monuments give into the life and thought of past civilizations. The tropical rain forest is also a monument, far older than the human species. It offers insight into the complex principles of ecological balance and into the processes at the heart of evolution. It will be sad if we cannot provide the comparatively small amount of effort and money required to safeguard at least a few samples for the instruction and wonder of future generations.



July and August and dropping the fruit later in the year. In others the cycle is regular but apparently not annual (e.g., *Ficus sumatrana*). In some cases no pattern is discernible (e.g., *Bhesa paniculata, Shorea dasyphylla*). Many of these cycles, although not following an annual rhythm, seem to be determined by climatic factors such as droughts and rainy periods.

© 1973 SCIENTIFIC AMERICAN, INC



Nobel Prizewinner, Nobel Prize work

Wassily Leontief won the 1973 Nobel Prize in Economic Science for inventing input/output analysis, the technique that gave the science of economics a powerful, practical technology.

When he explains input/output Leontief turns to one of his favorite props: the input/output chart prepared by the editors of SCIENTIFIC AMERICAN (see illustration). This handsome, eight-color, 70" x 46" chart presents the input/output coefficients for the U.S. economy as of 1963 prepared by the Office of Business Economics of the U.S. Department of Commerce, consolidated into 99 industrial and business sectors.

At Harvard, Leontief and his colleagues put this coefficient matrix in the computer to model the interindustry flow of materials, equipment and services that generated the benchmark trillion dollar U.S. GNP of 1970. Displayed in each of the nearly 10,000 cells of the interindustry matrix are the direct coefficients, the Leontief "inverse" coefficients and the commodity flows.

You can secure your own input/output wall chart plus five articles from the pages of SCIENTIFIC AMERICAN by Leontief and his colleagues. Simply supply the information indicated in the coupon below and your check in the amount of $10.00.

Please note that for $2.50 more you can secure the listing for PASSION*, a computer program written for the IBM 360 and 7094 series, with which you can put the table through its paces for economic analysis and forecasting (the Department of Commerce supplies the coefficients on tape at cost).

*Program for Algebraic Sequences Specifically Of Input-Output Nature.

Offprints of five SCIENTIFIC AMERICAN articles on input/output accompanying the chart 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
by Anne P. Carter

W. H. FREEMAN AND COMPANY
660 Market Street, San Francisco, California 94104

☐ I enclose $________. Please send me ________ input/output kits @ $10 each consisting of the wall chart and five articles.

☐ I enclose an additional $2.50. Please send me PASSION.

Name____________________

Company____________________

Address____________________

City__________ State__________ Zip__________

© 1973 SCIENTIFIC AMERICAN, INC

LASER SPECTROSCOPY

The introduction of the laser as a spectroscopic tool has made it possible to produce extremely narrow "resonances" in the optical emission and absorption spectra of gases

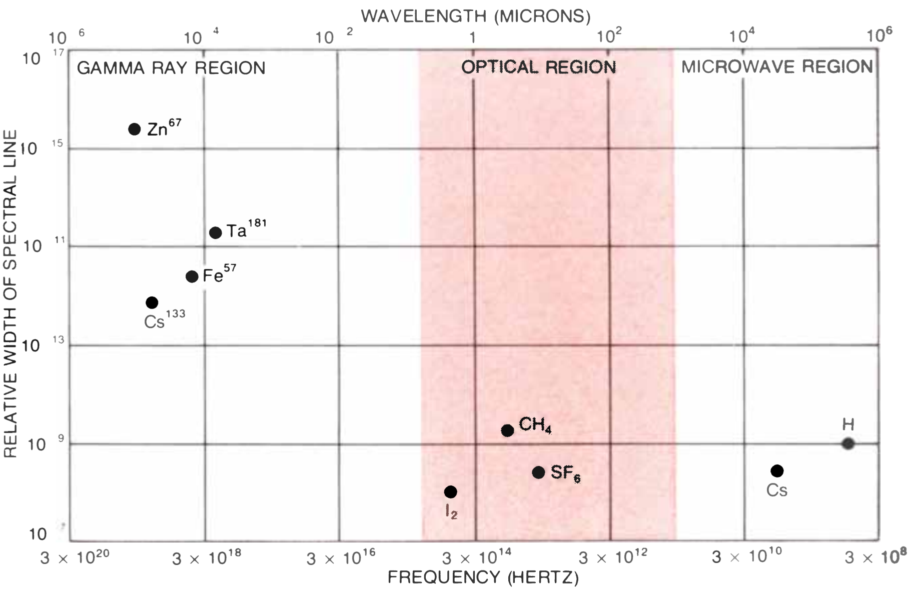
by M. S. Feld and V. S. Letokhov

Much of our current understanding of the fine-scale structure of matter and of how matter interacts with electromagnetic energy comes from spectroscopy, the study of the characteristic frequencies at which resonating atoms and molecules emit and absorb radiation. The discovery and accurate measurement of narrow, frequency-stable resonance lines in the emission and absorption spectra of substances continue to be a fundamental pursuit of physics, not only because advances in this area provide direct clues to the innermost processes of nature but also because they often lead to novel applications in many areas of science.

In the past few decades great progress has been made in generating and measuring extremely narrow resonance lines at wavelengths longer and shorter than those of light. In the microwave-radio region of the spectrum, for example, a technique has been developed to generate narrow resonance lines with the aid of molecular beams. In an arrangement consisting of two spatially separated microwave fields interacting with a beam of cesium atoms, one can obtain resonances between a particular pair of "hyperfine" energy levels of the cesium atom that are 50 hertz wide at a frequency of about 9,300 megahertz. (A hertz is one cycle per second; a megahertz is a million hertz.) The accuracy of this measurement corresponds to a relative line width of approximately five parts in 10^9. (The relative line width is the ratio of the actual width of the spectral line, measured in hertz, to the center frequency of the resonance, also in hertz.) Narrow resonances of this kind provide the basis for the atomic scale of time used today throughout the world.

Advances have also been made in the gamma ray region of the spectrum. In 1958 Rudolf Mössbauer discovered that extremely narrow resonances can be produced in transitions that occur between certain energy levels of atomic nuclei embedded in a crystal lattice. These resonance lines, the narrowest known at present, enable one to make physical measurements with an accuracy of one part in 10^{15}.

Thus techniques for producing extremely narrow resonance lines have been developed in both the low-frequency and the high-frequency ends of the electromagnetic spectrum. Until recently, however, little progress was made in achieving such narrow resonances in the intermediate spectral range, which spans the optical and infrared frequencies. Here the narrowest relative line widths available were only about one part in 10^6. The recent introduction of the laser as a spectroscopic tool has already led to an improvement

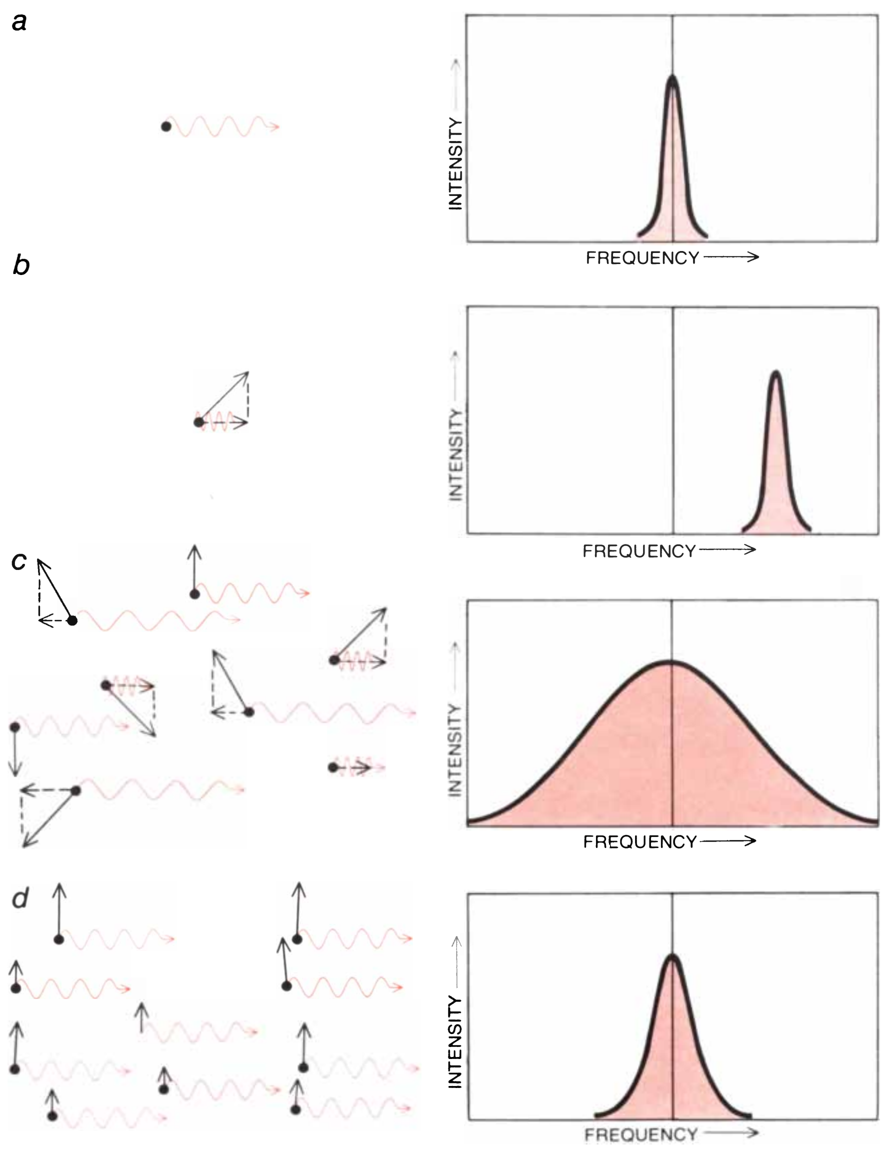


EXTREMELY NARROW SPECTRAL LINES have been measured in recent years in several regions of the electromagnetic spectrum. In the high-frequency, short-wavelength gamma ray region (*left*) narrow resonance lines are generated in transitions that occur between certain energy levels of atomic nuclei embedded in a crystal lattice by a process known as the Mössbauer effect. Mössbauer measurements for isotopes of four different elements are represented here: cesium (Cs^{133}), iron (Fe^{57}), tantalum (Ta^{181}) and zinc (Zn^{67}); the superscript number in each case denotes the number of nucleons (protons plus neutrons) in that particular isotope's nucleus. In the low-frequency, long-wavelength microwave region (*right*) narrow resonances are generated with the aid of molecular beams; microwave measurements made with a hydrogen (H) maser beam and a cesium (Cs) beam are shown. In the intermediate spectral range, which spans the optical and infrared frequencies (*middle*), the laser-saturation technique has made it possible for the first time to resolve relative spectral line widths with a comparable accuracy; laser measurements for three molecular gases are given: iodine (I_2), sulfur hexafluoride (SF_6) and methane (CH_4).

© 1973 SCIENTIFIC AMERICAN, INC

in this figure by several orders of magnitude. In this article we shall explain how the resonant interaction of intense, coherent laser light with an atomic or molecular gas has made it possible to resolve relative line widths in the optical and infrared spectral regions to an accuracy of better than one part in 10^9.

In what state of matter can the narrowest optical resonances be obtained? In a crystal the energy levels of impurity ions are strongly broadened by the vibrations of the crystal lattice. Even at low temperatures the relative width of the spectral lines is no better than one part in 10^5. The situation is even worse in an irregular medium such as a liquid or a glass. Owing to the random distribution of impurity ions within such a matrix, the energy levels are inhomogeneously broadened over the volume of the medium, resulting in relative line widths of no better than one part in 10^3. The narrowest resonances in the intermediate spectral range have been obtained in gases at low pressures, where interparticle collisions, which broaden the spectral lines, are minimal. In this case the spectral line widths are limited by the random motions of the atoms or molecules of the gas.



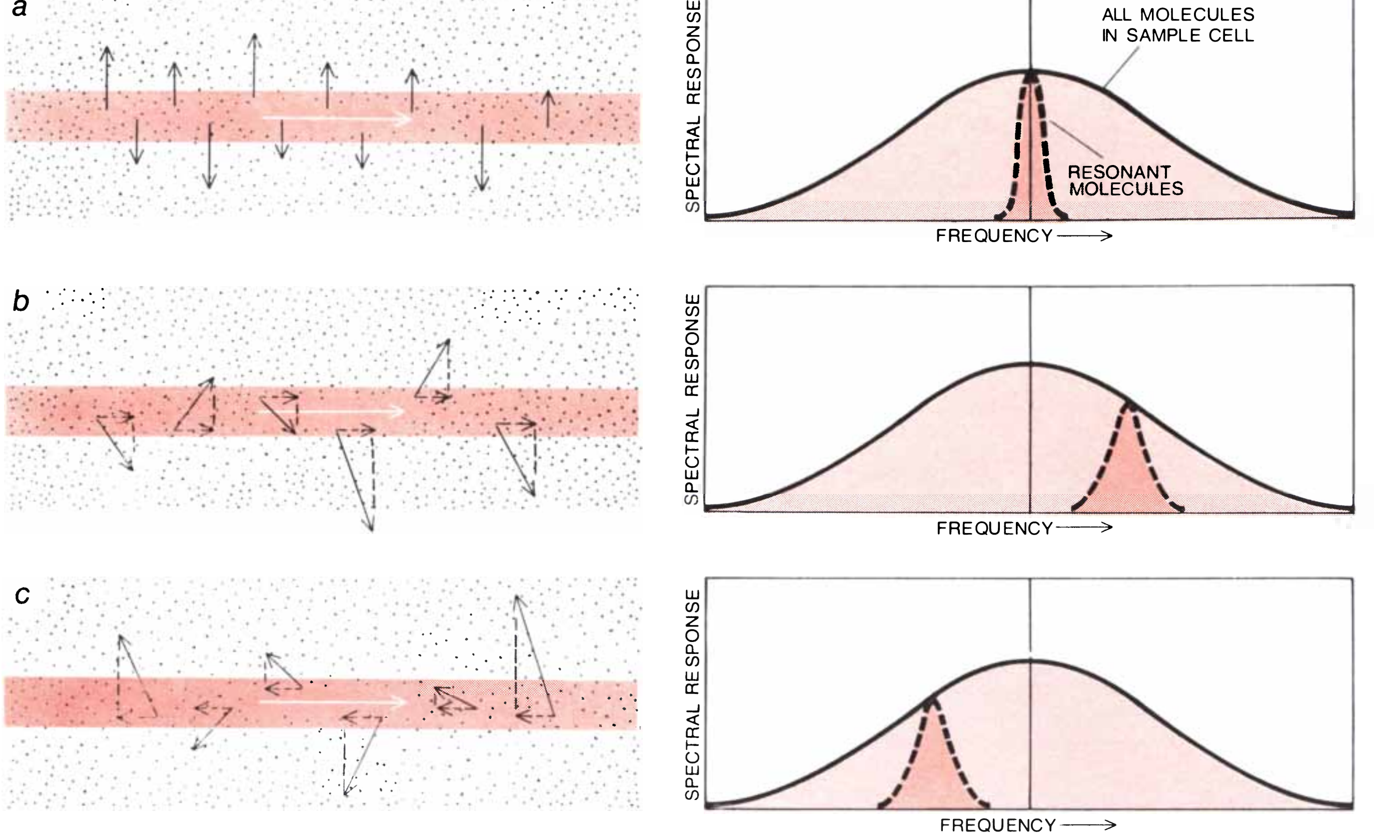
INFLUENCE OF DOPPLER EFFECT on the width of a spectral line associated with an atomic or molecular gas at low pressure is represented schematically in this series of diagrams. (The Doppler effect is the tendency of the wave fronts of the light emitted by a moving particle to be compressed in the direction of the particle's motion and to be expanded in the opposite direction.) According to quantum theory an isolated particle at rest (*a*) can emit light at a characteristic frequency called the resonant frequency. If the particle is moving (*b*), the frequency of this emission will be shifted by an amount that is proportional to the component of the particle's velocity in the direction of the emitted light. In a gas (*c*) particles move in all directions with varying speeds, giving rise to a broad distribution of Doppler shifts; as a result the spectral line corresponds to a bell-shaped curve, centered at the natural resonant frequency. One way of cutting down the Doppler width is to use a beam of particles (*d*); by reducing the particle motion in a direction perpendicular to the axis of the beam this method makes it possible to observe spectral lines that are much narrower than the Doppler width. This approach is limited in practice by the problem of producing an intense enough beam with a small enough divergence.

Consider an atom or a molecule that can make transitions between two energy levels, in the process emitting light at a frequency that (according to quantum theory) is proportional to the difference in energy between the two levels. It is a well-known fact that if the particle is moving, the line width of the emitted radiation, which can be extremely narrow, will not be centered at exactly the resonant frequency. Instead the frequency will be shifted by an amount that depends on the component of the particle's velocity in the direction of the emitted radiation [*see illustration at left*]. This Doppler effect occurs because the moving wave fronts of the emitted radiation are compressed in the direction of the particle's motion and are expanded in the opposite direction, giving rise to a shift in wavelength and therefore in frequency.

In a gas particles move in all directions with varying speeds, giving rise to a broad distribution of Doppler shifts. In a state of thermal equilibrium the distribution of particle velocities in a given direction corresponds to a bell-shaped curve. As a result the spectral line is also represented by a bell-shaped curve, centered at the resonant frequency. The net line width attributable to the Doppler effect is proportional to the average particle velocity, which in turn depends on the temperature of the gas and the mass of the individual particles. For atoms and molecules at room temperature the average particle velocity ranges from 10,000 to 100,000 centimeters per second, with the lighter particles having somewhat higher average velocities than the heavier ones. As a result the relative width of a Doppler-broadened spectral line is on the order of one part in 10^6.

Because an optical spectral line in a gas is composed of a large number of much narrower spectral lines of particles moving with different velocities, Doppler broadening is often referred to as inhomogeneous. It is obvious that by reducing the spread in particle velocities

© 1973 SCIENTIFIC AMERICAN, INC



INTERACTION OF LASER LIGHT with a Doppler-broadened spectral line is depicted here for the case of a low-pressure gas of resonant molecules that are in the absorbing phase. In general only molecules moving with a particular velocity component in the direction of the laser beam can interact with the beam. When the frequency of the light wave exactly coincides with the center of the bell-shaped Doppler profile of the spectral line (*a*), light will be absorbed only by those molecules for which the Doppler frequency shift is very small; such molecules move predominantly in a direction perpendicular to that of the light beam. If the laser frequency is higher than the center frequency of the resonance (*b*), molecules moving with a particular component of velocity in the direction of the light beam will be Doppler-shifted into resonance. If the laser frequency is lower than the center frequency (*c*), molecules moving in the opposite direction will be the interacting ones. The spectral response of the resonant group of molecules in each of the three possible situations takes place over a narrow frequency interval centered at the frequency of the applied laser radiation.

it should be possible to cut down the Doppler width and thereby obtain narrower resonances. One way of doing this is to use a beam of atoms or molecules in which the particles are highly collimated (all moving in the same general direction). By this stratagem the particle velocities in directions perpendicular to the axis of the beam can be substantially reduced. Accordingly spectral lines observed in this direction can be between 10 and 50 times narrower than the Doppler width, depending on the divergence of the beam. Unfortunately further narrowing is not attainable, the chief difficulty being that of producing an intense enough beam with a small enough divergence. The narrow optical resonances produced by the laser techniques described below are equivalent to those that would be obtained with a high-intensity molecular beam having a divergence much smaller than can be achieved in practice. Before describing these techniques in detail, however, it is advisable to review the factors that determine the width of a spectral line when Doppler broadening is absent, since this is the limit to be aimed for.

Several effects contribute to the homogeneous width of a spectral line, that is, the line width associated with a group of gas molecules all moving with the same velocity. The most fundamental effect is radiation broadening caused by the spontaneous decay of an excited atom or molecule. According to quantum theory, the energy of an atomic state can be determined only within a range of energies that is inversely proportional to its lifetime. The frequency spread of the emitted light is in turn proportional to this energy range. Accordingly the broadening of a spectral line caused by spontaneous decay is inversely proportional to the lifetime of the excited atomic state. This process is called natural broadening.

The lifetimes of the excited states that give rise to the strongest atomic and molecular optical transitions are extremely short, typically a hundred-millionth of a second. Even for such transitions the natural line width is at least an order of magnitude smaller than the Doppler width. Many excited states with considerably longer lifetimes also exist; the optical transitions associated with these states produce much narrower natural line widths. Included in this category are the metastable states of atoms and the vibrational states of molecules. The natural line widths arising from these states can be millions of times narrower than the corresponding Doppler widths.

A second source of homogeneous line broadening arises from collisions between particles in the gas. The collisions interrupt the periodic movement of the electrons in an atom or of the atomic vibrations in a molecule. As a result the periodicity of the radiation process is altered, with the consequence that the radiative interactions can last only for a time equal to the average time between successive collisions. The continual in-

© 1973 SCIENTIFIC AMERICAN, INC

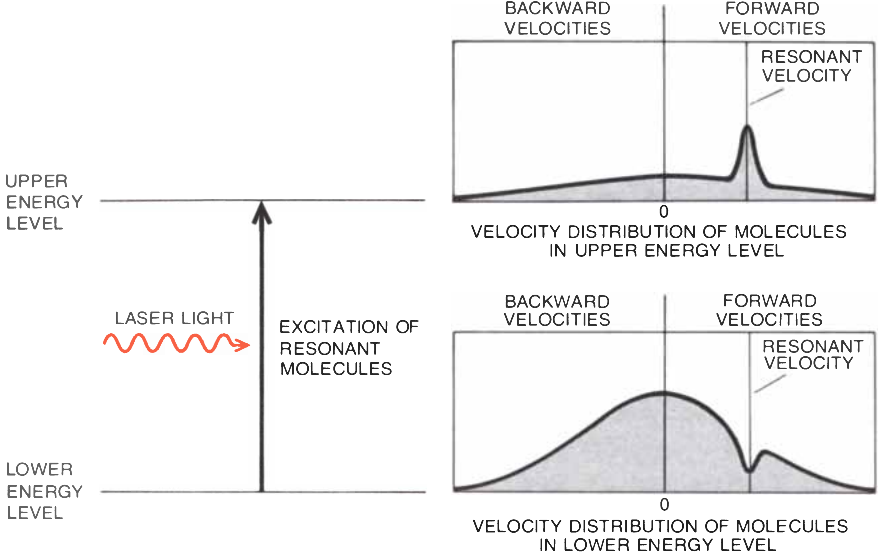
terruption of the radiation process in this way broadens the spectral lines. This model of collisional broadening was introduced in 1915 by H. A. Lorentz and is often called Lorentz broadening.

Even fairly weak particle interactions cause changes in the speed and the direction of motion of the passing particles, and both kinds of change tend to interrupt the radiation process. Accordingly the effective time between line-broadening collisions can be considerably shorter than the "geometrical" collision time, which is based simply on the size of the particles. At a gas pressure of one torr (1/760 of atmospheric pressure) the average time between line-broadening collisions is on the order of a ten-millionth or a hundred-millionth of a second. At such a pressure the Lorentz broadening of a molecular transition is thousands of times greater than the natural line width. The number of collisions per second, and therefore the Lorentz broadening, is proportional to the gas pressure. In order to reduce the collisional broadening to a point where it is comparable to natural broadening, one must operate at pressures below a millitorr (a thousandth of a torr). At such low pressures, however, other line-broadening mechanisms become important.

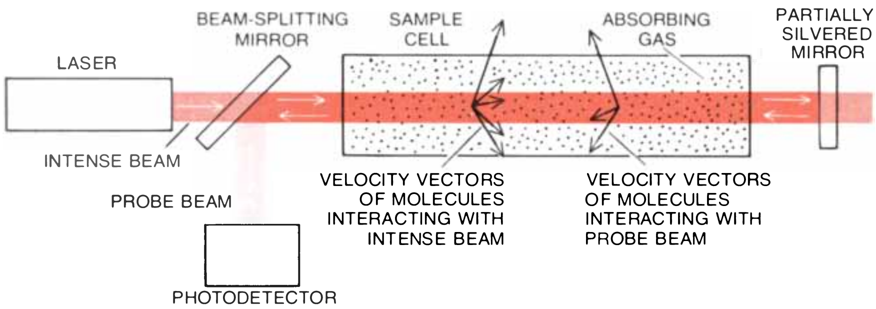
As the pressure is reduced the average distance traveled by a particle between collisions increases, and at low enough pressures this length can become comparable to or even greater than the size of the cell that contains the gas. In this pressure range the time between collisions is no longer determined by interparticle collisions but rather by collisions with the cell walls. This effect broadens the spectral line by an amount that varies inversely with the mean distance between the cell walls. Although the effect is quite small, it can still give rise to a line broadening that exceeds the natural width of some infrared molecular lines.

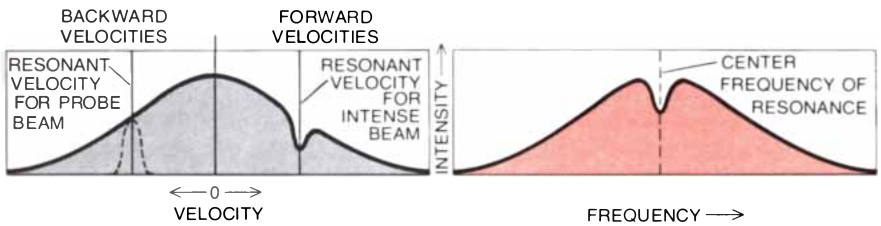
Another contribution to the width of a spectral line results from the transit of particles through the light beam used to study the line. At gas pressures above one torr this effect is not noticeable because the mean time between collisions is much shorter than the transit time. At the extremely low pressures at which the laser studies are carried out and for transitions with long lifetimes, however, the transit effect can become the dominant line-broadening mechanism.

At sample-cell pressures in the millitorr range the high light intensities available from laser sources can also contrib-



LASER-SATURATION EFFECT is observed when a laser beam is intense enough to excite some of the molecules in a gas from a lower energy level to an upper energy level (*left*). The saturation of the energy-level populations will occur only for molecules that can be Doppler-shifted into resonance with the laser radiation. As a result in the excited state there will be an excess of molecules with the resonant velocity, whereas in the lower level there will be a deficiency of such molecules (*right*). The particular resonant velocity at which this distorting effect appears in the usual bell-shaped velocity-distribution curve is proportional to the "detuning" of the laser frequency from the molecular center frequency.





NARROW RESONANT CHANGES produced by the laser-saturation effect can be observed in a simple experimental arrangement in which an intense laser beam is incident on a gas-filled sample cell (*top*). After traveling through the cell a small portion of the beam is reflected back in the opposite direction by means of a partially silvered mirror. The reflected radiation serves as a probe beam of the same frequency as the intense beam but oppositely directed. The intense beam interacts with those particles that move with a particular axial velocity; the probe beam interacts with those molecules that have the same axial speed but are moving in the opposite direction. Hence the two beams interact with two distinct groups of molecules located symmetrically on opposite sides of the molecular velocity distribution (*curve at lower left*). This distortion of the velocity-distribution curve can in turn produce a narrow resonant "dip" in the absorption of the probe field (*curve at lower right*).

© 1973 SCIENTIFIC AMERICAN, INC

I am you.

My name is Noritsune Chiba, and these are my kids. They're giving me a workout . . . it seems like they'll never run out of energy.

I'm trying to make sure they don't. I'm an Hitachi engineer. And energy is my business.

For the last four years I've coordinated Hitachi's contributions to a hydroelectric plant at Ludington, Michigan. A really enormous project.

At night, when power from atomic and fossil fuel plants would otherwise go to waste, we use it to pump nearly 2,000 tons of water per second up hill from Lake Michigan into an artificial lake. Then during the day, when power *is* in demand, we let it flow down again—through turbines, in order to generate electricity.

Building the colossal pump/turbines and generator/motors for this project has required all kinds of new technology. For instance we had to develop a new thick steel welding technique for the turbine runner. And we had to design a thrust bearing capable of supporting over 2,000 tons.

The best thing about the project is the result. The people of the American Midwest will now have an additional 1,872,000 kilowatts during the hours of peak demand. What's more, they'll have their additional power without additional pollution.

Ludington, Michigan is half-way round the world from where I live. But even so, I feel like I've done something for my family. I feel that the technology I've helped develop will help everybody.

I feel that when I work for Hitachi, I'm working for all of you.

Because my work will benefit me.

And I am you.

HITACHI
Resourceful people

Hitachi America, Ltd.
Head Office: 437 Madison Avenue, New York, N.Y. 10022
Tel: (212) 758-5420
Branch Offices: San Francisco, Chicago, Atlanta.

● Power Generation & Transmission Equipment Industrial Machinery ● Transportation Equipment ● Communications Equipment ● Electronics & Home Appliances

© 1973 SCIENTIFIC AMERICAN, INC

Give somebody you love the gift of sharpened perception.

*Suggested list price. †Comparison based on suggested list T88/T108 film.
Details on camera comparison available upon request from Polaroid Corporation, Cambridge, Massachusetts 02139

© 1973 SCIENTIFIC AMERICAN, INC

Pictures on the spot encourage the selective process.

Any camera will stimulate a beginner (of any age) to look at the world. But only an instant picture camera can teach its owner to really see what he's looking at. Because the Polaroid Land film in that camera allows the user to immediately compare his photograph with the reality he attempts to portray.

It is at this unique moment of truth that the photographer can see what he may have missed at first glance.

Often, a slight change in position can enrich his picture by including contrasting elements, or by emphasizing an essential quality in the subject. And because your beginner can re-shoot on the spot, he gets the immediate reward of a better picture. Along with a lesson in the art of observation.

With all the Polaroid Land cameras to choose from, there are two reasons why Square Shooter 2 is the ideal teacher.

From technological complexity comes operational simplicity.

Here is a camera that is truly a servant of the eye. It delivers crisp color shots in 60 seconds without interfering with one's visual concentration.

To begin with, the viewfinder incorporates an ingenious rangefinder.

For most shots, the photographer simply covers the subject's face with the little red square in the viewer. At that point the camera will be in ideal focus at five feet (the best distance for both flash and non-flash shots of people). The excellent, three-element, true focusing lens can also give sharp pictures from 3½ feet to infinity.

When the shutter release is pressed, an electric eye automatically reads the light. (When flashcubes are used, it also reads the light of the flash.) The electronic shutter then operates at the proper speed (ranging from ½ second to 1/500th) to give the correct exposure.

60 seconds later, with virtually no mechanical distractions, your beginner has his picture.

Even the price is an eye-opener: $24.95

When we were designing the Square Shooter 2, we knew we were creating a superb camera for new photographers. So we concentrated on keeping its quality high . . . and its price low.

That's why we ended up with a camera equipped like models costing $20 more and why we ended up with a camera that uses an inexpensive, square, color film that can save up to 25% on every shot.†

So it could end up in the hands of your beginners this Christmas.

Polaroid's Square Shooter 2. Only $24.95*

© 1973 SCIENTIFIC AMERICAN, INC

Somebody has to provide the technology so the problems get solved

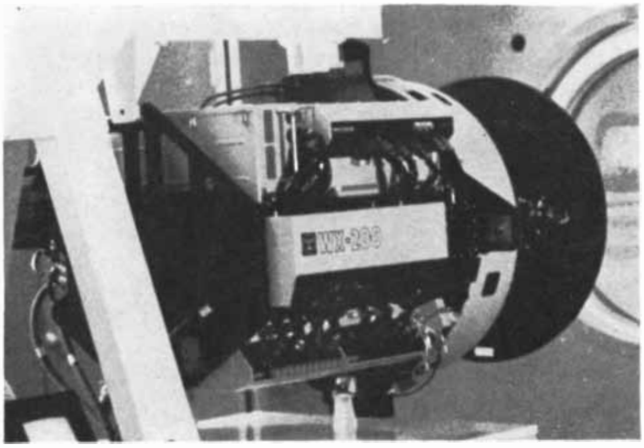
Problem: **A developing nation needs a modern, national communications system.**

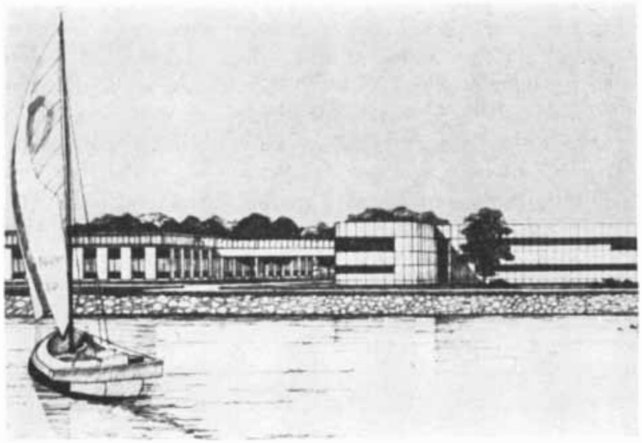
Solution: **Fly a balloon.**

We've just tested our first TCOM (Tethered Communications) station over the Bahamas. TCOM is an aerodynamic all-weather balloon connected to a ground station. It's also a unique communications/television relay system that can be installed in months at a fraction of the cost of coaxial cable installations or a synchronous satellite system. One balloon covers at least 125,000 sq. km. That means Liberia or Honduras.

Two would serve Equador or Senegal. In addition to radio and telephone service, TCOM can provide color TV, telephoto, and digital data transmission channels. Maybe better communications will clear up some of the world's misunderstandings. We've bet a lot of our own money on it.

© 1973 SCIENTIFIC AMERICAN, INC





Problem: The high cost of avionics.

Solution: Low-cost WX system.

Westinghouse has developed a family of modular airborne radars that can reduce total cost (both purchase and maintenance) by as much as four to one. For example, initial cost of our centerline design (WX 200) is $200K instead of the $600K of equivalent current models, plus it will deliver 100 hours MTBF (mean time between failures). It weighs 350 pounds instead of 700 and will fit most military aircraft instead of just one. So far, there's a substantial amount of our own money in this designed-to-cost product.

Problem: The environmental problem.

Solution: Apply industrial know-how.

Should Americans apply the proved, multi-disciplinary research methods of industry to the environment? We think so, and have announced plans for a multimillion-dollar Environmental Center that will be next door to our Ocean Research Center on Chesapeake Bay. The combined operation will comprise an impressive collection of scientists and engineers zeroing in full time on everything from agriculture to oil production, from water and sewage to power generation and the fish industry. Maybe not tomorrow, but there are solutions.

You can be sure if it's Westinghouse.
For our new brochure, write
W. R. Smanko, Marketing Manager,
Defense & Public Systems,
Westinghouse Electric Corporation,
Pittsburgh, Pa. 15222.

Westinghouse helps make it happen

© 1973 SCIENTIFIC AMERICAN, INC

ute to the homogeneous line width by a process known as power broadening. In order to avoid this problem the intensity of the applied laser field must be limited.

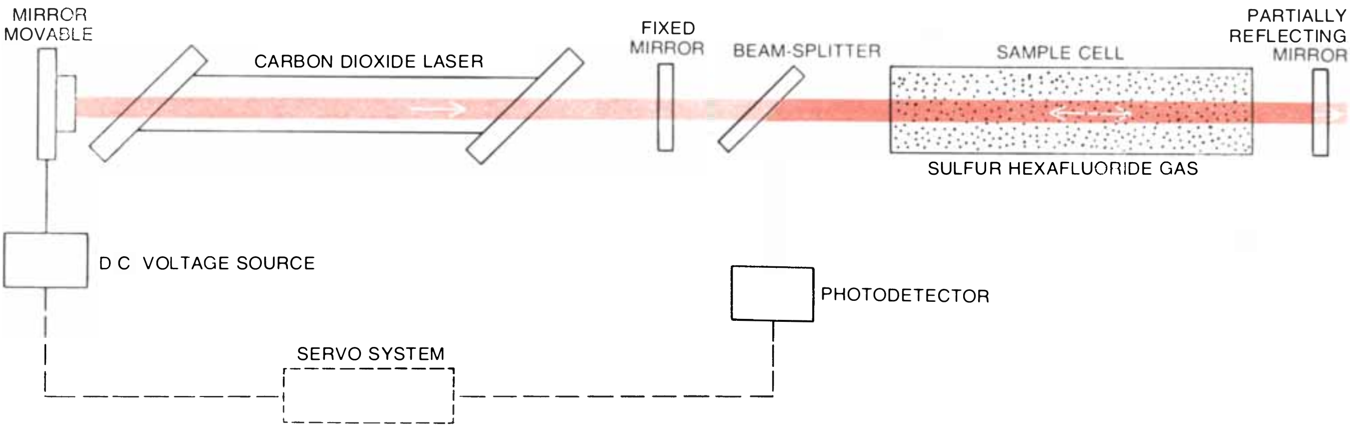
Let us now consider the interaction of a plane wave of coherent laser light with a Doppler-broadened spectral line. To be specific, let us assume that the resonant molecules are in the absorbing phase. (Similar considerations hold for emitting molecules.) First, suppose that the frequency of the light wave exactly coincides with the center of the bell-shaped Doppler profile. Light will then be absorbed only by molecules for which the Doppler frequency shift is very small, in other words, by those molecules having little or no component of motion in the direction of the light beam [*see illustration on page 71*]. Molecules with a velocity component along the axis of the beam will be Doppler-shifted out of resonance and hence cannot interact with the light wave.

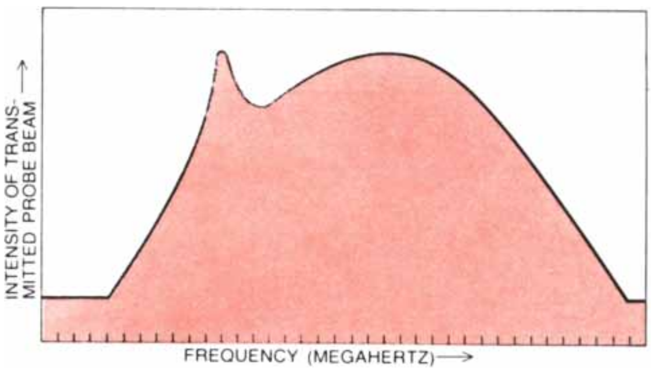
If, on the other hand, the light wave is "detuned" in frequency from the center of the Doppler profile, then molecules moving in the perpendicular direction will no longer be able to absorb the light. Instead light will be absorbed by molecules whose radiation frequency is Doppler-shifted into resonance with the applied laser field. These molecules have a component of velocity along the axis of the light beam. The magnitude of this axial velocity depends on the extent of the detuning of the frequency of the light waves from the center of the Doppler profile; the greater the detuning, the larger the axial velocity. Furthermore, the direction of motion of these molecules depends on the sign of the detuning of the laser frequency. If the laser frequency is higher than the center frequency of the resonance, the interacting molecules will be moving in the direction of the light beam, whereas if the laser frequency is lower than the center frequency, the molecules selected will be moving in the opposite direction. The main point is that only molecules moving with a particular velocity component along the light beam can resonate with the laser field. The spectral response of this group of molecules takes place over a narrow frequency interval that is equal to the homogeneous line width and is centered at the frequency of the applied laser radiation.

If the light wave is intense enough, a sizable fraction of the molecules in the lower energy level can be excited into the upper level in the absorption process [*see top illustration on page 72*]. This phenomenon is referred to as the saturation of the level populations. Clearly saturation will occur only for the molecules that are Doppler-shifted into resonance with the laser field. As a result in the excited state there will be an excess of molecules with the resonant axial velocity, whereas in the lower level there will be a deficiency of such molecules.

These changes in the molecular velocity distribution can produce narrow resonant changes in absorption. For example, consider an intense beam of laser light falling on a sample cell that contains absorbing gas molecules, and suppose that after traveling through the cell a small portion of the beam is reflected back in the opposite direction by means of a partially silvered mirror. The reflected beam, which has the same frequency as the intense beam but is oppositely directed, serves to probe the velocity distribution of the absorbing gas [*see bottom illustration on page 72*].

The intense beam selectively interacts with those particles that move with a particular axial velocity determined by the detuning of the laser beam from the molecular center frequency. Since the probe beam propagates in a direction opposite to that of the intense beam, it interacts with molecules that have the same axial speed but are moving in the opposite direction. Therefore if the common frequency of the two light beams does not coincide with the molecular center frequency, the oppositely directed waves will interact witn two distinct groups of molecules located symmetrically on opposite sides of the molecular velocity distribution. Thus in this case the absorption of the probe beam is unaf-





ACTUAL EXPERIMENT performed recently by one of the authors (Letokhov) and his colleagues at the Institute of Spectroscopy in Moscow employed a carbon dioxide (CO_2) laser to study narrow resonances in molecules of sulfur hexafluoride (SF_6). A sample cell filled with SF_6 at low pressure was subjected to a beam of light from the CO_2 laser (*diagram at top*). A small part of the transmitted light was reflected back in the reverse direction to serve as the probe beam. When the transmission of the probe radiation was studied as a function of the laser frequency (*curve at left*), the shape of the resulting curve revealed narrow resonances with corresponding line widths of between .2 and .5 megahertz.

© 1973 SCIENTIFIC AMERICAN, INC

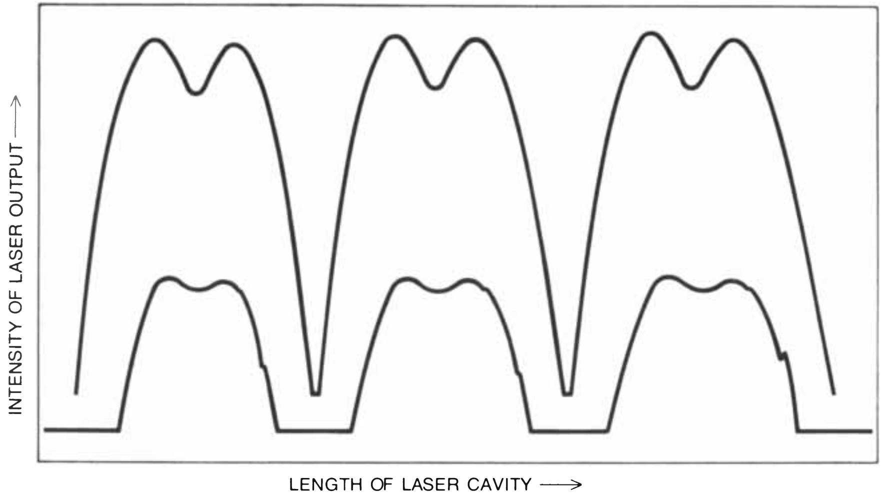
fected by the presence of the intense beam.

If the applied laser radiation is tuned to the center of the Doppler profile, however, then both waves will interact with the same group of molecules, namely those having no component of motion along the axis of the beams. Therefore at this frequency the weak probe beam will interact with the molecules saturated by the intense wave (that is, the molecules for which the population difference between levels has been reduced by the saturation effect). Since the absorption of light is proportional to the difference in population between the lower and the upper levels, the absorption of the probe wave will be decreased. Thus as the laser frequency is tuned across the Doppler profile the absorption of the probe wave will exhibit a resonant "dip" exactly at the center of the Doppler profile with a width equal to the homogeneous line width.

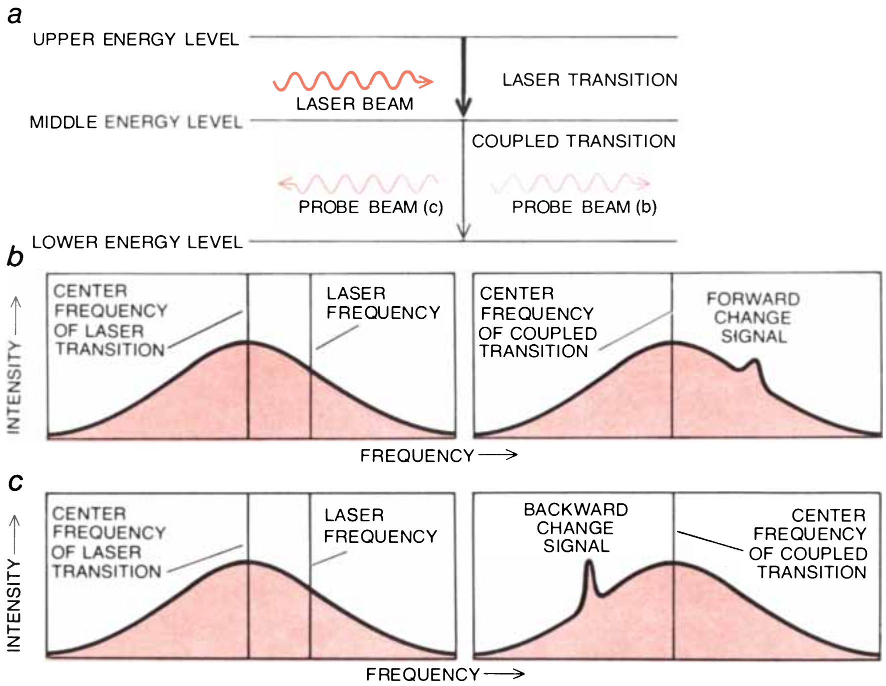
To illustrate this technique we shall now describe an actual experiment conducted by one of us (Letokhov) and his colleagues at the Institute of Spectroscopy in Moscow. In the experiment a carbon dioxide (CO_2) laser was used to study narrow resonances in molecules of sulfur hexafluoride (SF_6). The CO_2 laser produces intense monochromatic radiation at a set of infrared wavelengths in the region of 10 microns. Several of these laser wavelengths coincide with vibrational absorption lines of gaseous SF_6. In the experiment in question a sample cell filled with SF_6 at low pressure was subjected to a beam of light from a CO_2 laser [*see illustration on opposite page*]. A small part of the transmitted light was reflected back in the reverse direction to serve as the probe beam. The transmission of the probe radiation was then studied as a function of the laser frequency.

The attentuation of the probe beam observed in this way revealed narrow resonances with widths between .2 and .5 megahertz, the exact line width depending on the gas pressure. At a pressure of five millitorr the homogeneous line broadening of gaseous SF_6 is known to be about .1 megahertz, whereas the observed width of the actual resonance line is .2 megahertz. The additional broadening is attributable to the transit time of molecules through the light beam and to the power broadening of the resonance by the high intensity of the laser beam.

The narrow optical resonances produced in this manner enable one to measure the centers of Doppler-broad-

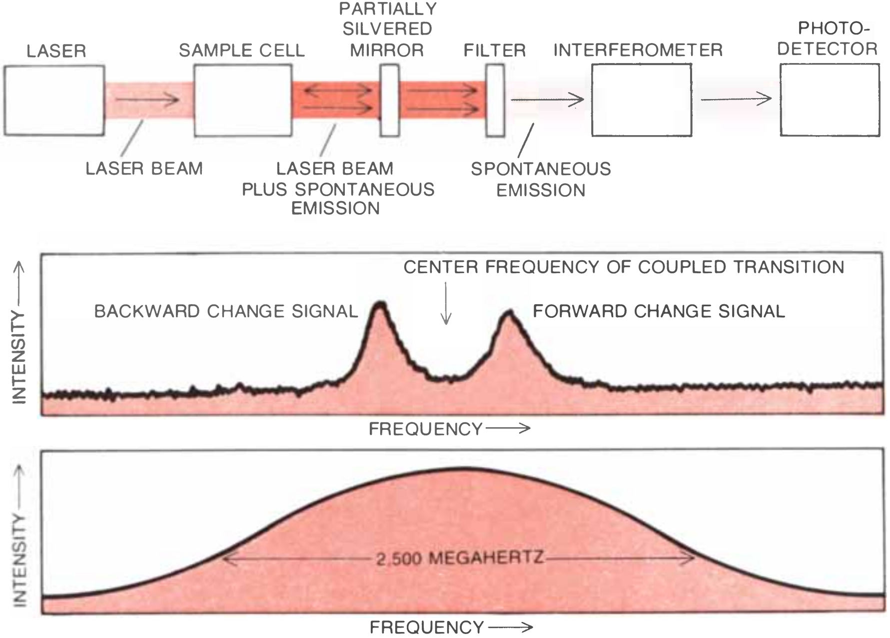


"LAMB DIP," a form of narrow saturation resonance that manifests itself in the output signal of a gas laser rather than in the attenuation of an absorbing gas, was originally postulated by Willis E. Lamb, Jr., in 1962. In this approach the laser frequency is tuned through the Doppler-broadened gain profile of the laser (by changing the length of the laser cavity), causing a narrow resonant decrease (the Lamb dip) to appear exactly at the center of the tuning curve. The first experimental observation of the Lamb dip was made in 1963 by Abraham Szöke and Ali Javan at the Massachusetts Institute of Technology. In the two experimental curves shown the output of a helium-neon laser oscillating at 1.15 microns is studied as a function of the length of the laser cavity for two different values of laser gain; the Lamb dip is the shallow depression in the peak of each gain profile. The Lamb-dip technique and the closely related "inverted-Lamb-dip" approach both allow the center frequency of an atomic or molecular transition to be established with a high accuracy.



LASER-INDUCED LINE NARROWING is a term used to describe the production of narrow resonances in "coupled" transitions, that is, transitions that share a common energy level with the laser-saturated transition. In the three-level scheme shown in *a*, for example, two of the energy levels interact with an intense laser field and a third, lower level does not. Atoms in the middle level can make transitions to the lower level as well as to the upper level. As a result of the saturation effect the intense laser field changes the atomic population of the middle level over a narrow range of velocities. When a probe beam colinear with the laser beam is tuned in frequency through the coupled transition, this velocity change will result in an extremely narrow change in emission (or absorption) superimposed on the broad Doppler background. The frequency at which this change signal appears depends on whether the probe beam propagates in the same direction as the laser beam (*b*) or in the opposite direction (*c*). The two narrow change signals, called the forward change signal and the backward change signal respectively, are located symmetrically on opposite sides of the Doppler-broadened frequency profile of coupled transition.

© 1973 SCIENTIFIC AMERICAN, INC



BY REFLECTING a traveling-wave laser beam back on itself, as shown in the diagram at top, it becomes possible to have both the forward and the backward change signals appear together on opposite sides of the Doppler-broadened frequency profile. In this situation one can determine the center frequency of the coupled transition with an accuracy limited only by the homogeneous spectral line width. The experimental results shown at bottom were obtained with this arrangement. Instead of a probe beam the spontaneously emitted light at the coupled transition was observed along the axis of the laser beam. In the lower trace, which shows the direct spontaneous emission recorded by an interferometer, the broad Doppler background signal completely obscures the narrow change signals. In the upper trace this background is removed by means of a special modulation technique. The center frequency of the coupled transition is located midway between the two change signals. Note the slight width asymmetry between the forward and the backward change signals.

ened atomic and molecular spectral lines with great accuracy. This capability in turn makes it possible to measure accurately the wavelengths of energy-level transitions in atoms and molecules. Such quantum measurements are important in testing theories of atomic and molecular structure and in establishing accurate values for many fundamental physical constants.

Another important application of laser spectroscopy is in the study of closely spaced atomic and molecular energy levels whose separate structure is ordinarily masked by the Doppler broadening of the spectral lines. By effectively eliminating Doppler broadening the new laser technique enables one for the first time to resolve the fine structure of these spectral lines. This capability is of particular importance in the case of hydrogen, the simplest atom, where a precise determination of the fine structure is a fundamental objective of spectroscopy. Significant progress in this area has been made recently by Arthur L. Schawlow and his collaborators at Stanford University.

The laser technique described above is not limited to the case where the forward wave is strong and the backward wave weak. It can also be applied when both waves are intense. Indeed, the original technique for producing narrow saturation resonances—the "Lamb dip" technique proposed by Willis E. Lamb, Jr., in 1962—was developed for just this situation. In Lamb-dip studies the narrow resonance manifests itself in the output signal of a gas laser rather than in the attenuation of an absorbing gas. Consider a gas laser consisting of a Doppler-broadened amplifying medium placed between two flat, parallel mirrors. (In an amplifying medium the population of the upper energy level exceeds that of the lower energy level, the reverse of the situation in an absorbing medium.) Because of reflections the laser radiation between the mirrors consists of waves of equal intensity traveling in opposite directions. Therefore the preceding discussion applies here as well. Accordingly, as the laser frequency is tuned through the Doppler gain profile (by changing the length of the laser cavity) a narrow resonant decrease, the Lamb dip, will appear exactly at the center. Hence just as in the case of an absorbing gas, the center frequency of the laser transition can be established with a high degree of accuracy.

The first observation of a Lamb dip was made in 1963 by Abraham Szöke and Ali Javan at the Massachusetts Institute of Technology [*see top illustration on preceding page*]. In their experiment the output of a helium-neon laser oscillating at 1.15 microns was studied as a function of the length of the laser cavity. The observed dip is rather broad in this case, since the lifetimes of the excited neon states are short and the pressure at which optimum laser gain is obtained is high (a few torr).

A modified version of this approach, called the inverted-Lamb-dip technique, is particularly useful for obtaining extremely narrow resonances in the laser-output tuning curve. In this technique a second cell that contains an absorbing gas at a low pressure is placed in the laser resonator along with the amplifying medium. The laser frequency must be tunable through the Doppler profile of the absorber chosen. The absorber adds a small loss to the laser cavity, resulting in a slight overall reduction in the laser-output intensity. When the laser frequency is tuned to the center of the absorber resonance, however, the saturation effect causes an additional reduction in the population difference between the levels of the absorbing transition and a corresponding decrease in the attenuation of the absorption cell. Consequently as the laser is tuned within the homogeneous line width of the absorber's center frequency the laser-output power increases. Under suitable conditions (for example in molecular absorbers at very low pressure) this line width can be far narrower than that of the laser amplifier. Therefore as the laser frequency is tuned an extremely sharp increase in laser output appears, superimposed on the comparatively broad Lamb dip of the amplifying cell. This effect is called the inverted Lamb dip because its sign is opposite to that of the normal laser-output tuning curve. Extremely narrow resonances of this type are ideally suited for constructing atomic clocks of unsurpassed accuracy.

The range of possibilities opened by the newfound ability to selectively saturate a portion of the velocity distribution of a gas is not limited to single atomic or molecular transitions. Narrow resonances closely related to those described above can also be produced in "coupled" transitions, that is, transitions that share a common energy level with the saturated transition. This extends the usefulness of the saturation effect con-

© 1973 SCIENTIFIC AMERICAN, INC

siderably. Let us see how narrow resonances manifest themselves in a pair of coupled Doppler-broadened transitions.

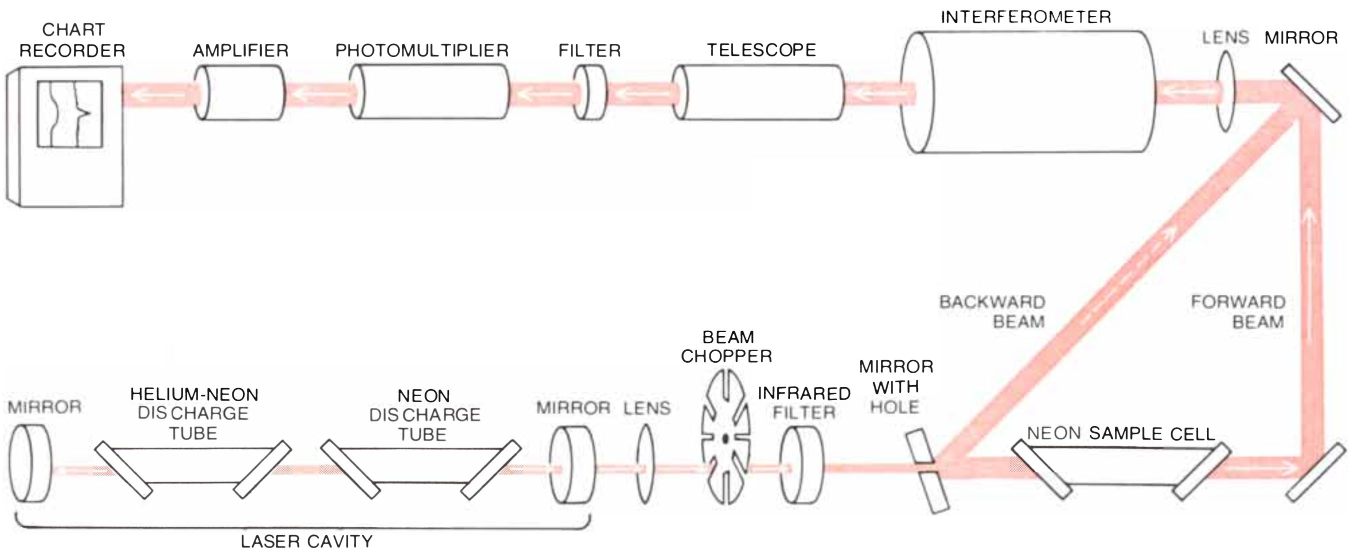
It usually happens that an atom in a particular energy level can make transitions to several other levels. For example, consider an energy-level scheme consisting of three different levels; two of the levels interact with an intense laser beam and a third, lower level does not [*see bottom illustration on page* 79]. Assume that atoms in the middle level can make transitions to the lower level as well as to the upper level; let us call the upper transition the laser transition and the lower transition the coupled transition. As a result of the saturation effect the intense laser radiation changes the population of the middle level over a narrow range of velocities. Now if a monochromatic probe beam colinear with the laser beam is tuned in frequency through the coupled transition, this velocity change will result in a change in absorption (or emission) superimposed on the broad Doppler background, just as in the case of a single transition. The detuning of this change signal from the center frequency of the coupled transition will be proportional to the detuning of the laser frequency from the center frequency of its transition, since increased laser detuning causes molecules with larger axial velocities to be selected from the molecular velocity distribution, thereby giving rise to a larger Doppler shift of the change signal.

The position of the change signal with respect to the Doppler-broadened frequency profile of the coupled transition also depends on the relative direction of propagation of the two beams. This dependence arises because the sign of the Doppler shift of the change signal depends on whether the probe field is propagating in the same direction as or in the opposite direction to the direction of motion (along the beam axis) of the molecules selected by the laser beam. Accordingly the change signals produced in these two cases will be located symmetrically on opposite sides of the Doppler profile of the coupled transition. To distinguish between the two cases the change signal produced when the laser beam and the probe beam are propagating in the same direction is referred to as the forward change signal, whereas the change signal produced when the two beams propagate in opposite directions is called the backward change signal. The widths of the change signals are determined by the homogeneous line widths of the transitions and therefore can be much narrower than the Doppler width.

The production of such narrow resonances in coupled transitions is called laser-induced line narrowing. This technique has been widely used to study closely spaced energy-level structures in coupled Doppler-broadened transitions. Note that this line-narrowing effect is inherently anisotropic (dependent on direction), since the forward and backward change signals appear at different frequencies (except when the laser is tuned to exact resonance with its transition). This anisotropy can be profitably exploited, as will be seen below.

Identical line-narrowing effects can also be observed without a probe beam by studying the spontaneous emission at the coupled transition emitted along the axis of the laser beam. The intensity of the spontaneous emission at the coupled transition is proportional to the number of atoms at the middle energy level. (In contrast, the absorption or stimulated emission at the coupled transition is proportional to the population difference between the middle and lower levels.) Therefore a population change at the middle level over a narrow range of velocities will produce a corresponding change in spontaneous emission at the coupled transition over a narrow frequency interval. To study this change signal one analyzes the frequency profile of the spontaneous emission.

As noted above, the forward and backward change signals are located symmetrically on opposite sides of the Doppler profile. Hence by studying the forward and backward change signals together one can locate the atomic center frequency of the coupled transition with an accuracy limited only by the homogeneous line width. The two change signals can be made to appear simultaneously by simply reflecting the laser beam back on itself [*see illustration on opposite page*]. The component of the laser beam that propagates in the forward direction will resonate with atoms of a certain axial velocity, whereas the backward-propagating component will



EXPERIMENTAL ARRANGEMENT shown here was used by one of the authors (Feld) and his colleagues at M.I.T. to resolve closely spaced spectral lines of neon with high precision by studying the forward and backward line-narrowing signals produced in spontaneous emission. Two types of experiment were performed with this apparatus. In one series of measurements the small frequency separations between the spectral lines of different neon isotopes (an effect known as the isotope shift) were analyzed. In another series of measurements the hyperfine energy-level structure of a particular neon isotope (abbreviated Ne^{21}) was determined. By selectively blocking the beams emitted from the sample cell the forward and backward change signals could be observed separately.

© 1973 SCIENTIFIC AMERICAN, INC

resonate with atoms that move with the same axial speed but travel in the opposite direction. Therefore in this situation the forward and backward change signals will appear together at frequencies that are located symmetrically about the center frequency of the Doppler profile of the coupled transition.

An experimental result obtained with such an arrangement is shown in the bottom part of the illustration on page 80. In this case the laser transition is the 1.15 micron neon transition of the helium-neon laser and the coupled transition occurs at .61 micron. The .61-micron spontaneous emission is studied by means of an interferometer, which displays the frequency spectrum of the emitted light. In the lower trace, which shows the direct spontaneous emission from the interferometer, the broad Doppler background signal completely obscures the narrow change signals. In the upper trace this background is removed by means of a special modulation technique. The center frequency of the .61-micron transition, located midway between the two change signals, can be precisely determined from this trace.

Close examination reveals that the two change signals are not identical in shape, the left-hand one being somewhat narrower and taller than the right-hand one. This interesting asymmetry cannot be accounted for by the argument given above, which describes the change signals as a simple manifestation of the change in the velocity profile. In actuality the change signals are further modified by effects such as "coherent two-quantum transitions" in which an atom initially in the upper level makes a transition to the lower level "coherently," that is, without loss of phase memory. This process is sensitive to the relative orientation of the laser beam and the beam probe. The asymmetry of the spectral lines arises from such effects. In this example the atomic parameters are such that the asymmetry happens to be rather small, but in other cases it can be quite sizable. This phenomenon was first observed by Helen K. Holt of the National Bureau of Standards.

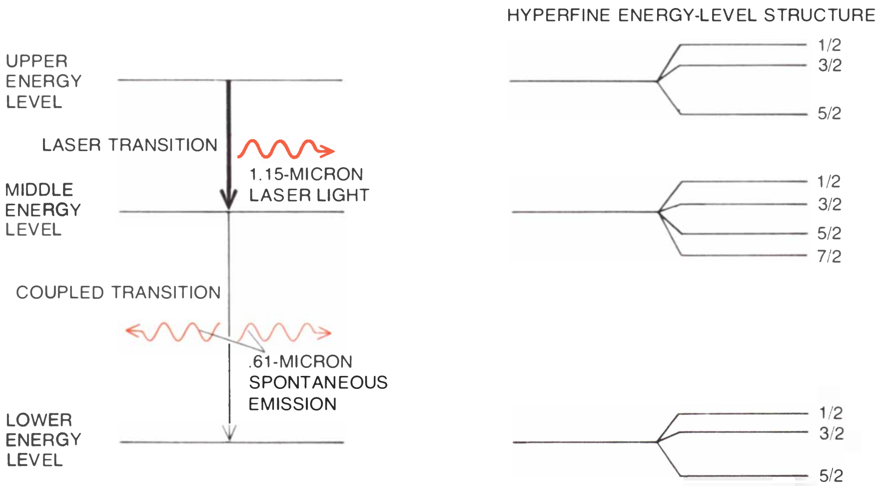
The narrow resonances observed in coupled transitions have already been utilized in a number of applications. To give some idea of the range of possibilities two examples will be presented here. First, it will be shown how closely spaced spectral lines of neon can be resolved with high precision by studying the line-narrowing signals in spontaneous emission. Second, it will be shown how the directional anisotropy we have described can be exploited to produce a new type of optical amplifier with unidirectional properties.

The neon atom, which has 10 protons in its nucleus, has three stable isotopes: Ne^{20}, Ne^{21} and Ne^{22}. (The superscript number gives the total number of nucleons—protons plus neutrons—in the nucleus.) Ne^{20} is the most plentiful, accounting for more than 90 percent of the neon found in nature. Most of the remainder is Ne^{22}; Ne^{21} is found in trace amounts only. Owing to slight differences in nuclear mass and volume, the spectral lines of each neon isotope appear at a slightly different wavelength. This effect is known as the isotope shift. Ne^{21} is particularly interesting because, as a result of its having an odd number of nucleons, its nucleus is somewhat egg-shaped rather than round. As a result the nuclear charge distribution is distorted, producing a "quadrupole" nuclear moment. This irregularity slightly alters the paths of the electrons in the Ne^{21} atom, causing the spectral lines to split into sets of closely spaced hyperfine components.

It is evident that by studying the isotope shifts and hyperfine splittings one can obtain much information about the nuclear structure of neon. Unfortunately in ordinary optical spectra this closely spaced structure is masked by the broad, overlapping Doppler line widths and is extremely difficult to resolve. The laser-induced line-narrowing effect completely eliminates this Doppler broadening, and the spectroscopic information can be recovered.

In an experiment one of us (Feld) has conducted with his colleagues at the Massachusetts Institute of Technology the output beam of an intense single-mode 1.15-micron helium-neon laser was focused into a sample cell containing neon at low pressure [*see illustration on preceding page*]. Any desired mixture of neon isotopes can be introduced to the sample cell. The .61-micron spontaneous emission from the sample cell, emitted in either the forward or the backward direction, is analyzed by means of an interferometer. A beam-chopper, placed between the laser and the sample cell, causes the change signal to appear and disappear a few hundred times per second. The chopped signal is detected with a photomultiplier. By sending the output signal into an amplifier tuned to the chopping frequency, it is possible to suppress the spontaneous-emission background and considerably enhance the signal-to-noise ratio.

The spontaneous-emission line-narrowed signal of a single neon isotope, Ne^{22}, is shown in the bottom illustration on page 79. In that case the laser field was reflected back on itself by means of a mirror, so that the forward and backward change signals could be observed together. If a second neon isotope is mixed in, an additional pair of change signals will appear. By studying the displacement between the change-signal pairs, the isotope shifts at both laser and coupled transitions can be determined. Accordingly, in addition to producing resonances much narrower than those of



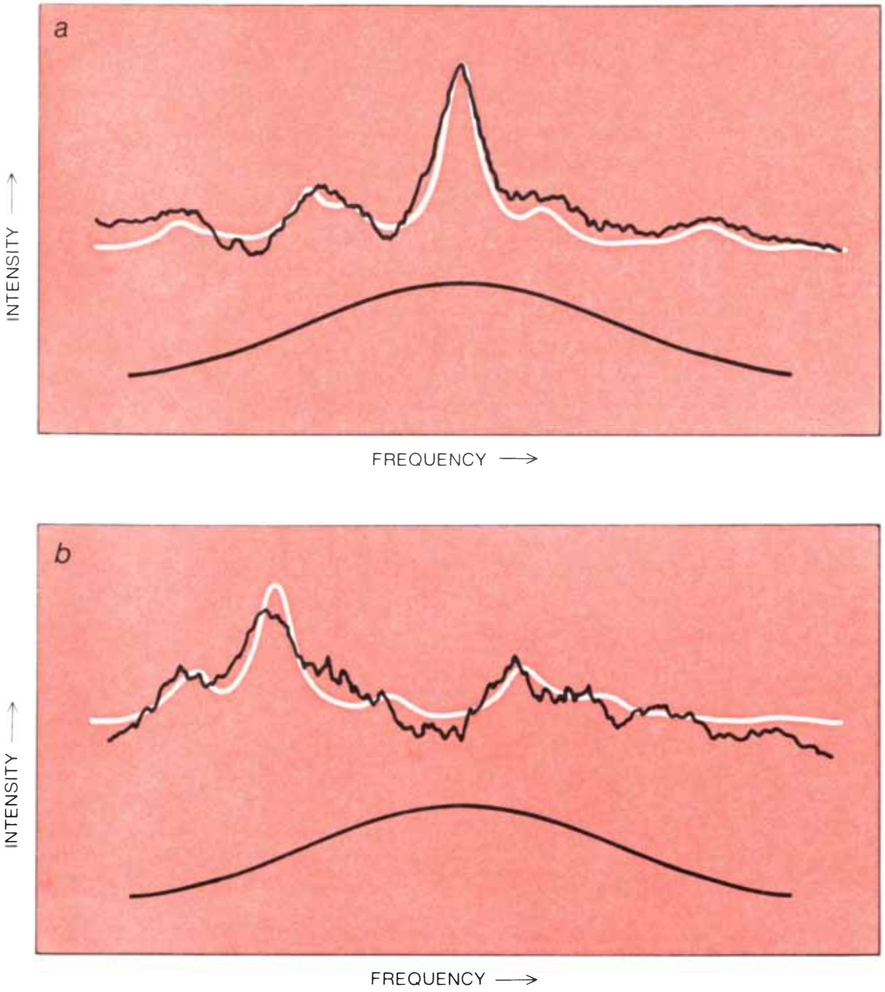
HYPERFINE ENERGY-LEVEL STRUCTURE of Ne^{21} is extremely complex, owing to the distorted shape of the Ne^{21} nucleus, which contains an odd number of nucleons (protons plus neutrons). The resulting "quadrupole" nuclear moment slightly alters the paths of the electrons in the Ne^{21} atom, causing each spectral line to be split into a set of closely spaced hyperfine components. In all 18 distinct pairs of coupled transitions are formed. In this illustration the hyperfine energy levels are denoted by their standard spectroscopic labels (*numbers at far right*). The hyperfine splitting is greatly exaggerated for the sake of clarity.

© 1973 SCIENTIFIC AMERICAN, INC

ordinary spectra, the intensity patterns obtained by this laser technique are also richer than those of ordinary spectra, containing information about both laser and coupled transitions.

Let us now consider how the laser technique is used to measure the hyperfine energy-level structure of Ne^{21}. In this case pure Ne^{21} is put into the sample cell. The distorted Ne^{21} nucleus causes each of the three energy levels to be split into a set of closely spaced components, giving rise to 18 distinct pairs of coupled transitions [*see illustration on opposite page*]. Thus the spectral-line structure here is much more complex than it is in the isotope-shift experiments. In order to make the intensity patterns as simple as possible the two change signals are analyzed separately.

Typical experimental spectra for the Ne^{21} intensity patterns in both the forward and backward directions are shown in the illustration at the right. In each case the upper experimental trace shows the narrow change signals with the background removed; the lower trace, recorded without the aid of the beam-chopping technique, also includes the Doppler-broadened background. Note that ordinarily the hyperfine structure is entirely masked by the overlapping Doppler widths. The superimposed white traces are theoretical fits to the data. These curves were obtained from theory by varying the extent of the nuclear distortion until close agreement was obtained. The final result gives an accurate new measurement of the quadrupole moment of the Ne^{21} nucleus. This is only one example of a host of measurements that were formerly impossible. The introduction of the laser to spectroscopy is causing a rebirth of interest in the spectroscopic study of atoms and molecules and is making accessible information that was not formerly within reach.



TYPICAL EXPERIMENTAL SPECTRA are given here for the Ne^{21} intensity patterns in both the forward direction (*a*) and the backward direction (*b*). In each case the upper experimental trace shows the narrow change signals and the lower trace shows the Doppler-broadened background observed without the tuned amplifier. The white curves superposed on the upper traces in each case are theoretical fits to the data obtained by varying the extent of the assumed nuclear distortion until close agreement was obtained. The final result gives an accurate new measurement of the quadrupole moment of the Ne^{21} nucleus.

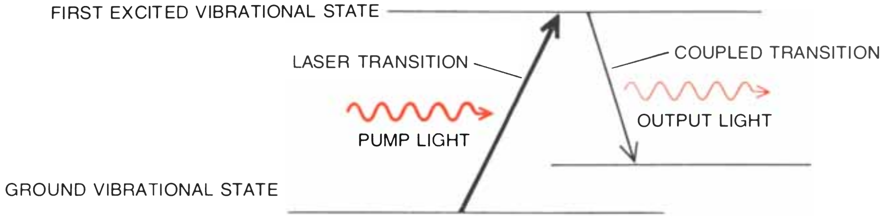
As a final example of the application of narrow resonances in coupled transitions, let us now turn to a device currently being developed at M.I.T. that has the property of being able to amplify light waves of a given frequency traveling in one direction but to attenuate light waves of the same frequency traveling in the opposite direction. This device, in effect a unidirectional laser amplifier, may be useful in the area of laser communications and other applications that require the complete isolation of the input signals from the output ones. The idea makes use of the anisotropy inherent in the laser-induced line-narrowing effect.

Let us begin by considering a three-level molecular system consisting of two rotational energy levels in the ground, or lowest-energy, vibrational state and a rotational level in the first excited vibrational state, forming a pair of coupled, Doppler-broadened transitions [*see top illustration on next page*]. In this case the common energy level is the highest of the three; accordingly the energy configuration is referred to as a "folded" system rather than a "cascade" system, such as the one illustrated in the case of neon. Normally most of the molecules in this particular folded configuration will be in the energy levels of the ground vibrational state, with very few in the uppermost energy level. Thus both transitions will normally be in the absorbing phase. If an intense monochromatic laser beam resonates with one of the transitions (the laser transition), however, the number of atoms in the common energy level will be increased over a narrow range of velocities, producing a resonant decrease in absorption over a narrow frequency interval at the coupled, or probe, transition [*see bottom illustration on next page*].

Now suppose the laser beam is tuned to the high-frequency side of the Doppler-broadened frequency profile of its transition. Because of the Doppler effect, if the beam is propagating in the forward direction (that is, in the same direction as the laser beam), this resonant decrease will appear at a frequency that is higher than the center frequency of the coupled transition; if it is propagating in the backward (or opposite) direction, the decrease will appear at a frequency that is lower than the center frequency of the coupled transition. (If the beam is detuned *below* the center frequency of the laser transition, the positions of the forward and backward change signals will be reversed.)

Assuming that the laser is sufficiently

© 1973 SCIENTIFIC AMERICAN, INC



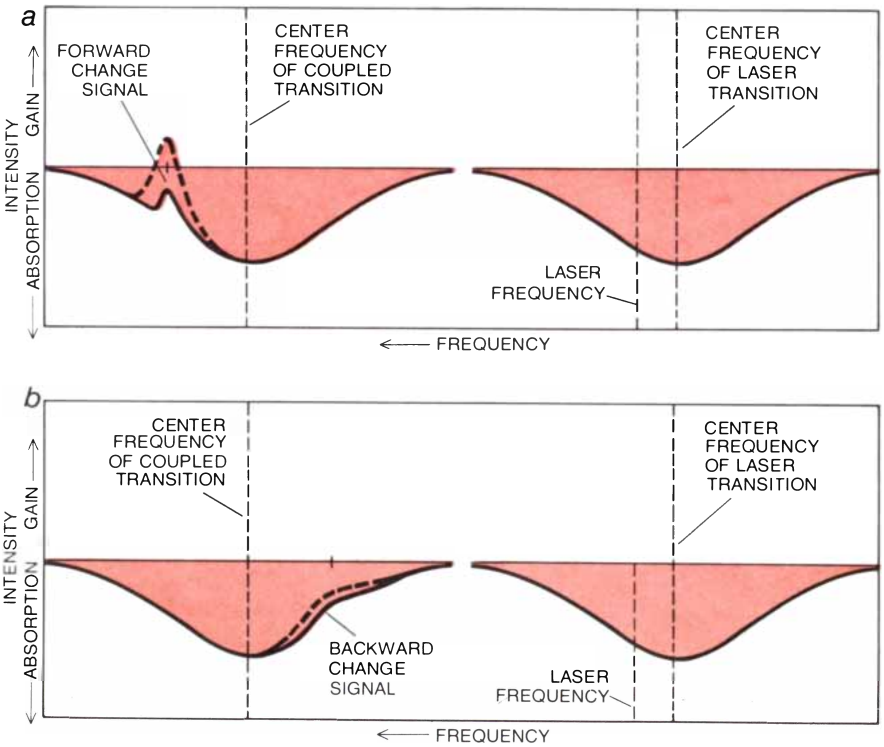
"FOLDED" ENERGY-LEVEL SCHEME used as the basis of a unidirectional laser amplifier currently being developed at M.I.T. consists of two rotational levels in the ground, or lowest-energy, vibrational state of the molecular system and a rotational level in the first excited vibrational state, forming a pair of coupled, Doppler-broadened transitions. Both transitions are normally in the absorbing phase. If an intense laser beam resonates with one of the transitions, however, the absorption profile of the coupled transition will be changed over a narrow frequency interval (*see absorption profiles in illustration below*).

detuned from the center of its Doppler profile, the two change signals will be well resolved. As the intensity of the saturating field is increased, the magnitude of the changes in the absorption profile may increase enough to change the sign of the absorption coefficient, resulting in a directionally dependent amplification within narrow frequency intervals. A light wave at the frequency of the forward change signal propagating in the forward direction will then be amplified, whereas a wave of the same frequency propagating in the backward direction will be attenuated. Similarly, a wave at the frequency of the backward change signal will be amplified in the backward direction but attenuated in the forward direction.

As explained above, owing to coherent two-quantum transitions, the line shapes of the forward and backward change signals will not be the same, the forward change signal in this case being taller and narrower than the backward change signal. Therefore the magnitude of the absorption decrease observed in the forward direction will be greater than that observed in the backward direction. In particular, as the intensity of the laser beam is increased the reversal from absorption to amplification first appears at the forward change signal, where the magnitude of the effect is largest. In this case laser amplification is obtained only for a wave propagating in the forward direction, whereas in the backward direction the coupled transition remains in the absorbing phase within its entire Doppler profile. In fact in some cases such gain, or amplification, can take place only in the forward direction, regardless of the intensity of the laser beam.

These unidirectional effects are now being studied at M.I.T. in hydrogen fluoride gas (HF) at room temperature. In these experiments a sample cell containing low-pressure HF is subjected to the intense monochromatic light of a pulsed HF laser. The HF laser produces laser lines at a number of wavelengths around 2.4 microns, any one of which can be selected by tuning the laser with a diffraction grating. The "pump" radiation, strongly absorbed by one of the absorption lines of the HF gas in the sample cell, produces unidirectional gain at the coupled transition at 2.7 microns.

In order to investigate the unidirectional nature of the laser gain, the sample cell is placed in a laser resonator; if the sample gas has enough gain at a certain frequency, it should break into laser oscillation at that frequency. A three-mirror resonator in the shape of a ring is used (rather than a two-mirror cavity) in order to be able to compare the laser oscillation produced in the forward direction with that produced in the backward direction [*see illustration on opposite page*]. To couple the pump radiation into the sample cell, one of the mirrors is specially coated so as to transmit the pump radiation at 2.4 microns but to reflect radiation at the coupled transition at 2.7 microns. Since the medium amplifies light at 2.7 microns, it can give rise to laser oscillation when it is placed inside the ring cavity. Because the gain in the forward direction is expected to

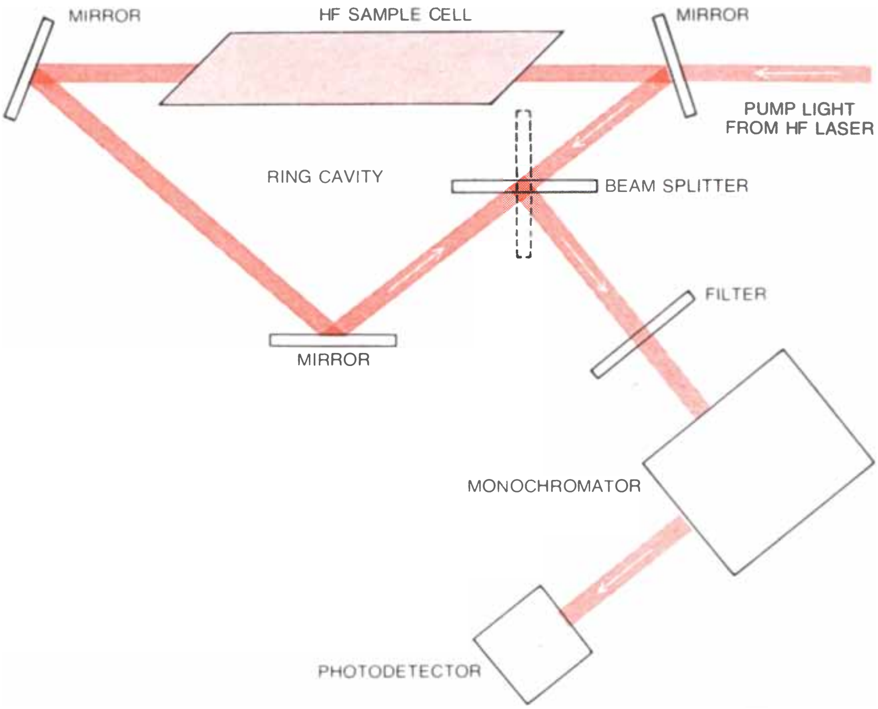


ALTERED ABSORPTION PROFILES are obtained when an intense laser beam resonates with one of the transitions of the folded three-level system shown in the illustration at top. Since the laser field increases the number of atoms in the middle level over a narrow range of velocities, a resonant decrease in absorption will appear in the Doppler-broadened curve associated with the coupled transition. Assuming that the laser is tuned to the high-frequency side of the Doppler profile of its transition, if the probe beam is propagating in the same direction as the laser beam, the resonant decrease will appear at a frequency that is higher than the center frequency of the coupled transition (*a*). If the probe beam is propagating in the opposite direction, the decrease will appear at a frequency that is lower than the center frequency of the coupled transition (*b*). As the intensity of the saturating field is increased, the magnitude of the changes in the absorption profiles may increase enough to change the sign of the absorption coefficient, resulting in a directionally dependent amplification within narrow frequency intervals. Owing to special quantum effects, the forward change signal in this case is taller and narrower than the backward change signal.

© 1973 SCIENTIFIC AMERICAN, INC

be much greater than the gain in the backward direction, the laser radiation traveling in the direction of the pump radiation should be much more intense than that traveling in the opposite direction.

To observe this forward-backward asymmetry one places within the laser cavity a thin piece of glass that intercepts the beam at a 45-degree angle. The glass reflects a few percent of the light into a detector. By changing the orientation of the glass, either the forward wave or the backward wave can be examined. In studies of this kind it is found that the laser light generated in the forward direction is from 50 to 100 times more intense than the light traveling in the backward direction, thereby confirming the unidirectional effect. It is expected that a more refined setup of this kind may be useful in laser communications systems.



RING-SHAPED LASER CAVITY was devised by the M.I.T. group to investigate the unidirectional nature of the laser gain observed in their new light-amplification system. The three-mirror cavity is used (rather than a two-mirror cavity) in order to be able to compare the laser oscillation produced in the forward direction with that produced in the backward direction. To observe the forward-backward asymmetry a thin piece of glass is placed within the laser cavity. The glass, which intercepts the beam at a 45-degree angle, reflects a few percent of the light into a detector. By changing the orientation of the glass (*broken lines*), the forward and backward waves can be examined separately and thus compared.

Many other important applications of laser-induced narrow optical resonances could be mentioned. For example, the use of narrow molecular resonances for stabilizing the frequency of a gas laser is now becoming routine. The initial experiments in this area were carried out independently about five years ago by several research groups in the U.S. and the U.S.S.R. In one important experiment performed at the National Bureau of Standards laser laboratory in Boulder, Colo., an inverted-Lamb-dip resonance was observed in the output of a 3.39-micron helium-neon laser containing a low-pressure methane absorber. The observed line width of this resonance is about 100,000 hertz, yielding a relative line width of one part in 10^9. Moreover, the experimenters were able to "lock" the frequency of the laser oscillator to the center of this resonance by means of a feedback technique, thereby producing an ultrastable source of coherent radiation.

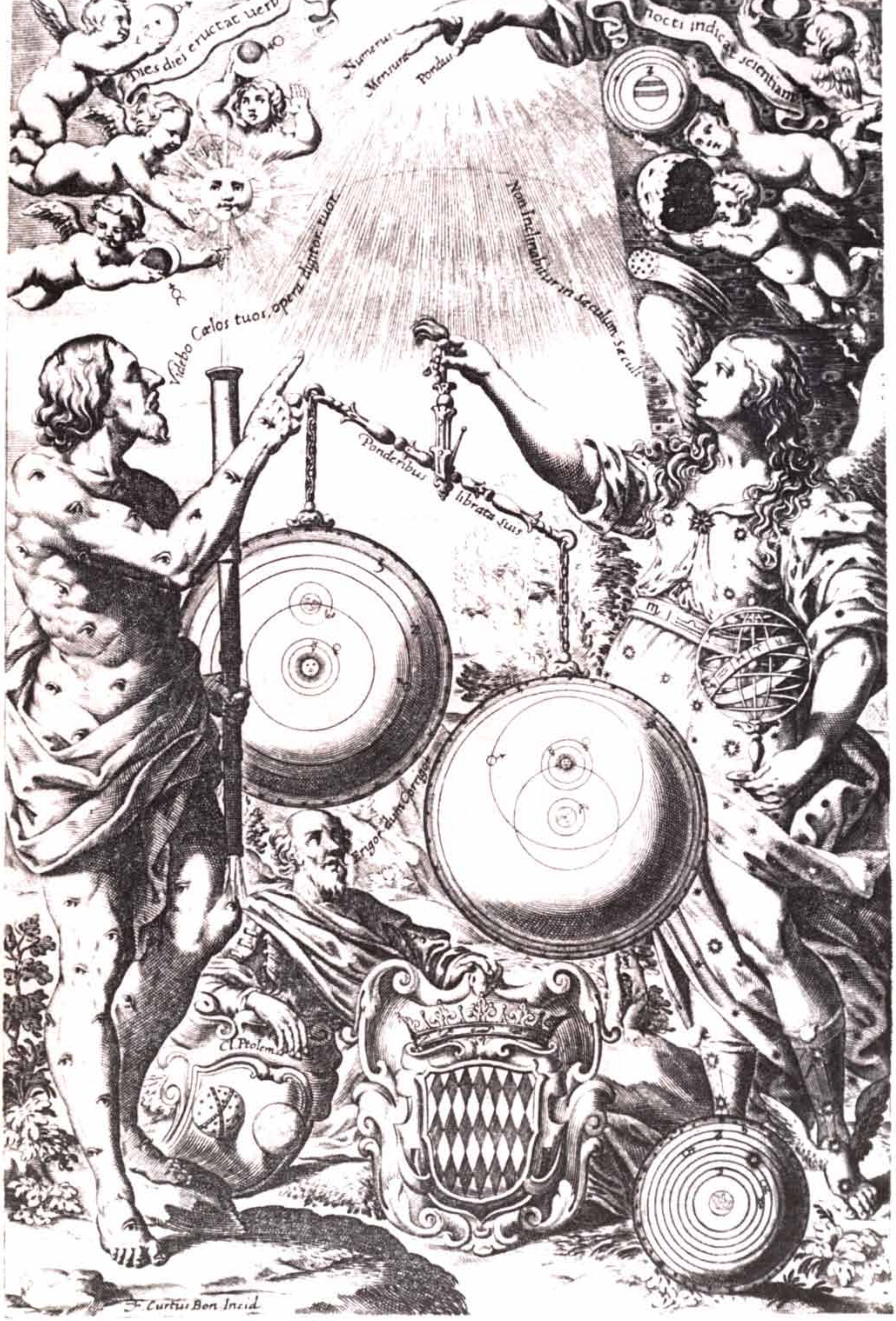
A further advance was achieved recently at the Institute of Semiconductor Physics in Novosibirsk, where it was found that at very low pressures (less than a millitorr) the shift of the center frequency of the inverted-Lamb-dip resonance becomes anomalously small as the gas pressure is changed. Working at extremely low pressures, the investigators have attained a frequency reproducibility of about one part in 10^{13} and a long-term stability of about one part in 10^{14}. The latter value is the best ever recorded for electromagnetic oscillators of any type.

Such high precision makes it possible to employ laser radiation as a primary standard of length and time. The use of frequency-stabilized lasers as atomic clocks is of particular importance, because measurements of time can be made with a precision exceeding those of length by many orders of magnitude. The recent achievement by Javan and his co-workers at M.I.T. in developing a technique to measure the frequency of a light wave, and thus the time interval between optical cycles, is of great importance in evolving laser atomic clocks. In the near future it is expected that the accuracy of frequency-stabilized lasers such as the methane-stabilized helium-neon system will surpass the accuracy of the microwave atomic clocks that serve as the present standard of time and frequency. Moreover, such advances will allow time and length to be combined in a single standard.

The effects described in this article are all based on the ability of an intense monochromatic light beam to change the energy-level populations of a resonant medium over an exceedingly narrow range of particle velocities. It may be possible to extend this principle to other regions of the electromagnetic spectrum. For example, it may be possible to produce narrow absorption and emission resonances of this type in the gamma ray region. Such a technique would complement the present method of producing narrow gamma ray resonances, based on the Mössbauer effect. An advance in this direction would allow a frequency bridge to be built between the optical and the gamma ray regions of the spectrum, just as the new laser techniques are now bridging the frequency gap between visible radiation and microwaves.

The concept of altering a molecular velocity distribution is not new. More than 100 years ago James Clerk Maxwell postulated the existence of an imaginary demon who could select molecules of a particular speed out of the thermal velocity distribution, thereby seemingly violating the entropy principle embodied in the second law of thermodynamics. The laser-saturation effect described here is the realization of Maxwell's demon. As this article has shown, the application of laser-saturation techniques to atomic and molecular systems can reveal aspects of nature formerly accessible only to the imagination.

© 1973 SCIENTIFIC AMERICAN, INC



© 1973 SCIENTIFIC AMERICAN, INC

COPERNICUS AND TYCHO

In which the author, exploring who read Copernicus' book at the time of its appearance, discovers Tycho's personal copy of it. Tycho's notes show how he evolved his non-Copernican model of the solar system

by Owen Gingerich

In the flamboyant frontispiece to G. B. Riccioli's *Almagestum novum* (*New Almagest*), published in 1651, Urania, the goddess of the heavens, holds a balance that is weighing the Copernican world system against the Tychonic system [*see illustration on opposite page*]. In the Copernican system all the planets revolve around the sun. In the geocentric Tychonic system, which Tycho Brahe proposed several decades after Nicolaus Copernicus had advanced his heliocentric model, the sun travels around the fixed earth, carrying the rest of the planets with it. For Riccioli the geocentric system put forward by Tycho carried the most weight. Today we view Tycho's scheme as a giant step backward, but we are nonetheless disconcerted by the fact that it was proposed by the most innovative astronomical observer since antiquity. Tycho's bold plan for increasing the accuracy of observations places him far more securely in the mainstream of modern astronomy than Copernicus himself.

Just this past May I made a discovery that now puts Tycho's view in a more favorable light. Bound into an edition of Copernicus' *De revolutionibus orbium coelestium* in the Vatican Library I found the original working copy of Tycho's cosmological notes. It is perhaps unnecessary to add that this came as a great surprise. These hitherto unknown personal notes record the germination of Tycho's conception and contain the first sketches of his planetary system.

To appreciate the full significance of the notes it is necessary to look afresh at the context of Copernican astronomy in the 16th century. When Copernicus introduced his heliocentric arrangement, the earth became one of the family of planets revolving in off-centered circles around the sun. Copernicus sought a system that was "pleasing to the mind," and he was particularly delighted with his proposal because the planets naturally ranked in order from the sun according to their speeds, with the slowest one revolving in the largest orbit. (At the time the slowest planet known was Saturn.)

In contrast, Tycho's planetary system, in which the earth regained its privileged central status, at first seems clumsily contrived. More important in the context of astronomy a century before Newton, however, is that the immobile earth of the Tychonic system fitted the accepted laws of physics where the moving-earth Copernican model did not. Tycho complained that Copernicus' system "ascribes to the earth, that hulking, lazy body, unfit for motion, a motion as quick as that of the ethereal torches, and a triple motion at that." Nevertheless, to most of Tycho's contemporaries this complaint hardly mattered; the majority of 16th-century astronomers considered astronomical systems as being elaborate geometric hypotheses quite removed from physics. The gradual acceptance of a celestial physics integrated with terrestrial physics, culminating in the synthesis by Newton, is undoubtedly the most significant scientific aspect of the Copernican revolution.

The ultimate goal of a planetary model is to predict the planets' positions. In this respect the geocentric epicyclic system proposed by Ptolemy around A.D. 140 succeeded admirably. In order to be taken seriously any alternative proposals had to do as well. Copernicus realized that; thus only a few pages of *De revolutionibus* directly concern the heliocentric cosmology. The bulk of it is devoted to technical details leading to tables describing the motions of the planets. In the 16th century Copernicus was regarded as a master mathematician not for his innovative cosmology but for his ability to cope with the details of predicting the positions of the planets.

Actually the tables of *De revolutionibus* offered little improvement over those of Ptolemy. That is not surprising considering the lack of a suitable base of observations from which to compute the tables. Copernicus was forced to rely heavily on the same observations Ptolemy had recorded. Not until Tycho initiated his vast program of systematic observations in the 1570's did anyone fully realize how faulty the tables were, or whether Copernicus had offered any improvement.

Although the astronomers of Copernicus' day had only rather primitive instruments, it was possible to make certain observations quite accurately without any instruments at all. Copernicus' earliest recorded observation, in 1497,

FRONTISPIECE TO "ALMAGESTUM NOVUM" (*New Almagest*) by G. B. Riccioli, published in 1651, shows the earth as the bearded man at the left covered with eyes, holding a telescope and gazing up at the newly discovered marvels of the heavens: the odd shape of Saturn (due to its rings) in the top right corner, Jupiter with its four bright satellites just below, the rough appearance of the moon's surface and a comet. In the top left corner the cherubim, from top to bottom, are holding Mars, Venus, the sun and Mercury. To earth's right is the star-covered goddess of the heavens, Urania, holding an armillary sphere in her left hand and a balance in her right. The balance is testing the Copernican heliocentric system of the universe against the geocentric system of Tycho Brahe. For Riccioli the Tychonic system carried more weight. Ptolemaic system is discarded at Urania's feet; Ptolemy himself is watching over proceedings and commenting: "I erred so that I could be corrected."

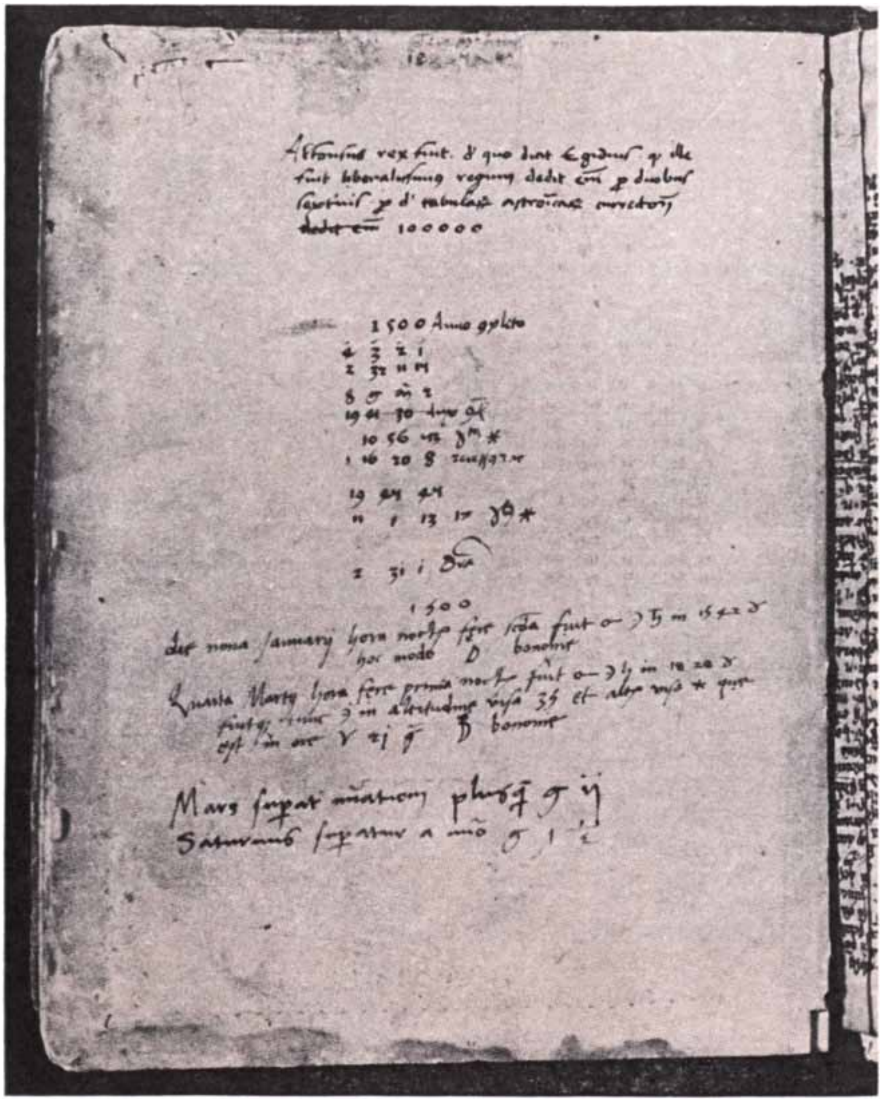
© 1973 SCIENTIFIC AMERICAN, INC

was one of these. He was then a young man of 24, studying canon law at the University of Bologna. He had temporarily left his native Poland following his undergraduate studies in Cracow. On March 9 he watched the moon approach Aldebaran, the brightest star in the constellation Taurus, finally occulting (eclipsing) it at 11 P.M. Later he used the observation in his book as a test of the moon's varying distance from the earth.

In 1503, when Copernicus was 30, he returned to Poland to take up a lifetime post as a canon of the cathedral of Frombork, an appointment arranged through the benevolent nepotism of his uncle Lucas Watzenrode, who was the bishop. Copernicus served as administrator of the cathedral estates and as private secretary and personal physician to his uncle. His tenured position as canon gave him the time and security to pursue his astronomical work, and in 1504 he could have made a particularly interesting series of observations.

In that year all five of the visible planets (Mercury, Venus, Mars, Jupiter and Saturn), as well as the sun and the moon, moved into the constellation Cancer, affording a spectacular series of close planetary approaches. Phenomena as wonderful as these naturally attracted the close attention of astrologers; the conjunctions of Saturn and Jupiter are so rare, occurring only once every 20 years, that they were accorded the greatest astrological significance. In those days the positions of the planets were predicted on the basis of the Alfonsine Tables, which had been compiled in the 13th century by the astronomers of Alfonso X, king of Léon and Castile. Based on the Ptolemaic system, they predicted that Jupiter would move past Saturn on June 10, when the planets were too close to the sun for easy observation. Important conjunctions of Jupiter with Mars, however, were anticipated on January 4 and on the morning of February 22, and a conjunction of Saturn with Mars fell on March 18.

Anyone as interested in astronomy as Copernicus was could scarcely have failed to observe these phenomena. Like occultations of stars by the moon, conjunctions of the planets can be observed rather accurately without instruments. If Copernicus had watched the planets during the winter of 1503–1504, he would have found that the almanac's predictions missed the conjunctions by about 10 days. Although there is no direct record that he made such observations, Jerzy Dobrzycki of the Institute for the History of Science in Warsaw suggested to me a way by which we can be certain that the astronomer followed the planetary motions in the year of the great conjunction.



LAST LEAF of Copernicus' copy of the Alfonsine Tables for computing the planetary positions contains a cryptic note by Copernicus in his own handwriting. The note, the last two lines on the page, states that Mars was ahead of its predicted position by more than two degrees and that Saturn was behind its predicted position by 1½ degrees. If the absence of a remark about Jupiter indicates that its predictions had no appreciable error, then the only time that all of these conditions were fulfilled was during the conjunctions of the planets in February and March of 1504. Thus these two undated lines become convincing evidence that Copernicus did in fact observe the conjunctions in 1504 (*see illustration on opposite page*).

In the library of the University of Uppsala there are preserved many volumes from Copernicus' personal library, brought to Sweden in 1627 by the army of Gustavus Adolphus during the Thirty Years' War. Two leather-bound astronomical volumes decorated in the style of Cracow craftsmen of the late 15th century are of particular interest. The bindings suggest that Copernicus bought these books and began to annotate them while he was still an undergraduate and already deeply interested in astronomy. One book includes an ephemeris for 1492 to 1506; the other includes the edition of the Alfonsine Tables for 1492. Bound into the back of this second volume are 16 extra leaves on which Copernicus had added carefully written tables and miscellaneous notes. At the bottom of the last page there is written in highly abbreviated Latin:

Mars superat numerationem plus quam gr. ij
Saturnus superatur a numeratione gr. 1½

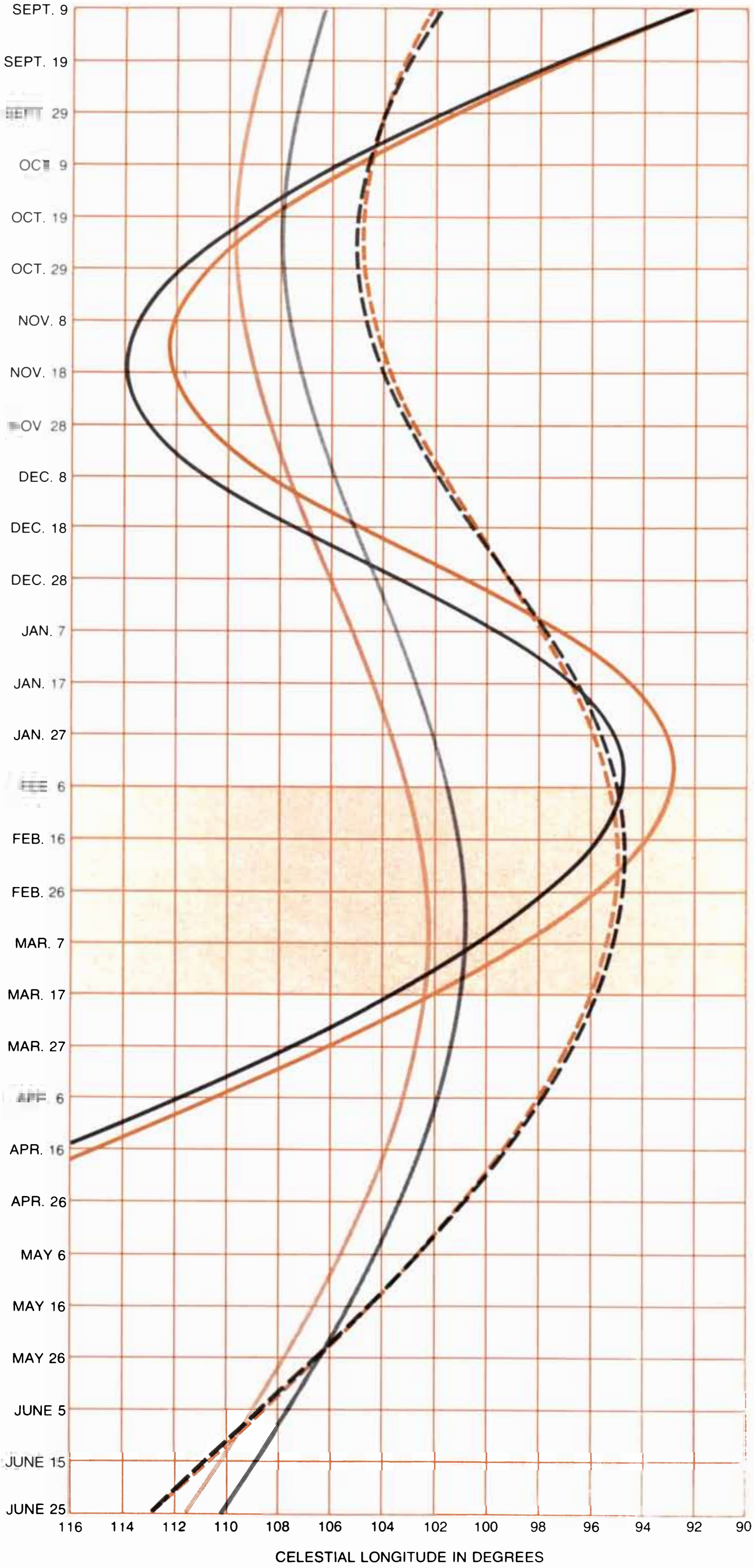
The translation is: "Mars surpasses the numbers by more than two degrees; Saturn is surpassed by the numbers by 1½ degrees."

To analyze this cryptic, undated state-

© 1973 SCIENTIFIC AMERICAN, INC

ment we can use a powerful tool made available for the first time several years ago through the use of a fast electronic computer. Bryant Tuckerman of IBM recomputed the actual positions of the planets from 601 B.C. to A.D. 1649, providing a standard with which old almanacs and ephemerides can be compared. The longitude predicted by the Alfonsine Tables for each of the superior planets (Mars, Jupiter and Saturn) shows a characteristic periodic error. In the Ptolemaic system a planet's position is predicted by computing its motion in the large orbital circle called a deferent, together with its motion in an epicycle, or secondary circle, centered on the edge of the deferent. The deferent and the epicycle each contribute their own inaccuracies, so that the resulting error pattern is distinctive and reflects a combination of the two motions. In Copernican terms the error in a planet's predicted position results from inaccuracies in the available knowledge of both the earth's motion and the planet's motion around the sun.

From graphs of the error patterns we can see that at the time of the conjunctions in February and March of 1504 there was an almost unique combination of errors: Jupiter was just about precisely on schedule but Saturn ran behind the predictions by some 1½ degrees and Mars was ahead by just over two degrees. If the absence of a remark about Jupiter indicates that its actual position showed no appreciable error from its predicted position, then these figures precisely match Copernicus' undated record. The two lines he wrote at the back of his copy of the Alfonsine Tables thus



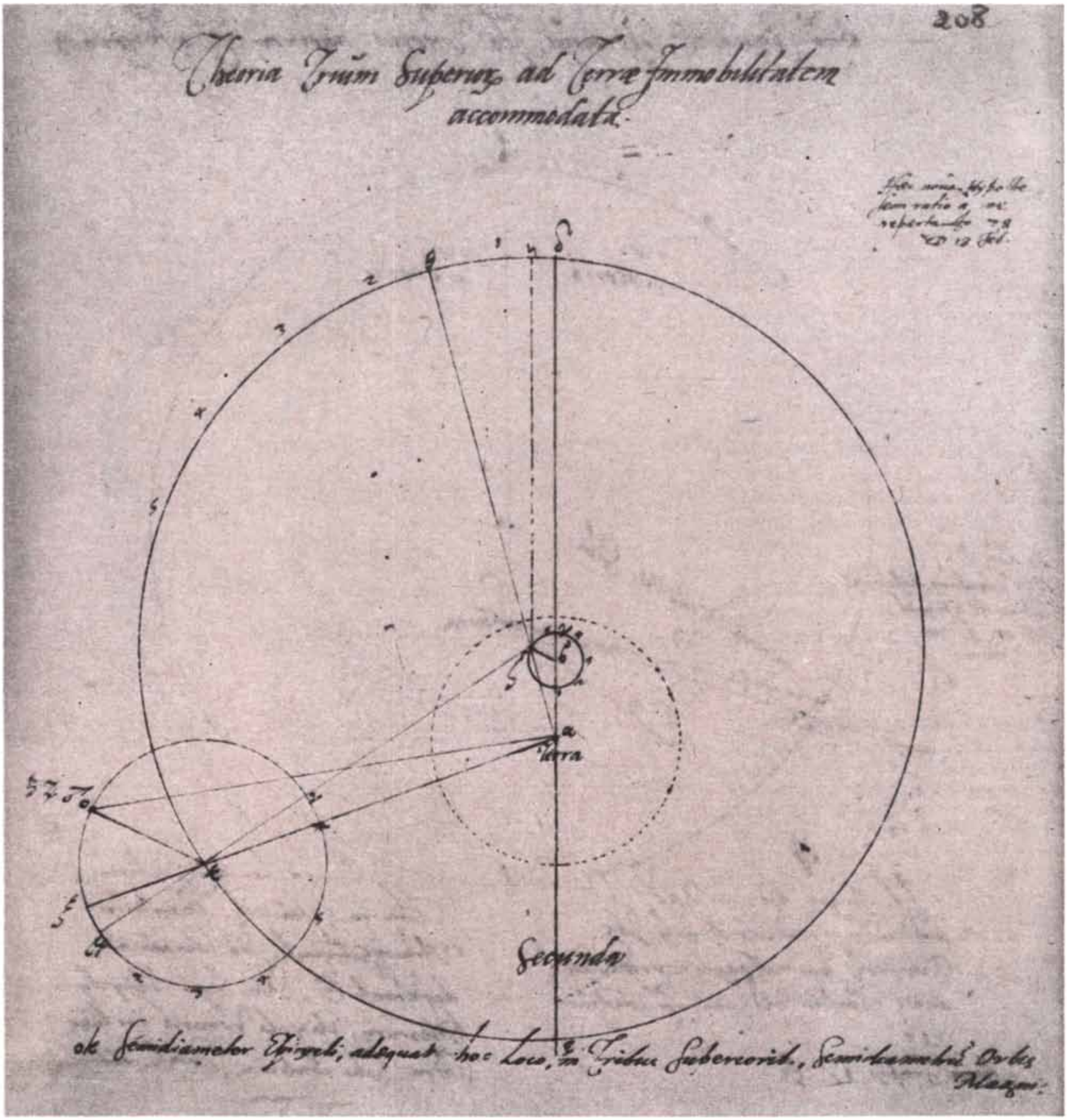
PREDICTED AND ACTUAL positions of the superior planets during the winter of 1503–1504 are displayed together. The author calculated the predicted positions of the planets from the Alfonsine Tables, and Bryant Tuckerman of IBM computed the actual positions of the planets from modern tables. Each of the planets went into a westward retrograde motion during the interval, so that Mars came into conjunction with Jupiter and with Saturn on three separate occasions. The errors documented by Copernicus apply only to the conjunctions in February and March of 1504 (*band in light color*). As can be seen, the predicted positions of Mars (*line in dark color*) differ from the actual positions (*line in black*) by about two degrees; the predicted positions of Saturn (*line in light color*) differ from the actual positions (*line in gray*) by 1½ degrees. The predicted positions of Jupiter (*broken line in dark color*), however, agree well with its actual positions (*broken line in black*).

© 1973 SCIENTIFIC AMERICAN, INC

become convincing evidence that he did observe the conjunctions in 1504.

It would be interesting to know whether or not these celestial events crystallized Copernicus' desire to reform astronomy. If they did, there would be a remarkable parallel between Copernicus and Tycho, who as an impressionable youth three great conjunctions later resolved to devote himself to astronomy when he saw that there were still errors in the ephemerides in 1563. At that time the Alfonsine Tables showed an even larger error for Saturn, nearly two degrees, so that the prediction of the great conjunction was a month too late. Ephemerides computed by Johannes Stadius from the Prutenic Tables, which were in turn based directly on Copernicus' work, fared much better; they were off by only a day or two, but that was still enough to shock the 16-year-old Tycho.

Even if the discrepancies between the tables and the heavens impressed Copernicus with the need for reform, he never used the discrepancies as a major argument for his radical new cosmological system. This move was quite prudent; Copernicus knew that such errors could be corrected merely by changing the parameters of the old system. Instead he argued for his heliocentric system on philosophical and cosmological grounds, and a major consideration was its simplicity. In his *Commentariolus*, a small



TYCHO'S FIRST GEOCENTRIC DIAGRAM, for the superior planets, was found by the author in the unpublished manuscript pages bound into the back of Tycho's personal copy of Copernicus' *De revolutionibus orbium coelestium,* now in the Vatican Library in Rome. It states at the upper right corner: "This new hypothesis occurred to me in the year [15]78 on the 13th day of February."

© 1973 SCIENTIFIC AMERICAN, INC

UOP TEAMWORK IN TECHNOLOGY

"WHAT GOES UP A CHIMNEY? NOTHING."

Highlights of a dialog between John O. Logan, President of Universal Oil Products Company, and Richard Speer, UOP Executive Vice President.

Mr. Logan: What it boils down to, then, is that with most air pollutants, we have a system of control.

Mr. Speer: Not only of control, but often of virtual elimination. And for a broad range of industries. Even the most serious offenders.

Mr. Logan: "Serious" is certainly the right word, Dick. What's most disturbing to me is that of the five major air pollutants, *each one* is considered injurious to health. Sulfur dioxide, in particular. But we've licked that problem, too, even for high-sulfur fuel users.

Mr. Speer: That's true, John. Actually, we have several proven systems for removing SO_2 from industrial flue gases. It's now possible to curb these noxious emissions with up to 95% efficiency. Some of these systems can simultaneously reduce *fly ash* by as much as 99%.

Mr. Logan: The ecologists' goal, of course, is a 100% pollution-free atmosphere. I don't think that's being too idealistic, do you, Dick?

Mr. Speer: Not when you realize that simply controlling stack gases and automotive exhaust fumes alone would eliminate 92% of it. The remaining 8% will yield to technology, too.

Write for free booklets on UOP's stake in the environment crisis, Ten UOP Plaza, Des Plaines, Ill. 60016.

© 1973 SCIENTIFIC AMERICAN, INC

Alloy technology: One of the strengths that make us

There are times when nothing less than an alloy steel will give you the strength-to-weight ratio, longer life, or toughness required for a particular job. That's when it's time to call Republic, the country's leading producer of alloy steels.

Whether it's a steel for aerospace, nuclear, anti-pollution, antiseptic or esthetic applications, or a long wearing gear or bearing steel, there's probably no alloy steel we have not already made or could not make. And that includes steels with as little as 70 percent iron or with more than 99 percent iron.

Canton, Ohio, is the birthplace of alloy steels. And nowhere in the world is there a bigger or better combination of facilities for electric furnace melting, vacuum processing, and strand casting of steels than in Republic's Central Alloy District.

When a job calls for a steel with superior performance, you probably need an alloy steel. And if more than ordinary skill in production is a must, think of Republic. Nobody knows more about alloy steels, or has produced more of them, than we have. It's one of the strengths that make us the new steel company.

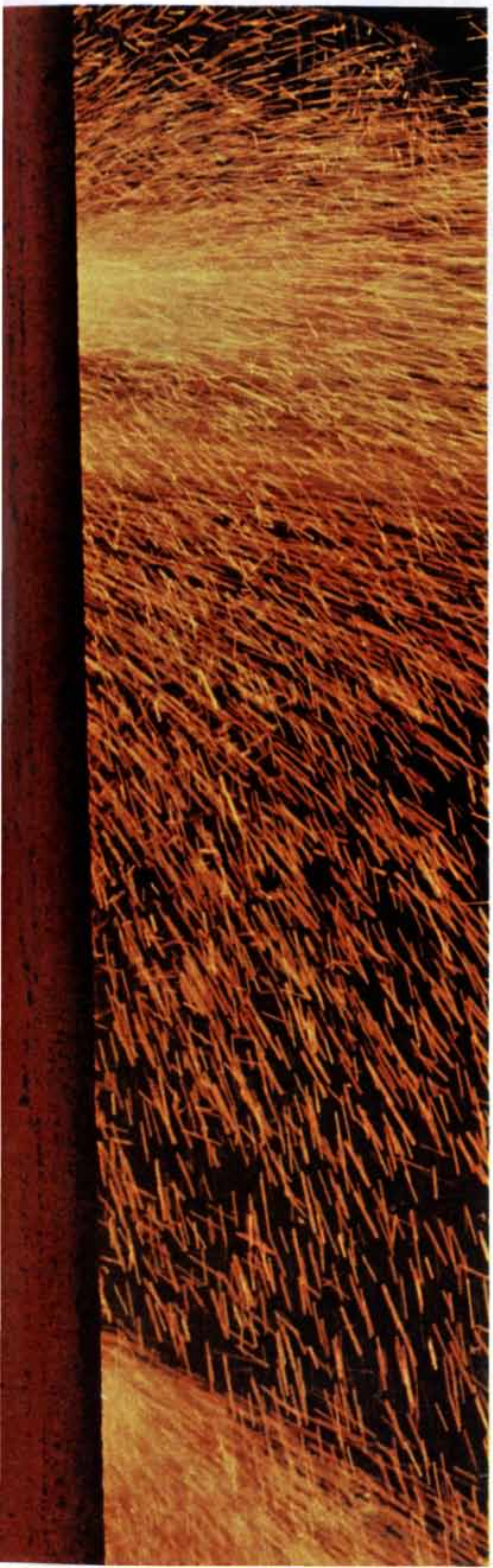
Flame-cutting an alloy steel billet at the strand caster in Canton.

Alloy forgings

Republic has been instrumental in expanding the use of alloy steels for hot, warm, and cold forgings. This forged idler bearing replaced a casting at an annual savings of $15,000 and gave the customer freedom from porosity and surface defects, dimensional uniformity, and improved appearance.

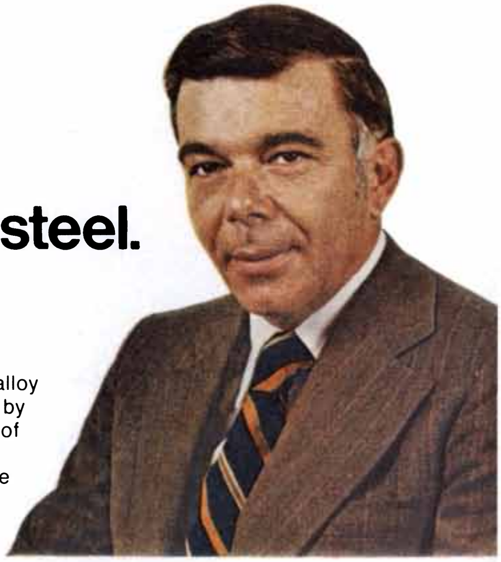
© 1973 SCIENTIFIC AMERICAN, INC

the new steel company.



Alloy gear steels

Republic makes more gear steels than any other company in the United States. This gear is made from one of Republic's triple alloy steels, a family of steels designed for best performance and economics, whatever the job.



We do more than just make steel.

Tom Perry, Chief Metallurgist, Republic Steel:

"Large-scale commercial production of alloy steels was started in this country in 1907 by one of the companies that is now a part of Republic Steel. We've been in the alloy business for a long time, and we welcome your inquiries about alloy steels. Write to T. E. Perry, Republic Steel Corporation, Cleveland OH 44101."

Republicsteel
The new steel company

© 1973 SCIENTIFIC AMERICAN, INC

Ford LTD Country Squire for '74. When you buy your wagon, make sure you can buy these features.

1. Exceptional comfort and appearance up front offered with the Squire Luxury Group

2. Ford's famous 3-way doorgate

3. Seats fold away easily

4. Steel-belted radial ply tires

5. Optional power mini-vents

6. Adjustable roof rack

7. Standard spare tire extractor

1974 Ford LTD Country Squire shown with optional vinyl roof, vinyl insert bodyside moldings, deluxe luggage rack, deluxe wheel covers, WSW tires, Squire Luxury Group and front cornering lamps.

The closer you look, the better we look.

1. Unexpected wagon luxury is reflected in the split bench seats of super soft vinyl and deep 25 oz. cut pile carpeting. Ford also offers exclusive DuraWeave vinyl trim that looks and breathes like cloth, cleans and wears like vinyl.

2. The Country Squire's convenient 3-way doorgate and power tailgate window are standard. You can have dual-facing rear seats, even a recreation table for the kids.

3. Ford's design lets you convert from passenger to cargo wagon with ease. There's lockable below-deck stowage space too, and a cargo area dome light.

4. Power front disc brakes and steel-belted radial ply tires are both standard this year.

5. You can order optional convenience features like power mini-vent windows, dual remote control mirrors and a power tailgate lock.

6. The Country Squire offers an adjustable roof rack that makes it easy to secure your extra cargo. Optional vinyl roof now comes in a variety of colors.

7. Ford's innovative spare tire extractor makes changing less of a chore.

See your Ford Dealer for a closer look at a great family wagon. Ford LTD Country Squire for '74.

Wagonmaster again in '74.

FORD WAGONS

FORD DIVISION Ford

© 1973 SCIENTIFIC AMERICAN, INC

tract written about 1512 and circulated only as a manuscript, he wrote concerning the planetary motions that "eventually it came to me how this very difficult problem could be solved with fewer and much simpler instructions than were formerly used, if some assumptions were granted me." Copernicus went on to outline his new heliocentric arrangement of the planets, indicating that the apparent celestial motions could be explained by a triple movement of the earth itself: the revolution on its own axis, the orbital motion around the sun and the libration, or wobble, of its axis that accounts for the precession of the equinoxes.

In addition to putting forward the heliocentric concept, Copernicus awarded virtually the same weight to a second philosophical principle: the Platonic-Pythagorean concept that celestial movements must be composed of uniform circular motions. That principle constituted a strong criticism of one of the chief Ptolemaic devices: the equant. In order to understand the equant and the force of this argument against it, one must first notice the chief features of Ptolemy's planetary mechanism. The earth was placed near, but not exactly at, the center of a set of the large deferent circles. Each planet moved with uniform circular motion on an epicycle that was on the deferent. The epicycle produced the planet's periodic retrograde motion among the stars, in which the planet appeared to stop temporarily and then "back up" westward in the sky before stopping again and resuming its usual easterly path. In the Copernican system the epicycle is seen as the result of the earth's own orbital motion around the sun: the retrogression of a superior planet is caused by the faster-moving earth passing that planet. In the case of Mars the irregularity generated by the epicycle to account for retrograde motion could modify the position of the planet by as much as 45 degrees of arc compared with the effect of uniform circular motion on the deferent alone.

In addition to the irregularity of the planet's motion produced by the epicycle, a nonuniform motion of the center of the epicycle on the deferent was also required. To achieve this nonuniform motion Ptolemy devised the equant: an axis of uniform motion off center within the deferent. Only from that position would the planet appear to move with uniform circular motion. In addition the earth was placed equally off center in the opposite direction. In the case of Mars the equant and the off-center displacement could modify the uniform motion by a substantial amount, up to 12 degrees of arc to the east or west. The use of the equant, the epicycle and the eccentric deferent gave Ptolemy adequate flexibility for coping with the superior planets and with Venus; with the addition of one small central circle he was able to manage Mercury as well.

Copernicus opened his *Commentariolus* with an attack on the Ptolemaic equant, which appeared to violate the principle of uniform circular motion. "A system of this sort seems neither sufficiently absolute nor sufficiently pleasing to the mind," he wrote. "Having become aware of these defects, I often considered whether there could perhaps be found a more reasonable arrangement of circles from which every apparent inequality would be derived and *in which everything would move uniformly about its proper center, as the rule of absolute motion requires*." A major theme of Copernicus' work thus became the geometric elimination of the equant. Copernicus turned to an epicyclet, or small epicycle, to effect the substitution. The result was that, although he simplified the planetary system by removing the large epicycles, his devotion to the principle of uniform circular motion caused him to introduce new complexities.

At the end of his *Commentariolus* Copernicus remarked: "All together, therefore, thirty-four circles suffice to explain the entire structure of the universe and the entire ballet of the planets." Commentators in the 19th century used their imagination to embellish Copernicus' statement and, without checking the facts, began to propagate the story that Ptolemy's rather simple system had become overlaid with dozens of additional secondary circles by the time of Copernicus.

Alfonso X may have contributed to the legend at the end of the 13th century; he is reputed to have told his astronomers that if he had been present at the Creation, he could have given the Lord some hints. This anecdote has fed the mythology, so that a recent *Encyclopaedia Britannica* article even asserts that 40 to 60 epicycles were required for each planet! Actually even at the time of Copernicus observational astronomy was still in such a primitive state that there could have been no observational basis for such a cumbersome improvement.

The same type of computer-aided analysis that was used to decipher Copernicus' brief note on Mars and Saturn has now laid to rest this popular legend about the overwhelming complexity

Plant a THINK TANK anywhere and watch the minds grow!
home-office-school-park-club-churches-laboratory

Unique instructional games designed by university professors to make learning fun through brain-to-brain action. Beginning games can be mastered by young children— final games will challenge intelligent adults. These are the famous GAMES FOR THINKERS from WFF 'N PROOF Publishers.

WFF'N PROOF (logic)	$8.75
QUERIES 'N THEORIES (science)	8.75
EQUATIONS (mathematics)	5.50
ON-SETS (set theory)	5.50
PROPAGANDA (social studies)	6.50
ON-WORDS (word structures)	5.50
CONFIGURATIONS (geometry)	5.50
TRI-NIM (problem solving)	4.50
REAL NUMBERS (arithmetic)	2.25
WFF (beginner's logic)	1.75
QWIK-SANE (puzzle)	1.75
TAC-TICKLE (pure strategy)	1.25
Teacher's Manual	1.25
RODIN'S THINKERS BOOKENDS	11.00
Complete 12-kit THINK TANK & Teachers Manual	
with bookends (Save 10.25)	59.50
without bookends (Save 9.25)	49.50

Order from: **WFF 'N PROOF, 1111-NG**
Maple Avenue, Turtle Creek, Pa. 15145
*postage included in above prices
Fully guaranteed. Dealer inquiries invited.

Gifts that are a COMPLIMENT to receive!

FREE catalog

over 1000 unique tools, handy kits, precision instruments, technical supplies.

Our 21st year of service to the World's finest craftsmen and technicians.

National Camera
2000 West Union Ave. Dept. JAC
Englewood, Colorado, 80110

Send a FREE copy of the nc Flasher

name

address

city

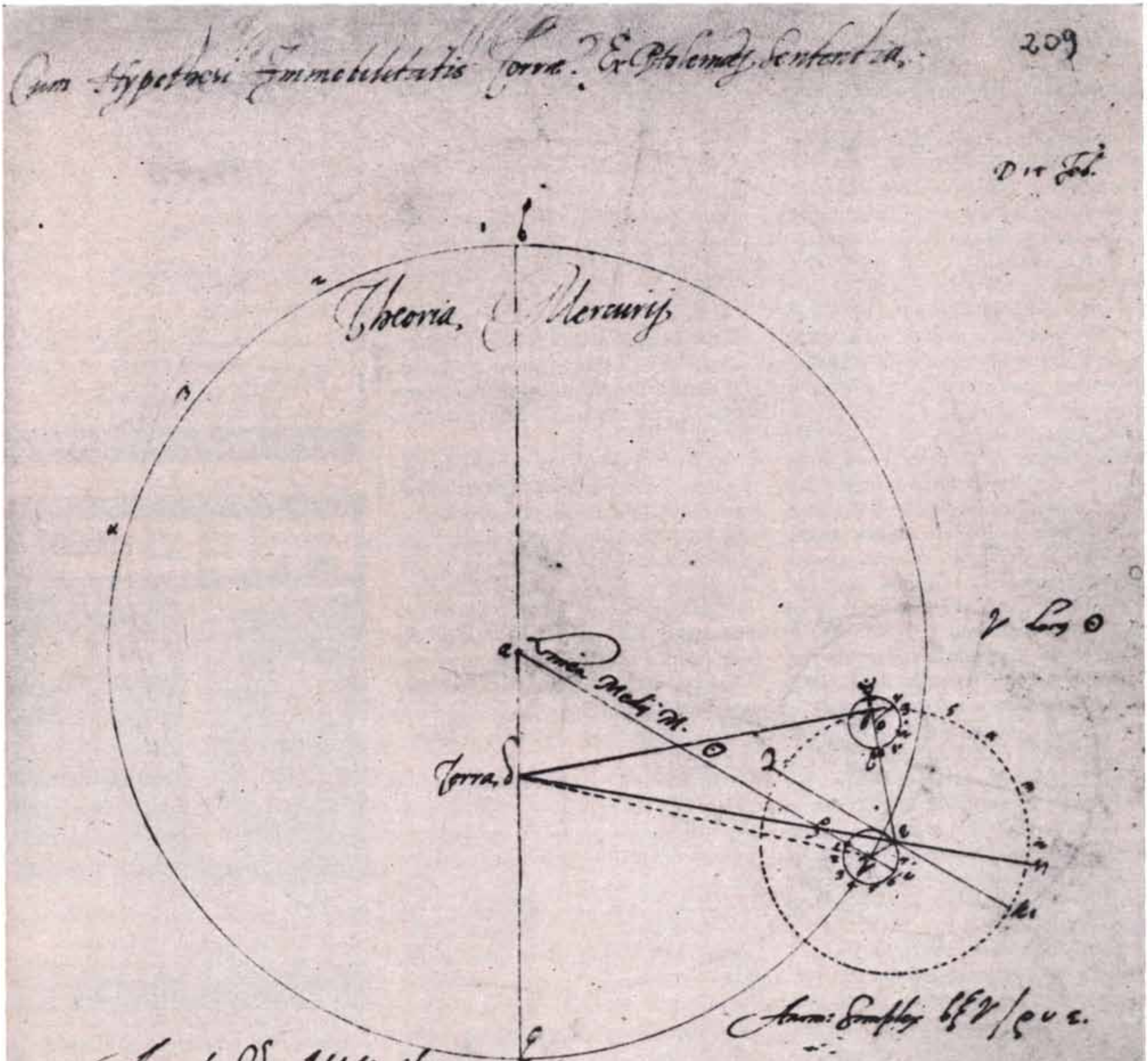
state zip

National Camera
2000 West Union Ave. Dept. JAC
Englewood, Colorado, 80110

© 1973 SCIENTIFIC AMERICAN, INC

of the geocentric system in the late Middle Ages. In order to test the story I carefully recomputed the Alfonsine Tables in their entirety to show that they are based on the classical and simple form of the Ptolemaic theory with only two or three minor changes of a parameter in the entire set. Next I used these 13th-century tables to compute a daily ephemeris for 300 years. When compared with Tuckerman's accurate modern computations of the planetary longitudes, the computerized Alfonsine predictions showed repetitive error patterns that were as characteristic as a fingerprint. All the old pre-Copernican ephemerides, made by the leading astronomers of the day, show precisely these same error patterns. Thus I have concluded that only the Ptolemaic scheme, with a single epicycle for each planet, was ever used for predicting planetary positions.

Is it possible that the epicycles-on-epicycles existed but just did not get to the level of almanac-making? Recent research in Islamic sources by E. S. Kennedy and his students at the American University of Beirut has revealed that elaborate models of precisely this kind were discussed by 13th- and 14th-century astronomers of the Maragha school, in particular by ibn al-Shatir at Damascus. Like Copernicus, they argued for the models on philosophical grounds, and it is unlikely that their scheme was



MERCURY HAS TWO EPICYCLETS (*smallest circles*) in Tycho's first attempt to account for the planet's motion in an orbit around the earth. Large circle is the deferent and the dotted one the epicycle. He notes that he drew the illustration on February 14, 1578.

© 1973 SCIENTIFIC AMERICAN, INC

ever used for actual planetary tables. Whether Copernicus conceived of the double-epicyclet replacement of the equant independently or whether he inherited it from the Arabs by some as yet unknown channel remains moot

During the 1520's Copernicus worked extensively to elaborate his ideas, particularly the planetary theory, if we are to judge by the sprinkling of planetary observations recorded in *De revolutionibus*. By this time he was well settled in northern Poland, but a variety of administrative duties frequently kept him away from his celestial researches. During that time Copernicus wrestled with the writing of a monumental treatise comparable in scope to Ptolemy's *Almagest*. It was to incorporate the twin principles that the sun is at the center of the solar system and that the planetary movements are based on uniform circular motion. The heavenly movements turned out to be more complicated than he had supposed in the *Commentariolus*. In particular the lines of apsides, or the lines between the earth and the equants in the Ptolemaic system, appeared to turn slowly with respect to the stars. Only a few observations, some of them contradictory, had come down through history, and Copernicus must have toiled with some frustration trying to satisfy them all. He eventually abandoned the double epicyclets of the *Commentariolus* in favor of an off-center deferent and a single epicyclet, a scheme that more readily accommodated the shifting apsides. For Mercury, however, he retained the double epicyclet to replace not the equant but the additional central circle postulated uniquely for that planet by Ptolemy. In the end Copernicus managed to pile up more small circles than Ptolemy.

The major part of *De revolutionibus* is devoted to a detailed analysis of the motions of the sun, the moon and the planets using combinations of large circles and small circles. This analysis, together with a mathematical commentary and tables of stars, constitutes 96 percent of the volume. Scarcely 20 pages of *De revolutionibus* are devoted to the new heliocentric cosmology. The opening chapters review the ancient arguments for a geocentric world view along with quaintly medieval counterarguments. They give little hint of what is about to come in the chapter titled "On the Order of the Celestial Orbits." That chapter is a resounding defense of the heliocentric system based entirely on aesthetics, particularly on the principle of simplicity In a powerful plea for the heliocentric world view Copernicus wrote: "At rest in the middle of everything is the sun. For in this most beautiful temple, who would place this lamp in another or better position than that from which it can light up the whole thing at the same time? Thus indeed as though seated on a royal throne, the sun governs the family of planets revolving around it."

The sun-centered system offered an elegant explanation for retrograde motion, including puzzling details that had no rationale in the Ptolemaic scheme. Furthermore, with the heliocentric arrangement of the planets the spacings between them are no longer arbitrary but are fully specified by the configuration. This is surely one of the most persuasive aesthetic considerations in favor of the Copernican cosmology. There is a whiff of reality here, particularly in Copernicus' resounding conclusion: "So vast without any question is this divine handiwork of the Almighty Creator." Yet very few people in the 16th century grasped the harmonious, aesthetic unity Copernicus saw in the cosmos.

Any thought that Copernicus was talking about a real system must have rapidly vanished from the minds of those few astronomers who managed to plod their way through the remainder of the treatise. Copernicus' application of the second aesthetic principle, uniform circular motion, was far from unambiguous. Like Ptolemy, he occasionally paused to mention alternative geometric arrangements. The crushing blow to any physical reality for the planetary epicyclets, if any were needed, comes in Book Six, where Copernicus was obliged to adopt details for predicting the latitudes of the planetary positions different from those he had used for predicting their longitudes. Although few readers ever managed to get that far, the hypothetical nature of the constructions was stated at the very beginning of the book—not by Copernicus but by an anonymous editor in the printshop. Most major astronomers of the ensuing decades found out that its author was a Lutheran theologian, Andreas Osiander, who probably preferred not to sign a statement in a book written by a Catholic and dedicated to the Pope. Osiander's introduction stated that the author, following his duty as an astronomer, had devised hypotheses so that the planetary positions could be calculated for any time. "But these hypotheses need not be true or even probable," he wrote. "If they provide a calculus consistent with the observations, that alone is sufficient."

The careful reader of *De revolutionibus* interested merely in the technical details of planetary motion might have been greatly inspired by Copernicus' adherence to the principle of uniform circular motion; he surely would have agreed with Osiander's analysis. On the other hand, a reader with a speculative turn of mind, seizing the aesthetics of the heliocentric principle, might have found himself in violent disagreement with Osiander.

Did the book actually have any careful readers? That question arose in a conversation I had three years ago with another student of Copernicus, Jerome Ravetz [see "The Origins of the Copernican Revolution," by Jerome R. Ravetz; SCIENTIFIC AMERICAN, October, 1966]. In our discussion we speculated that there are probably more people alive today who have read *De revolutionibus* carefully than there were in the entire 16th century. We counted on the fingers of two hands the candidates for that early era: (1) Georg Rheticus, the Wittenberg scholar who came to Poland and who persuaded Copernicus to publish his book; (2) Erasmus Reinhold, the Wittenberg professor who stayed home and who later composed the Prutenic Tables based on Copernicus' work; (3) Johannes Schöner, the Nuremberg scholar who was closely associated with the printshop and who was the man to whom Rheticus addressed his first published report on the Copernican system; (4) Tycho Brahe; (5) Christopher Clavius, the Jesuit who engineered the reform of the Gregorian calendar; (6) Michael Maestlin, Kepler's astronomy teacher, and (7) Johannes Kepler himself.

At the time I was on a sabbatical leave from the Smithsonian Astrophysical Observatory. Two days after talking with Ravetz I happened to visit the remarkable Crawford Collection of rare astronomical books at the Royal Observatory in Edinburgh. There I admired one of the prize possessions, a copy of the first edition of *De revolutionibus*, handsomely annotated in legible inks of several colors. As I examined the book I realized that the intelligent and thorough notations were undoubtedly made before 1551, that is, within eight years after the publication date of 1543. My speculation with Ravetz from two days earlier seemed to be knocked into a cocked hat, because it hardly seemed likely that, if intelligent readers of *De revolutionibus* were so rare, the very next copy of the book that I saw would be so well annotated.

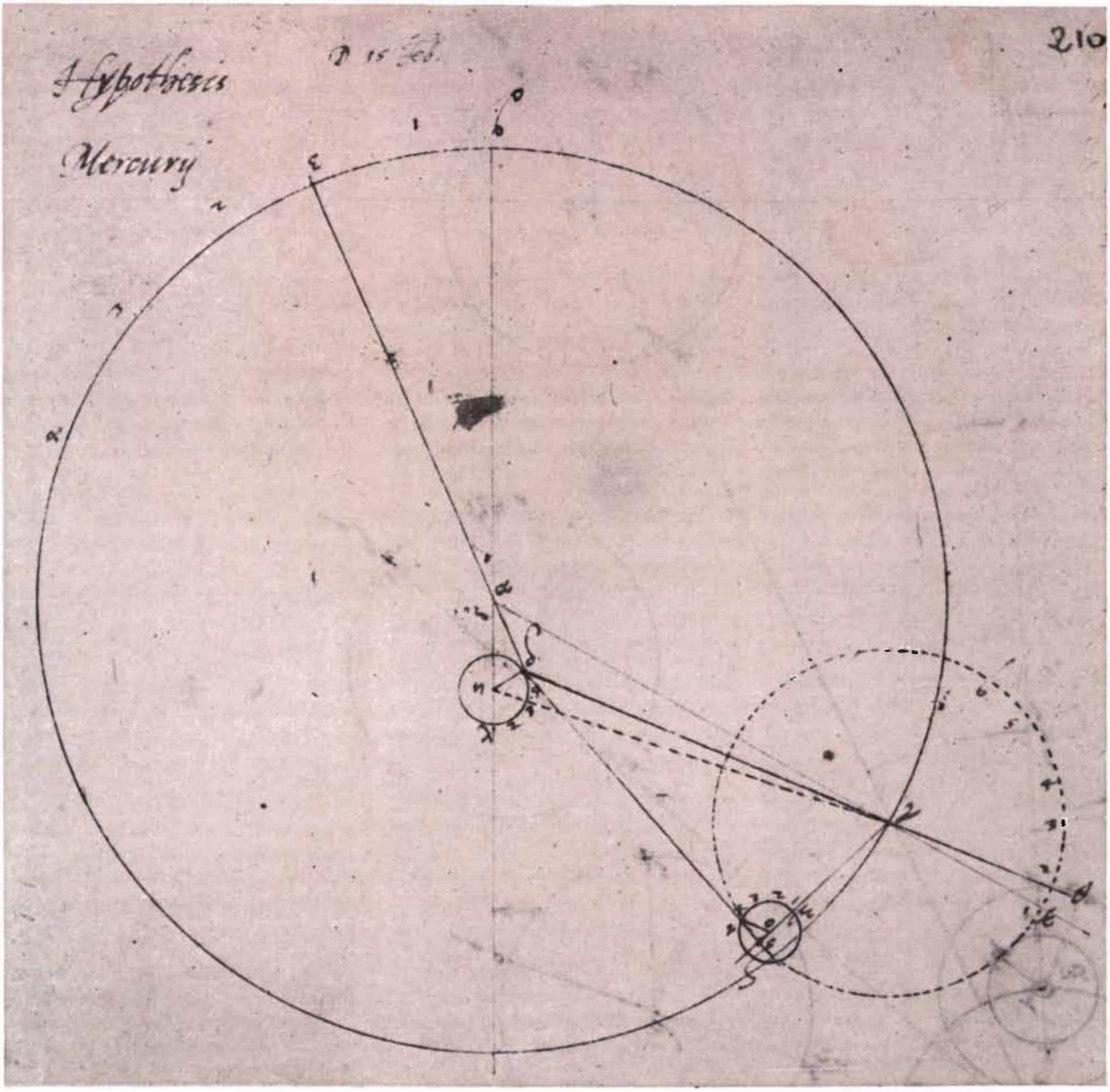
Then a second thought crossed my mind: Perhaps the Crawford copy had

© 1973 SCIENTIFIC AMERICAN, INC

been annotated by one of the handful of astronomers we had mentioned. The list quickly narrowed to Rheticus, Reinhold and Schöner, the only ones active before 1550. Internal evidence suggested that the reader was Erasmus Reinhold. Although his name is not in the book, I soon found the initials E R stamped into the decorated original binding. Within moments my initial enthusiasm was dampened when I made a rubbing of the cover: the letter S, previously hidden by a stain, appeared, making the initials E R S. It was not until two weeks later, when I was working at the British Museum and the Royal Astronomical Society, that I established that Reinhold always incorporated the Latinized form of his hometown Saalfeld, using the name Erasmus Reinholdus Salveldenis, in perfect agreement with the initials. Ultimately I was able to obtain additional specimens of Reinhold's distinctive handwriting, which settled the matter beyond all doubt.

One of the most interesting annotations in Reinhold's copy appears on the title page, where he had written in Latin: "The axiom of astronomy: celestial motion is circular and uniform or made up of circular and uniform parts." Reinhold was clearly fascinated by Copernicus' adherence to the principle of circular motion, whereas the paucity of annotations in the first 20 pages show that he was not particularly interested in the heliocentric principle. Apparently he accepted Osiander's statement that astronomy was based on hypotheses. Reinhold was intrigued by the model-building aspects of Copernicus' hypothesis and by the whole idea of alternative mechanisms for expressing the motions of the planets. Whenever such alternatives appeared in the book, he made conspicuous Roman-numeral enumerations in the margins.

Because Reinhold published the con-



EPICYCLETS ARE REARRANGED in Tycho's second attempt to explain Mercury's motion in an orbit around the earth, which he drew on February 15, 1578. In a similar manner he explored alternative models that would account for motions of planet Venus.

© 1973 SCIENTIFIC AMERICAN, INC

venient Prutenic Tables for carrying out the Copernican planetary calculations, he is frequently listed as an early adherent of the heliocentric cosmology. The nature of the tables, however, makes them quite independent of any particular cosmological system. Moreover, although his introduction is full of praise for Copernicus, nowhere does he mention the heliocentric cosmology. With his great interest in alternative mechanisms, there is reason to suspect that Reinhold was on the verge of independently discovering the Tychonic system, but he died of the plague at an early age before he could consolidate any cosmological speculations of his own.

Flushed with the success of identifying Reinhold's copy, I resolved to examine as many other copies of the book as possible in order to establish patterns of readership and ownership, always hoping to find further interesting annotations. For three years I systematically sought out copies in such far-flung places as Budapest and Boston, Leningrad and Louisville, Copenhagen and San Juan Capistrano. In the process I saw and photographed copies annotated by Kepler (in Leipzig), by Maestlin (in Schaffhausen, Switzerland), by Tycho (a second edition, in Prague) and by Rheticus (a presentation copy in Connecticut). I also found copies annotated by astronomers we forgot to put on the original list: the ephemeris-maker Johannes Stadius (at the United States Military Academy at West Point) and by Casper Peucer, Reinhold's successor as astronomy professor at Wittenberg (at the Paris Observatory). In all, I had managed to see 101 copies of *De revolutionibus* by this past spring. The investigation confirmed that the book had rather few perceptive readers, at least among those who read with pen in hand. In spite of that, however, the book seemed to have a fairly wide circle of casual readers, much larger than has been generally supposed.

In May I had the opportunity to visit Rome, where there were seven copies of the first edition that I had not examined. My quest took me first to the Vatican Library, where I went armed with shelfmark numbers provided by my Polish colleague Dobrzycki. Some of the books in the Vatican Library had come there with the eccentric Queen Christina of Sweden, who had abdicated her throne in 1654, abandoning her Protestant kingdom for Rome. Her father, Gustavus Adolphus, had ransacked northern Europe during the Thirty Years' War and among other things had captured most of Copernicus' personal library Dobrzycki had gone to Rome in search of Copernican materials that Queen Christina might have taken along. In the Vatican he found an unlisted copy of Copernicus' book among the manuscripts. Because the book was published just when Copernicus died Dobrzycki knew that it could not have belonged to Copernicus himself, and so he proceeded on to other materials. Fortunately for me, he gave me the number for the volume, which could not have been found in the regular Vatican card catalogues.

When I examined this copy, I realized that the extensive annotations in the margins must have been made by a highly skilled astronomer. At the end were 30 most interesting manuscript pages bound into the volume, full of diagrams made by someone working along the same lines as Tycho and dated 1578. Although there was no name anywhere on the volume, I conjectured that the annotations might have been made by the Jesuit astronomer Christopher Clavius, because his copy of *De revolutionibus* was one I had not yet found. In a state of considerable excitement I got in touch with D. J. K. O'Connell, the former director of the Vatican Observatory. With his help I obtained Xerox copies of two letters by Clavius from the Jesuit Archives. Eagerly I returned to the Vatican Library, only to have my hypothesis smashed within minutes. There was no possibility that the writing in the *De revolutionibus* was the hand of Christopher Clavius.

I left Rome in a baffled and troubled state for a conference on Copernicus in Paris. There, by a fantastic stroke of luck, I received the new facsimile of the second edition of *De revolutionibus* that is preserved in Prague, and which contains annotations by Tycho. I think my heart must have stopped for a moment when I saw the handwriting in the facsimile: I then realized that the first edition in Rome was probably also in Tycho's hand. What I had found in the Vatican Library was Tycho's original working copy, probably the most important Tycho manuscript in existence. The second edition in Prague was a derivative copy; it had been annotated by Tycho with the thought that it might possibly be published.

I rebooked my flights and went back to Rome. After I had put the Prague facsimile side by side with the Vatican copy, it took only a few minutes to prove this conjecture. Afterward the Vatican librarians traced the book to Queen Christina, who must have gained possession of it in 1648 when her troops captured the collections formed by Rudolph II in Prague.

On the title page of Tycho's copy in the Vatican appears the very same words that Reinhold had inscribed on his copy: "The axiom of astronomy: celestial motions are uniform and circular, or composed of uniform and circular parts." I had already known that in 1575, three years before the dated annotations in this book, Tycho had visited Reinhold's son in Saalfeld and had seen Reinhold's manuscripts. Knowing this, I had guessed that Tycho's own cosmological views grew from seeds planted at Wittenberg by a tradition that honored Copernicus but followed Osiander's admonition that it is the duty of the astronomer to "conceive and devise hypotheses, since he cannot in any way attain the true causes." The newly found Tycho copy dramatically confirmed this intellectual heritage, not only through the motto on the title page but also within the book itself, where numerous annotations are copied word for word from Reinhold. In particular Tycho, like Reinhold, specifically numbered any alternative arrangements of circles indicated by Copernicus. Like Reinhold, he must have viewed Copernicus as a builder of hypothetical geometric models.

The most exciting aspect of the Vatican volume is the sequence of 30 manuscript pages at the end. Apparently they are very preliminary working notes on Tycho's own geocentric system. The first opening is dated January 27, 1578, the day after the spectacular comet of 1577 had been seen for the last time. The diagrams on those two pages are heliocentric, and a note in the corner indicates that it was drawn according to the third hypothesis of Copernicus, corresponding to one of Tycho's enumerations marked in the margin of the printed book.

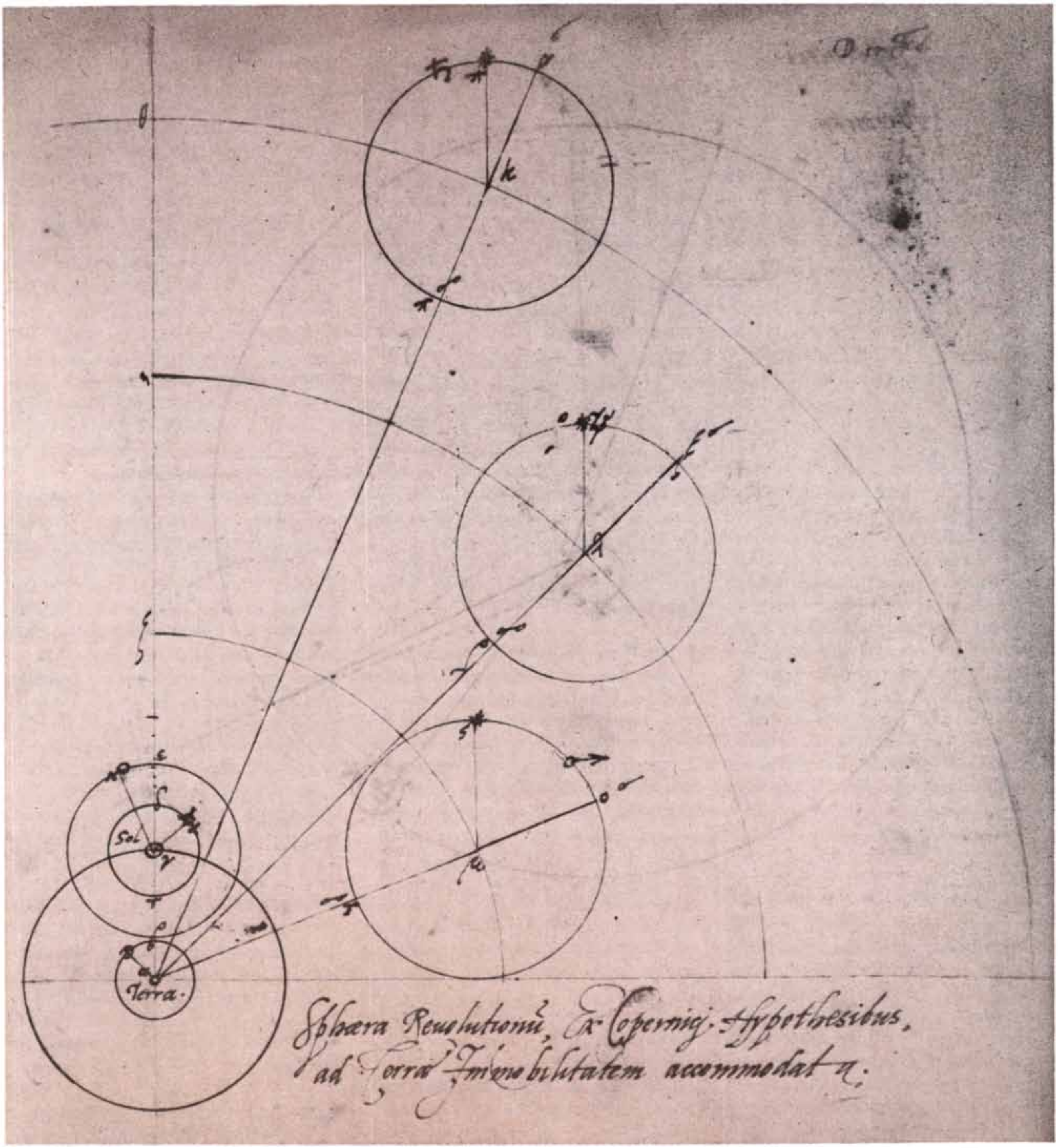
Diagrams drawn about three weeks later show a geocentric arrangement for the first time, and Tycho noted that "this new hypothesis occurred to me in the year [15]78 on the 13th day of February" [*see illustration on page 90*]. Seldom can we pinpoint the moment of a centuries-old discovery so precisely! In a series of charts Tycho explored alternative positions of the single epicyclet for Venus and the pair of epicyclets for Mercury.

Two days later, on the very next page, Tycho drew the most interesting diagram of the entire sequence [*see illustration on next page*] It is easy to recognize as a proto-Tychonic system: the earth is at the center, circled by the moon and the sun. Tycho placed the orbits of Mer-

© 1973 SCIENTIFIC AMERICAN, INC

cury and Venus around the sun. He still arranged the three superior planets in circles around the earth, but he made each epicycle the same size as the sun's orbit. He then drew a line from the earth to the center of each of the three epicycles and connected the center of each epicycle to its planet by a vertical line. This vertical line in each case is the same length as the distance between the earth and the sun by virtue of the fact that the size of the epicycles and the sun's orbit is the same; all that is necessary to finish the construction of the final Tychonic system is to complete the parallelogram by drawing a line from the sun to each superior planet [*see illustration on opposite page*].

Tycho was now surely within grasp of his final system. His caption, however, is worth notice: "The spheres of revolution accommodated to an immobile earth from the Copernican hypotheses." Tycho was playing the astronomical-geometry game, greatly under the influence of Copernicus, and somehow supposing that a geocentric system was compatible with



PROTO-TYCHONIC SYSTEM was drawn by Tycho on February 17, 1578. It is only one step removed from his final planetary system. In this diagram he shows all the planets. Venus and Mercury circle the sun; the sun circles the earth. The deferents of Mars, Jupiter and Saturn are centered on the earth; the epicycle for each planet is the same size as the orbit of the sun around the earth. Tycho then drew a line from the earth to the center of each epicycle and connected this center to its planet by a vertical line.

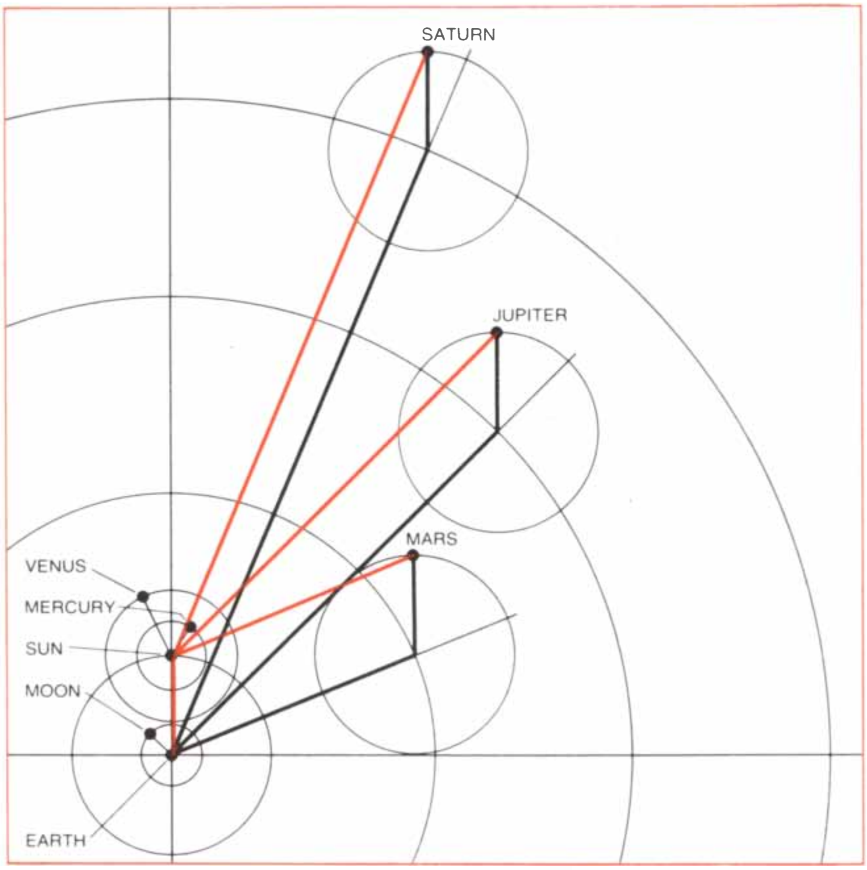
© 1973 SCIENTIFIC AMERICAN, INC

the heliocentric teachings of the master.

It is curious that Tycho did not publish his new system until a decade later. Tycho was a dynamic young man of 31 when he wrote this manuscript and already well established on the island of Hven, but perhaps still uncertain where his observations for the reform of astronomy would lead him. A passage in his *De mundi aetherei recentioribus phaenomenis* implies that he did not establish the Tychonic system until around 1583, five years after he drew these diagrams. I can only suppose that those five years were an important time of maturing. In that interval Tycho must have speculated on the movement of the great comet of 1577, realizing that it would have smashed the crystalline spheres of the ancient astronomy, had they existed, as it moved through the sky. Perhaps he began to look for greater certainty in astronomy and to suppose that the observations made with the giant instruments at his Uraniborg observatory could lead beyond hypothesis to physical reality. If so, like his contemporaries in that pre-Newtonian, predynamical age, he must have viewed the physics of the sluggish, heavy earth as a most important phenomenon to be preserved. We can well imagine that Tycho believed he was taking a great step forward toward understanding the physical reality of the universe when he adopted his own geocentric system.

Curiously enough, Tycho's system retained many of the advantages offered by Copernicus: the planetary orbits were linked together in a coherent unit, and retrograde motions were "naturally" explained. Although his scheme conceded little to the special properties of the sun among the planets, it carefully preserved the time-honored uniqueness of the central earth. Yet there was one aspect, absolutely crucial for the further development of physics, lacking in the Tychonic arrangement. In the Copernican system the planets are harmoniously ordered out from the sun so that the shorter the period, the closer the distance. It is this pattern that opened the way to the mathematization and mechanization of the universe.

In retrospect the Tychonic system, which weighs so heavily in Urania's balance, looks clumsy and wrong—a monumental step backward. Thus Tycho is today rejected as a cosmographer and he is lauded as the ingenious instrument builder whose systematic observations provided the foundations for Kepler's laws. Kepler in turn is hailed as the number-juggler whose elliptical orbits finally vanquished the ancient requirement of uniform circular components for celestial motions.



TYCHONIC SYSTEM can easily be obtained from Tycho's final diagram (*see illustration on opposite page*). Vertical line from center of each epicycle to its planet is the same length as the distance between the earth and the sun since the size of the epicycles and of the sun's orbit is the same. All that remains to finish construction of Tychonic system is to complete the parallelogram by drawing a line from sun to each superior planet (*color*).

Weighed against the Tychonic scheme, the heliocentric system appears neat and orderly to us living after the time of Newton. Indeed, it is precisely this elegant organization that Copernicus found pleasing to the mind, and which led to his cosmology. Early in *De revolutionibus* he wrote: "In this arrangement, therefore, we discover a marvelous symmetry of the universe, and an established harmonious linkage between the motion of the spheres and their size, such as can be found in no other way."

It was precisely in this arrangement that Kepler saw the real possibility of a celestial physics, and he took the first groping steps toward a dynamics of the heavens—dynamics that, when they were reshaped and powerfully formulated by Newton, ultimately proved to be the primary justification for the heliocentric universe. It may well be that Kepler's vision of a cosmic physics shaped the development of science far more significantly than the discovery of his three laws of planetary motion. And quite possibly Tycho's own insistence on a physically acceptable and not merely hypothetical astronomy influenced the young Kepler's views on the nature of the universe. It was in this tradition that both Kepler and Galileo taught us to use our senses to distinguish between the various hypothetical world views, allowing only the ones that were consistent with the observations.

Only in our own generation have we been able to break the terrestrial bonds; men flung out toward the moon have seen the spinning earth, a blue planet, sailing through space. Copernicus' daring concept has been vindicated. Seen by him only in the mind's eye, the concept of the moving earth became the essential first step toward a physics that embraced both the earth and the sky. Thus in reality the Copernican quinquecentennial celebrates the origins of modern science and our contemporary understanding of the universe. Fittingly we honor not only the renowned Polish astronomer but also his illustrious successors—Kepler, Galileo, Newton, and, in a new light, Tycho Brahe.

© 1973 SCIENTIFIC AMERICAN, INC

The Soaring Flight of Vultures

The six common vultures of East Africa can make a round trip of as much as 200 kilometers by skillfully riding updrafts. How they do so is examined with the aid of a powered glider

by C. J. Pennycuick

To watch a vulture soar effortlessly overhead for hours at a time is to become convinced that these birds are among the most skillful of fliers. Yet there are occasions when vultures cannot fly at all. Early in the morning on the East African plains one quite often meets little groups of vultures that had gathered at some small find the night before and then slept where they happened to be when night fell. If the birds are pursued, they take off, but they do not fly far before they land again. If they are forced to take off several times in rapid succession, they quickly become exhausted and can be caught by hand. Two of the commonest East African vultures, Rüppell's griffon (*Gyps rüppellii*) and the white-backed vulture (*Gyps africanus*), can easily be caught this way. Later in the morning, say after about 9:00 A.M., the technique sometimes still works on a vulture that is heavily gorged with food. More often the bird will fly straight ahead for a short distance, then turn sharply and at the same time start climbing. After turning in a few irregular narrow circles and intermittently flapping its wings, the vulture settles down to gliding in steady circles. It then continues to climb without flapping its wings and drifts downwind as it circles.

The reason these vultures have such difficulty flying under their own muscle power is that they are too big. There is a relation between the power required to fly, the power available from the muscles and the body weight that sets an upper limit to the weight of animals able to fly by muscle power. The larger vultures, storks and pelicans are quite near this limit and would barely be able to stay airborne were it not for their ability to extract energy from the atmosphere and use it for their locomotion.

The flight path of a bird that is gliding along at a steady speed (that is, not flapping its wings) is invariably inclined downward. The gliding bird therefore has a vertical downward component of velocity, called the "sinking speed." If the air through which the bird is flying happens to be rising at a speed greater than the sinking speed, the bird is carried up with it and acquires potential energy it can use later to glide through air that is not rising. Any system of maneuvers whose effect is to produce this result by taking advantage of some atmospheric process constitutes a method of soaring.

Soaring techniques can be classified according to the atmospheric process responsible for the rising air, or "lift" [*see illustration on page 105*]. The existence of lift in sufficient quantities, however, satisfies only part of the requirement for a successful soaring technique. Sufficient information must also be available to the bird to enable it to locate the lift and, having found it, to carry out the correct maneuvers to make use of it. If the bird executes the wrong maneuver, it will usually lose the lift.

A soaring bird can work with several different kinds of lift, for example slope lift, in which the air rises when a wind encounters a slope; thermal lift, in which columns or bubbles of air rise when heated from below by warm ground, and wave lift, in which the air rises in the course of undulatory motion downwind of an obstacle. The correct procedure for a bird using slope lift is for the bird to tack to and fro, remaining above the windward slope. If the lift happens to be due to a thermal, however, the bird must change over to circling, drifting downwind with the thermal instead of remaining over the slope. Wave lift, on the other hand, remains stationary with respect to the ground, and it must be worked in the same way as slope lift, except that there is no slope to indicate where the lift is. Inexperienced glider pilots often mistake wave lift for thermal; they circle in it and as a result drift downwind into the downgoing part of the wave. This error is apt to lead to a rapid and embarrassing descent *aux vaches,* as French pilots say. Present indications are that many, if not all, birds make the same mistake when they encounter wave lift.

Soaring birds are not the easiest birds to study, partly because the bird watcher, traditionally equipped with binoculars and rubber boots, cannot match their mobility and tends to lose track of them, and partly because one can never tell from the ground what kind of air movements a bird is soaring in. There is a limit to what one can deduce from even the most meticulously detailed ground observation, and in fact not a great deal of progress has been made with this approach since E. H. Hankin's classic book *Animal Flight* appeared in 1913.

Entirely new opportunities have been opened up with the advent in recent years of practical powered gliders. I have been extremely fortunate in having the use of one of the best of these, the Schleicher ASK-14, which was generously put at my disposal by Anglia Television and Okapia Film. The ASK-14 was developed from the well-known K-6E sailplane, and it is powered by a 26-horsepower engine. Because of its highly efficient aerodynamic design, the aircraft takes off and climbs in a lively manner with the aid of this tiny power plant. The engine is normally run for five or 10 minutes after takeoff until a thermal has been found, after which the engine is switched off and the propeller is feathered. The aircraft then becomes an excellent soaring glider, and the flight can be extended, usually for several hours, without further recourse to the engine. If

© 1973 SCIENTIFIC AMERICAN, INC

the thermals should fail, or if the pilot gets too low over some unsuitable place, the engine can be restarted to extract him from the difficulty.

I have flown the ASK-14 mainly over the Serengeti National Park in northern Tanzania and neighboring areas of Tanzania and Kenya. This area enjoys good soaring weather throughout most of the year, and it is frequented by a remarkable variety of species of soaring birds. Many of the birds are common enough to be encountered during nearly every flight.

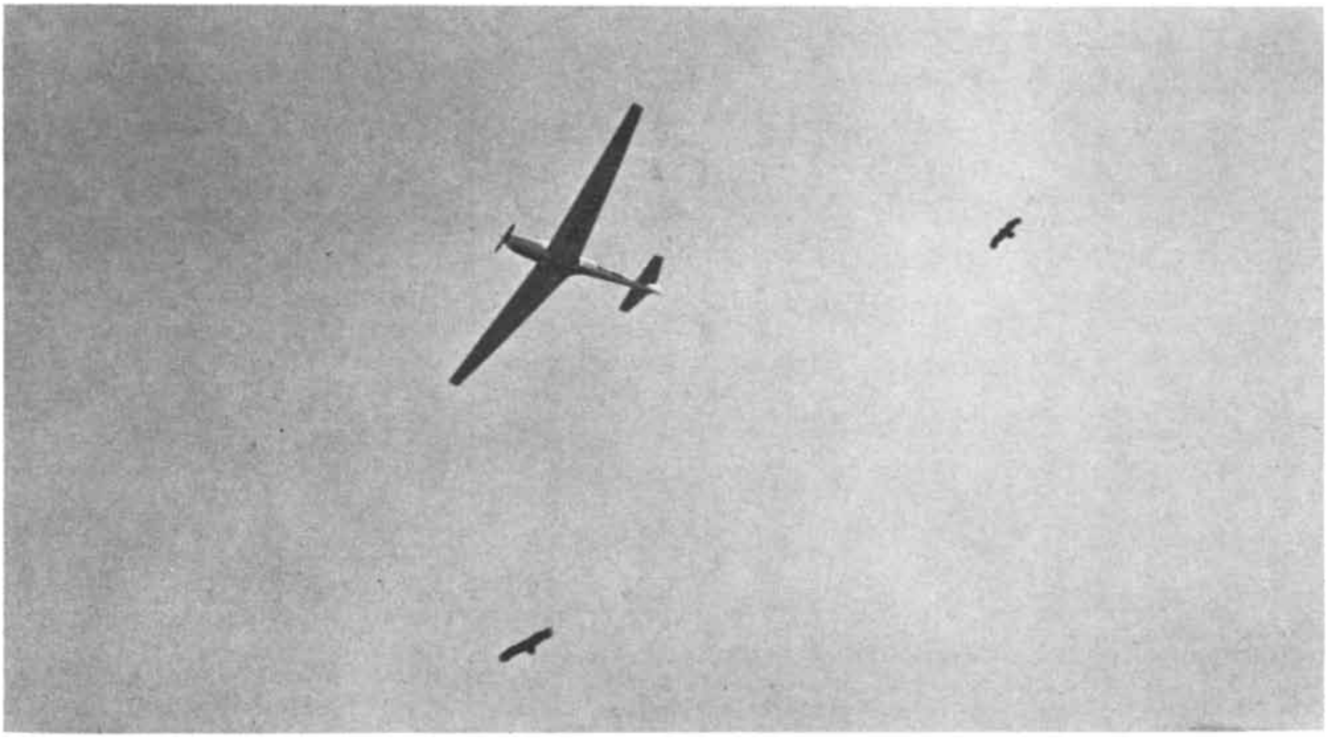
The common soaring birds of East Africa soar mainly in slope lift and thermals. Slope lift is, of course, useful only in the hillier areas and at comparatively low altitudes, and so in general thermals are the most important source of lift. When vultures are taking off from the ground, one can see at once that they are using some definite structure in the atmosphere rather than the randomly distributed kind of energy characteristic of turbulent air. As soon as one vulture is climbing successfully it is quickly joined by others (and often by other kinds of birds as well), until soon a group of birds forms, all circling around a common axis. This axis marks the "core" of a thermal, which at low altitudes is generally a vortex of the "dust devil," or columnar, type. "Dust devil" refers to the fact that over dry ground vigorous thermals of this type are often visible as whirling columns of dust. Higher up vortex-ring thermals may form, and the tops of many thermals of either type are marked by cumulus clouds. As far as the soaring bird or pilot is concerned, either type of thermal can be considered a circular patch of lift that drifts along with the wind. The appropriate soaring maneuver is to fly in steady circles of as small a radius as possible, in order to stay as close as possible to the middle of the core, where the lift is strongest.

A bird's ability to use thermals, either for staying airborne or for traveling cross-country, depends on its gliding performance. This is most often expressed in terms of its "glide polar," which is a graph of sinking speed plotted against forward speed. The glide polar for a glider can be measured directly. The same type of graph for a gliding bird can be produced by estimating the differences in horizontal and vertical speed between a glider with a known polar and the bird. In this way the glide polars of the ASK-14 and the white-backed vulture have been compared.

In a straight glide the glider can travel much faster than the vulture at a given gliding angle. This is owing partly to the glider's superior aerodynamic efficiency and partly to its higher wing loading (the ratio of weight to wing area). On the other hand, when the glide polar is translated into circling flight, the effect of the vulture's lower wing loading is that it can turn in much smaller circles at a similar rate of sink. This means that in a narrow thermal the bird can center its circle in the strongest part of the core, whereas the glider is obliged to fly in the weaker lift around the outside. Thus the vulture can often outclimb the glider, particularly at low altitude and early in the day, when the thermals tend to be weak and narrow, even though its sinking speed in straight flight is much the same. On one occasion, on a day of exceptionally narrow thermals, I was outclimbed by a tawny eagle (which has a still lower wing loading than the white-backed vulture), even though I had my engine running while the eagle was only gliding.

Many birds of prey are adapted primarily to using thermals as a means of remaining airborne in order to look out for food below. The African martial eagle (*Polemaetus bellicosus*), which preys on other birds, uses thermals in much the same way that smaller eagles and hawks use a rocky crag or a telephone pole. When foraging, it climbs by circling in a thermal to some modest height, usually from 300 to 600 meters above the ground, and then glides slowly along with its head pointing down, looking out for prey below.

Vultures use much the same technique in searching for carrion, but their tactics are based on the need to arrive promptly on the scene whenever and wherever a



POWERED GLIDER, its engine off and its propeller feathered, soars in rising air over the Serengeti National Park in northern Tanzania, accompanied by a pair of vultures that utilize the same lift to gain altitude effortlessly. The glider is a Schleicher ASK-14.

© 1973 SCIENTIFIC AMERICAN, INC

dead animal happens to turn up. By alternately climbing in thermals and gliding straight in different directions, they patrol over likely areas, usually between 200 and 500 meters above the ground. Starting from a height of, say, 300 meters, a vulture can reach any point on the ground within a radius of about 4.5 kilometers within six minutes. Points nearer at hand can be reached more quickly in a fast, steep dive; the steeper the angle is, the faster the vulture can glide. The mammalian scavengers, mainly the spotted hyena (*Crocuta crocuta*), react like the vultures to signs of activity in the distance (including descending vultures), but they have to work much harder to get to the site and have lower maximum speeds. Thus the vultures, although they cannot drive off the hyenas in a direct confrontation, can still compete with them effectively through their advantage in arriving quickly at an unpredictable source of food.

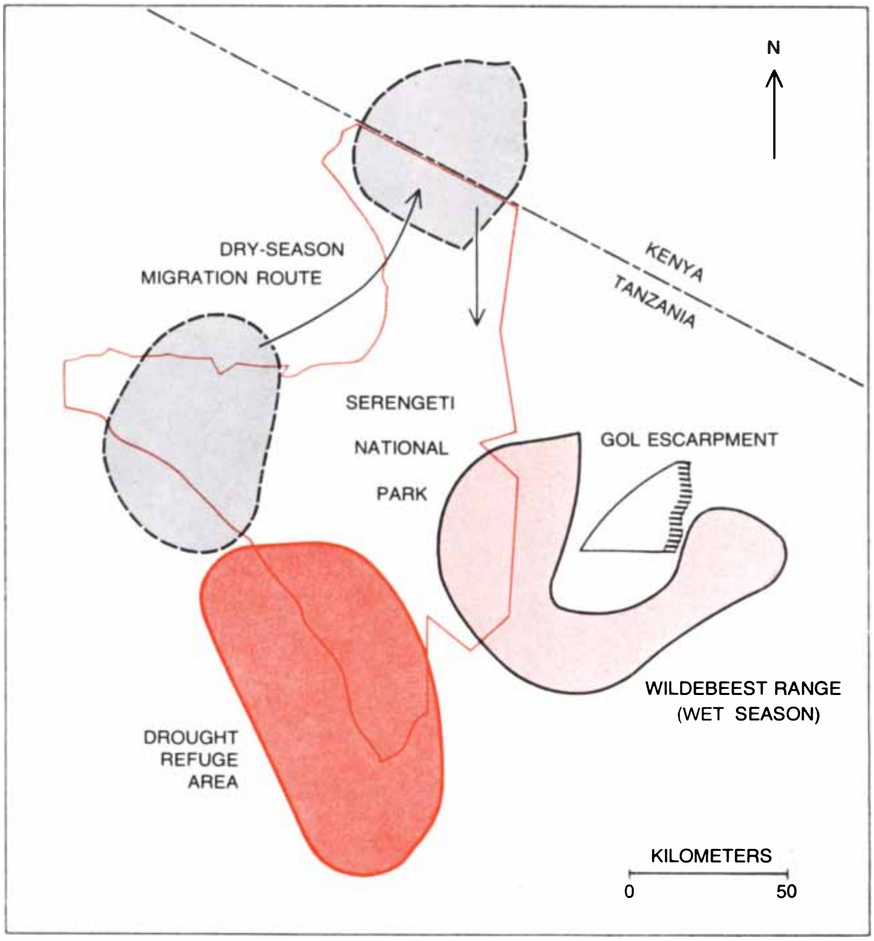
The African vultures have evolved two different approaches to the strategy of searching for food. One is to learn the geography of a home range and search it very thoroughly. In areas where game is scarce no other approach is possible. One of the special features of the East African fauna, however, is the existence of large populations of migratory ungulates, and this opens up another niche for scavengers adapted to take advantage of it. In the Serengeti, for instance, hundreds of thousands of wildebeest make an annual migration around a circuit some 500 kilometers in length, and comparable populations of zebras and Thomson's gazelles make similar migrations [see "A Grazing Ecosystem in the Serengeti," by Richard H. V. Bell; SCIENTIFIC AMERICAN, July, 1971].

To a sedentary scavenger the arrival of the migratory herds represents a temporary superabundance of potential food, but the herds move somewhat erratically and are apt to move out of reach as suddenly as they came. A scavenger that is adapted primarily to feeding on migratory game must dispense with a fixed home range and follow the migrating herds wherever they go. Thus it cannot learn the ground as thoroughly as a sedentary scavenger.

It seems that among the four large species of East African vultures two are basically sedentary and two are itinerant. This was postulated several years ago by Hans Kruuk, on the basis of differences in the behavior of the birds at the carcasses on which they were feeding. The two sedentary species, the lappet-faced vulture (*Torgos tracheliotus*) and the white-headed vulture (*Trigonoceps occipitalis*), never gather in large numbers; it is rare to see more than eight of the former and two of the latter at the same gathering. The two species manage to arrive first at carcasses much more often than their relatively small numbers would lead one to expect, indicating that these sedentary birds pursue a "thorough search" strategy. In contrast, the itinerant Rüppell's griffon and its fellow member of the genus *Gyps*, the white-backed vulture, often gather in the hundreds at a large carcass, but in spite of their numbers they do not usually arrive first. It would be an exaggeration to say that they never find their own food, but they seem to rely more heavily on following carnivorous mammals or other vultures and less on searching directly by themselves. Unlike the other two species, they never fight in the air. They seem to have no territorial behavior whatever, although they do squabble a good deal when they are actually feeding.

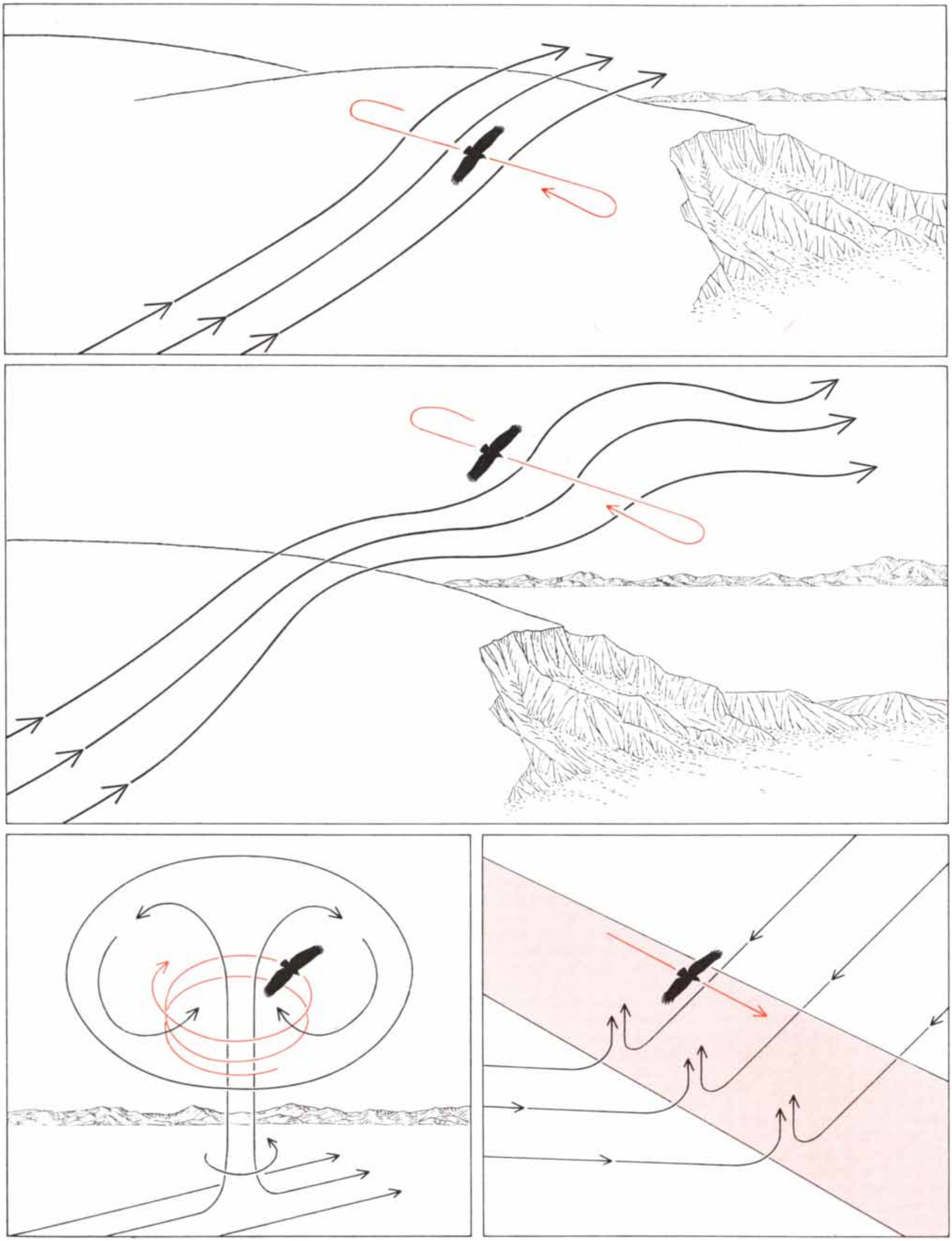
In the air the difference in behavior is evident even from a powered aircraft. Once the thermals are under way lappet-faced vultures and white-headed vultures may be met almost anywhere, usually in pairs, but the griffons concentrate over the migratory herds (particularly the wildebeest), often in spectacular numbers. When griffons are encountered away from concentrations of game, they are usually traveling steadily cross-country, commuting between their feeding area, which is changeable, and their nesting area, which is necessarily fixed. Because the two areas may be widely separated, the griffons have to be able to use thermals for cross-country travel as well as for staying aloft while foraging.

The bird that travels the farthest is Rüppell's griffon, which nests in colonies on cliffs. This habit, in which it differs from the white-backed vulture (a tree-nester), is most probably a reflection of



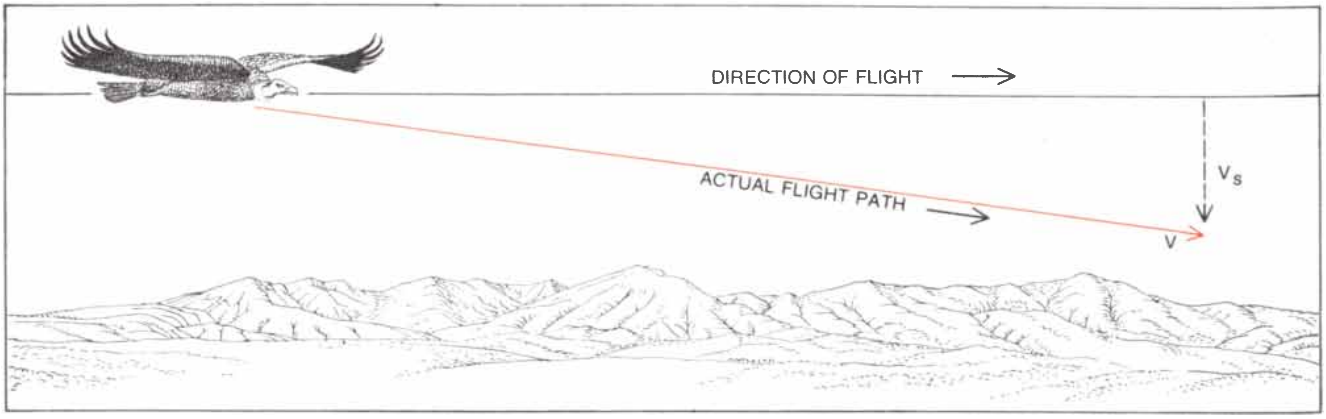
NESTING GROUND of the Rüppell's griffons that frequent the Serengeti National Park is the Gol Escarpment (*right*), a zone convenient to the grazing area preferred by wildebeest in the wet season when the griffons are raising their nestlings (*light color*). An unseasonable drought, however, will move the wildebeest to the west (*dark color*), forcing the griffons to travel 100 kilometers in each direction to get food for the nestlings. In the dry season, during the annual wildebeest migration (*gray zones*), the griffons follow them.

© 1973 SCIENTIFIC AMERICAN, INC



FOUR KINDS OF LIFT are exploited by different patterns of flight. Where air movement uphill provides "slope lift" (*top*), bird or sailplane should tack back and forth, heading sufficiently into the wind to stay within the same zone of rising air. The same pattern of flight is used to exploit "wave lift" on the leeward side of a slope (*middle*). To exploit a "thermal" (*bottom left*) the soarer travels downwind with the rising air column, circling within the thermal. When two air masses converge (*bottom right*), producing a line of "frontal lift," the soarer can either tack back and forth or set off in one direction and travel the entire length of the line.

© 1973 SCIENTIFIC AMERICAN, INC

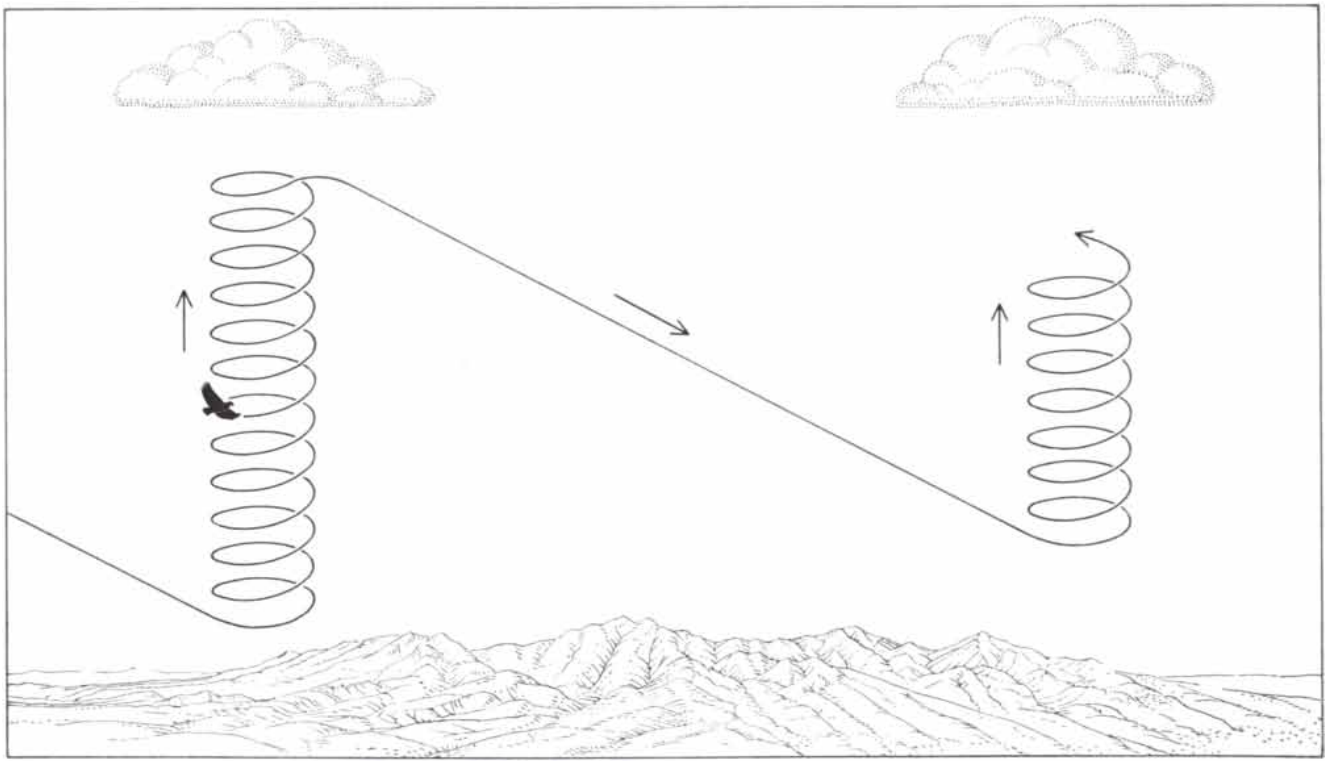


GLIDING BIRD in still air loses altitude at a "sinking speed" (V_s) while traveling forward at a "flight speed" (V); the ratio V/V_s is the bird's "glide ratio" and is equal to the distance traveled forward per unit of altitude lost. If the air, instead of being still, rises faster than the bird sinks, the bird will not lose but gain altitude and acquire potential energy proportional to the altitude gained.

the fact that, being mainly a bird of the more arid country to the north, it is near the edge of its range in the Serengeti. The only suitable cliffs in the Serengeti area are outside the national park along the eastern escarpment of the Gol Mountains, and here some 500 or so pairs of Rüppell's griffons nest. Their breeding season is so timed that they normally raise their young during the period from February to May. This is the rainy season, during which the main migratory ungulate populations are usually on the Serengeti and Salei plains, within easy reach of the nesting cliffs. It often happens, however, that the rains are interrupted by dry spells, and wildebeest and zebras are then forced to move away to the south and the west. That may oblige the griffons to travel 100 kilometers or more each way to get food for their young, which have to be fed daily by one parent or the other.

By following vultures on cross-country flights I have found that in good soaring weather, which usually prevails when the plains are dry, they can keep up average cross-country speeds of some 45 kilometers (28 miles) per hour. Thus they must travel two or three hours each way between the nesting cliffs and the dry-weather areas. In windy weather the vultures take off and start slope soaring along the cliffs at the first light. The prevailing winds are easterly, and by moving from slope to slope the vultures can make their way westward across the hills to the edge of the Serengeti Plain. There they have to wait for convection to begin (usually between 8:00 and 9:00 A.M.) before they can drift farther downwind across the plains by circling in the first weak thermals.

The best soaring hours of the day are usually between 11:00 A.M. and 4:00

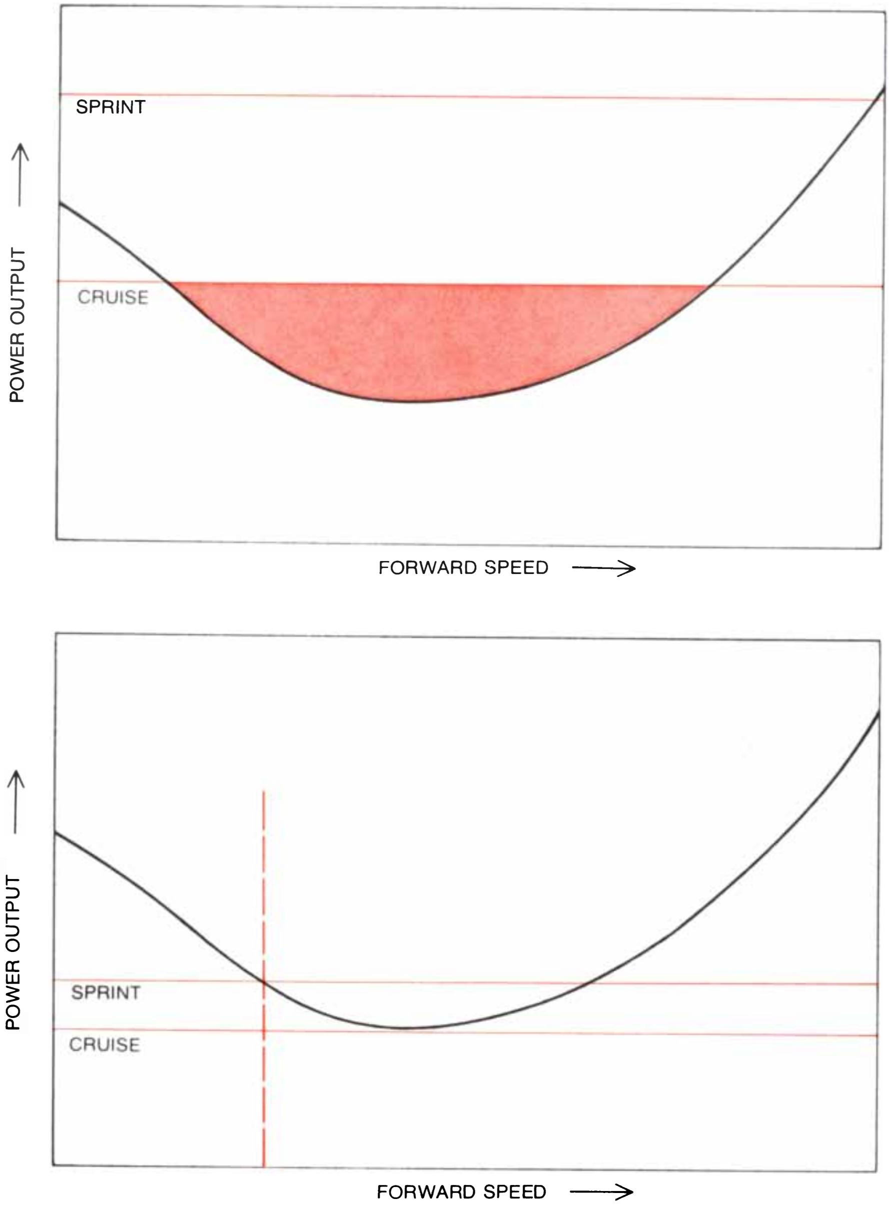


CROSS-COUNTRY FLIGHT is the behavior imposed on itinerant vultures such as Rüppell's griffon by the movements of prey. It requires climbing in successive thermals and gliding in the desired direction. In nesting season 200-kilometer flights are common.

© 1973 SCIENTIFIC AMERICAN, INC

P.M., when in dry weather frequent thermals provide rates of climb typically between two and four meters per second over an altitude range from very near the ground (say 1,600 meters above sea level) up to cloudbase (which is normally about 3,500 meters above sea level). A climb from the bottom to the top of this range usually takes 10 minutes or so, after which the bird can glide off straight in the direction it wants to go.

The speed on the straight glides is typically between 70 and 85 kilometers (45 and 55 miles) per hour. At these speeds the glide ratio is about 10 : 1, that is, the bird loses one meter of height for every 10 it travels forward. If it encountered no vertical motion in the air at all, it could glide some 18 kilometers in, say, 15 minutes before the need for another thermal became urgent. The total time needed to travel this distance, including the time for the climb, would be about 25 minutes, equivalent to an average cross-country speed of 43 kilometers per hour. In practice the vultures do not generally use the full altitude range available to them; they usually leave a thermal at between 2,500 and 3,000 meters above sea level. Moreover, they flatten their gliding angle considerably by slowing down as they fly through thermals and speeding up in between. On one occasion a Rüppell's griffon I was accompanying in the glider flew for 32 kilometers without circling by using this tactic and managed to lose only 520 meters of altitude—an achieved glide ratio of better than 60 : 1!



POWER REQUIRED FOR FLIGHT is less at moderate speeds (*trough of "u"*) and greater at hovering (*left*) and high (*right*) speeds. For a bird of medium size, such as a pigeon (*top*), continuously available muscle power (*lower line*) is enough for protracted flight over a wide range of speeds (*shaded area*) and sprint power (*upper line*) allows jump takeoffs. For a big bird such as a vulture (*bottom*) continuously available muscle power is not enough to allow protracted flight at any speed. The big bird must run, or dive from a high perch, to reach minimum flying speed (*broken vertical line*) and then use sprint power to remain airborne long enough to reach lift and begin relatively exertionless soaring flight.

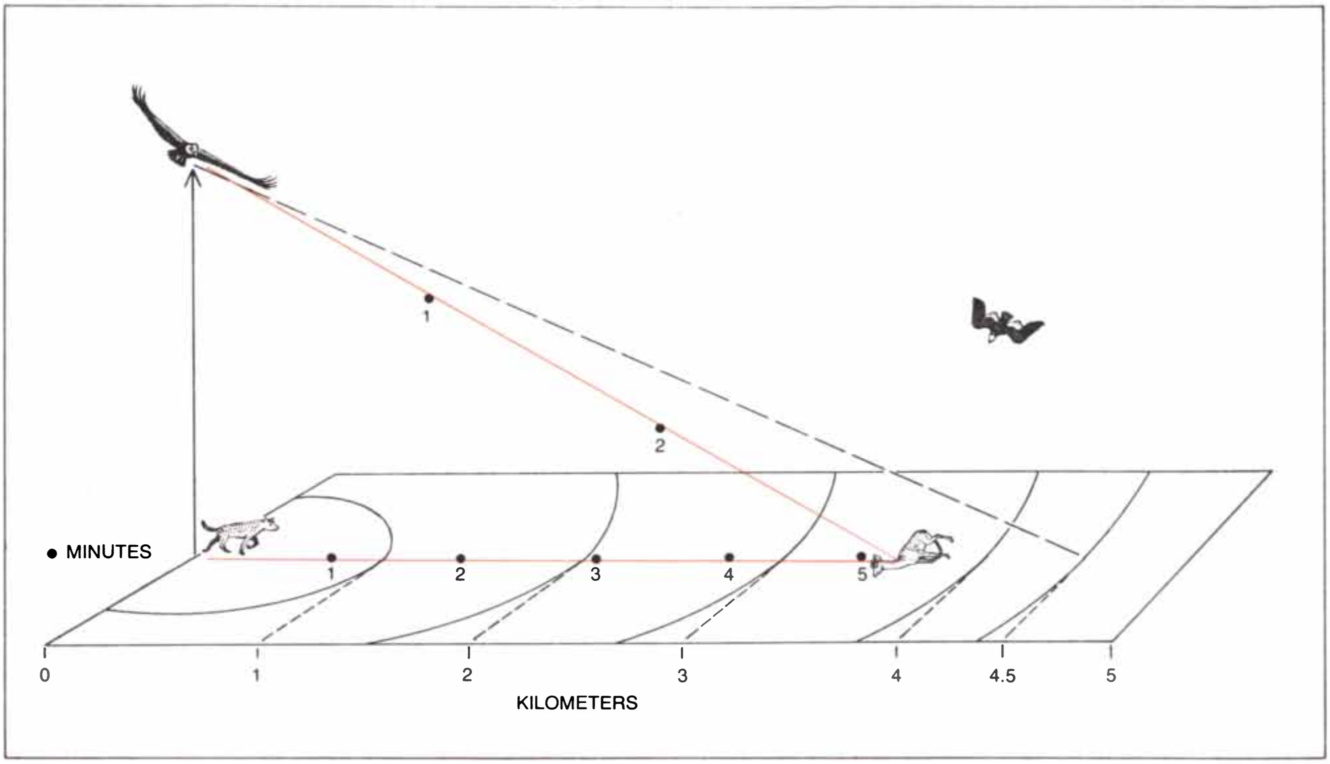
The griffon vultures' ability to forage at a distance of 100 kilometers from the nest gives them another competitive advantage over their formidable competitor the spotted hyena. Hyena pups are confined to a den for the first few months of their life, so that when the game concentrations are not in the immediate vicinity, the mother may have to travel many kilometers to get food, periodically coming back to suckle the young. A hyena's foraging radius cannot be reliably estimated, but it is certainly much less than that of a griffon vulture, because of the hyena's lower speed and the greater effort that travel on foot requires.

The biggest advantage low wing loading gives a bird is the ability to soar early in the day, when the first thermals are usually feeble dust devils, both narrow and weak. This advantage is important to foraging vultures: the earlier they become airborne in the morning, the better are their chances of getting pickings from the remains of animals that have died or been killed by predators during the night. In the heat of the day the thermals are broader and stronger, and the advantage in rate of climb to be had from a very low wing loading becomes insignificant; the beneficial effect on cross-country speed is more than offset by the loss of speed on the straight glides. To some extent birds achieve the best of both worlds, because they can reduce their wing area for fast flight. Even so the cross-country speeds they can achieve are modest compared with those of man-made gliders.

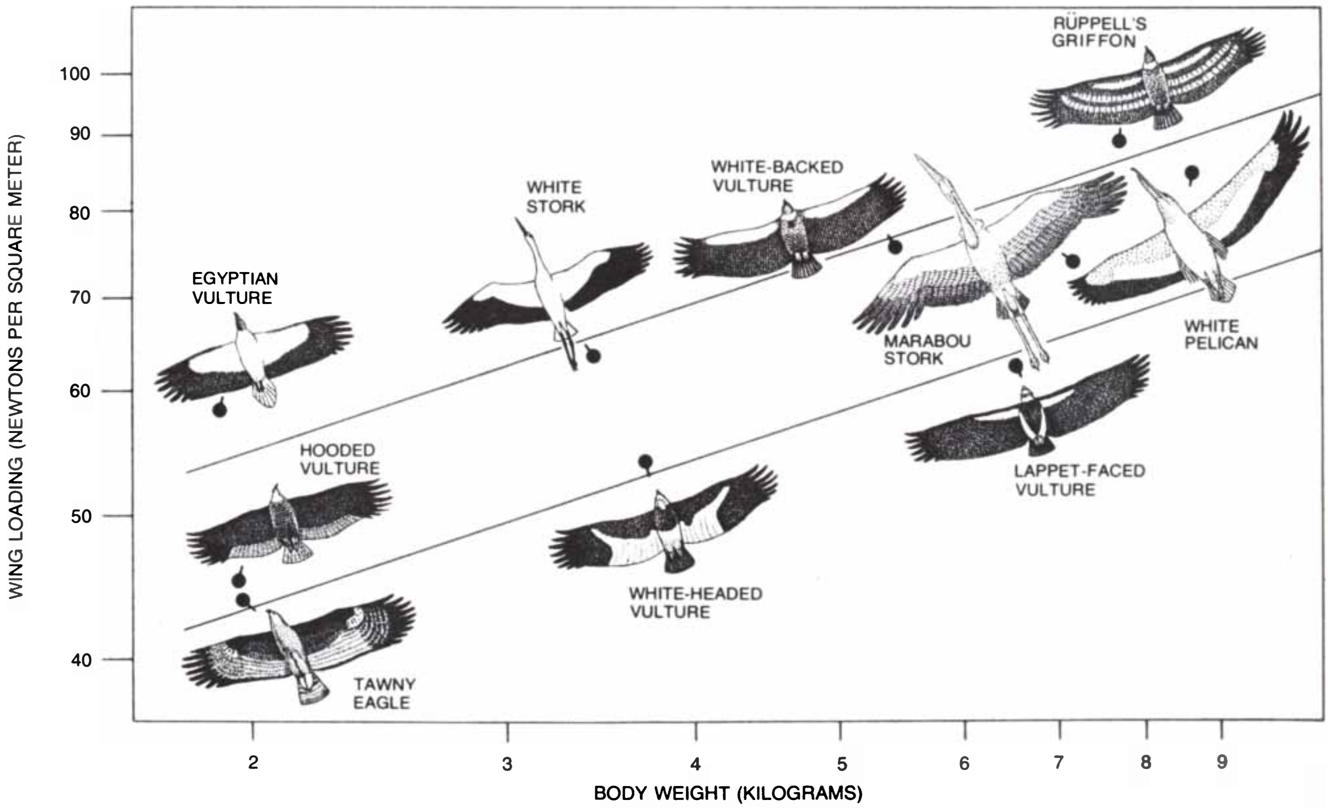
When the wing loadings of various birds are plotted against their mass on a double-logarithmic scale, the different vulture species segregate into two groups [*see bottom illustration on next page*]. The sedentary lappet-faced vultures and white-headed vultures have low wing loadings; they are specialized for being able to stay airborne in the weakest possible thermals. The griffons, being cross-country fliers, have compromised by having somewhat higher wing loadings.

Not much is known about the ecology

© 1973 SCIENTIFIC AMERICAN, INC



VULTURES' ADVANTAGE over scavenging quadrupeds when prey is sighted lies in being able to reach the carrion first. In this example the descent of a vulture in the distance (*right*) attracts the attention of a hyena and a lappet-faced vulture (*left*) to a carcass some 3.5 kilometers away. The vulture, targeting in at 70 kilometers per hour, reaches the carrion in three minutes, whereas the hyena, running at 40 kilometers per hour, needs 4.25 minutes to cover the same distance. A vulture flying 300 meters above the ground, as in this example, can reach any point 4.5 kilometers away in only six minutes and can get to closer points proportionately faster.



TEN SOARING BIRDS observed in East Africa fall mainly into two groups: five birds with a relatively heavy wing loading (*upper diagonal*) and four with a relatively light wing loading (*lower diagonal*). The wing loading of the 10th bird, the marabou stork, is intermediate on this double-logarithmic plot. The more lightly loaded birds, able to soar in thermals too small and weak for use by the others, hunt intensively over relatively small territories. The heavily loaded birds instead often fly cross-country for food.

© 1973 SCIENTIFIC AMERICAN, INC

of the two species of small vultures: the Egyptian vulture and the hooded vulture. Both frequent human habitations and garbage dumps, which the larger species do not. They also gather around dead animals and predator kills, and they tend to remain, picking up small scraps, after the bigger vultures have left. The Egyptian vulture's wing loading agrees with that of the high-loading group. The bird also resembles Rüppell's griffon in being a cliff-nester, although it does not form colonies. The hooded vulture, which falls in the low-loading group, sometimes gathers at carcasses in large numbers, but it is a solitary tree-nester.

Even in strong convection currents neither a bird nor a man-made glider can afford simply to glide along in one direction, relying on chance to bring it to the next thermal. All too often the ground is reached before a thermal is found. Thermals are mostly invisible, except for vigorous dust devils, but it is possible to increase the chance of encountering one by flying under a growing cumulus cloud or over a ground feature that looks likely to warm up differentially in the heat of the sun. A glider pilot's skill largely reflects his ability to notice such things, which in turn is based on his knowledge of atmospheric processes. Vultures and eagles are very good at finding the best lift, and they appear to make use of the visible signs in the same way the glider pilot does. For example, a common phenomenon in East Africa is the alignment of thermals into "streets" that are marked by lines of cumulus clouds. Here the thermals can be so close together that a bird or a glider pilot can fly from one to another, without circling and without losing height, for as much as 80 kilometers. Vultures regularly fly along thermal streets, and they will go out of their way to do so.

Vultures will also join other birds (or gliders) that are already climbing in a thermal, and often quite a large group will gather in this way. There is no "flock," however, in the sense of a continuing group. When the individual birds have gained enough height for their immediate needs, they leave the thermal separately in different directions, and the group disperses.

An entirely different kind of behavior is seen in the European white stork (*Ciconia ciconia*). This species is the longest-distance cross-country flier of them all, and it relies almost entirely on thermal soaring to make its annual migration between northern Europe and the southern half of Africa. On the wing loading diagram it falls in the high-loading group. In some years many hundreds of these birds spend the northern winter in East Africa rather than pressing on farther south. There they can often be seen traveling about in search of the best feeding areas.

The white storks rely on coordinated social behavior to increase their chance of finding thermals. It is rare to see one of these birds flying by itself; usually there are at least 20 of them together, and big flocks numbering several hundred individuals are common. When the storks are between thermals, they press on in the direction they want to go regardless of the appearance of the sky ahead. They will make detours to avoid rain showers but not to follow thermal streets or to fly under active-looking cumulus clouds. The members of the flock spread out laterally into a loose formation, and they fly steadily along on parallel headings. As soon as one part of the flock happens to fly into a thermal, the birds in that part start rising with respect to the rest. The others then alter their headings to converge on those birds that are rising fastest. Soon all the storks are concentrated in a spiraling column in the strongest part of the thermal, each of them constantly adjusting the position of its circle by reference to the relative rates of climb of its neighbors. At the top of the thermal all the birds leave together and once again spread out in their lift-searching formation. The net effect of this behavior is to increase the probability of finding thermals by searching a path 200 or 300 meters wide.

White storks tend to spend more time at the relatively high altitudes near cloudbase than vultures. The thinner air at high altitudes has much the same effect on performance as an increase of wing loading, and it increases cross-country speed provided that the thermals are large and strong. Glider pilots often continue their climb up into a cumulus cloud, but successful use of this tactic calls for a compass and at least one gyroscopic instrument. It is not quite clear whether storks can make an extended climb in cloud. They do enter cumulus clouds from the bottom, but on some occasions (and perhaps always) they stop circling just after they have entered the cloud and fly straight, skimming half in and half out of cloudbase, until they come out at the edge.

One of the most interesting species of East African soaring birds is the marabou stork (*Leptoptilos crumeniferus*). Marabous spend much of their time dabbling about in marshes and shallow water like other storks, but in addition they are partial to carrion, and they search for it like vultures. Their flight resembles that of white storks in some ways; for example, they sometimes travel in flocks. There is the curious difference, however, that although the marabous' formation on the straight glides is held just as steadily as the white storks', the marabou flock tends to spread out along the direction of travel rather than laterally. This behavior suggests that the marabous depend less than white storks on flock behavior for finding thermals. Supporting this notion is the fact that marabous often soar individually, like vultures, and will follow thermal streets.

The use of the flock as a thermal-searching unit is most highly developed in the white pelican (*Pelecanus onocrotalus*). On the interthermal glides the members of a pelican flock, which again may number several hundred individuals, spread out in an extended echelon, or multiple-*V*, formation, making a continuous line with no gaps. When the birds are circling, the entire flock turns in formation, so that from a distance one sees a periodic flash of white as they all catch the sun together. Pelican flocks travel in this way between the different lakes of the East African Rift Valley system.

The primary source of energy in soaring flight is of course that extracted from the motion of the atmosphere. For soaring birds, however, there is always some metabolic expense as well. The wings of the bird are not mechanically locked in the horizontal position but have to be held there by the pectoral muscles. All soaring birds, whatever their evolutionary origins, have a subdivided pectoralis muscle, and it appears that one division is a tonic muscle adapted for the function of sustaining tension. The metabolic cost of running this muscle is somewhat conjectural, but it is certainly much less than that needed for flapping flight. In small birds the actual saving is not very great, because the basal metabolism is large compared with the power needed for flight. In large birds the metabolic rate is relatively much less, and so a greater proportion of the total power can be saved by soaring. Some small birds, notably swifts, do soar, but soaring as the primary means of locomotion is chiefly characteristic of large species, most of which would have limited powers of flight without it. Like man, soaring birds extend their powers of locomotion by using a source of energy external to their own bodies; they are perhaps the only other group of animals that do so.

© 1973 SCIENTIFIC AMERICAN, INC

Slips of the Tongue

They are a good deal more than amusing (or embarrassing) errors of speech. The collection and analysis of such errors provides important clues to how speech is organized in the nervous system

by Victoria A. Fromkin

The Reverend William A. Spooner, dean and warden of New College, Oxford, is famous in the English-speaking world as the man who had a special talent for slips of the tongue in which two sounds of an intended utterance are transposed. Although it is not certain that he actually made slips of this type, many "spoonerisms" are legendary. "Work is the curse of the drinking classes," he is alleged to have said when he meant "Drink is the curse of the working classes." Among other well-known spoonerisms are (in an address to a rural audience) "Noble tons of soil" and (in chiding a student) "You have hissed all my mystery lectures. I saw you fight a liar in the back quad; in fact, you have tasted the whole worm." Perhaps the most endearing of these slips is "the queer old dean" for "the dear old queen."

Speech errors have been used in literature by such writers as Rabelais, Shakespeare, Schiller and George Meredith. Nearly 300 years before the transposition speech error became known as a spoonerism, Henry Peacham quotes in *The Compleat Gentleman* a man who said "Sir, I must goe dye a beggar" instead of "I must goe buy a dagger." In recent years humorous bloopers made by radio and television announcers have been published in books and even preserved on records. The general awareness of the regularity of the occurrence of speech errors is shown in a column by Herb Caen in the *San Francisco Chronicle* of March 7, 1972: "The Tuck-Fortner Report [newscasts] is off Channel 2, much to the relief of those who worry about spoonerisms. Oddly enough, it was Mike Tuck who committed the only near miss in the history of the program, introducing Banker Fortney Stark as 'Fartney Stork.' "

In *The Psychopathology of Everyday Life* Sigmund Freud attempted to show that "[such] disturbances of speech may be the result of complicated psychical influences, of elements outside the same word, sentence or sequence of spoken words." In discussing the unconscious forces that he postulated as the cause of speech errors, Freud speculated "whether the mechanisms of this [speech] disturbance cannot also suggest the probable laws of the formation of speech."

Karl Spencer Lashley, a pioneer in neurophysiology, regarded speech as the "window through which the physiologist can view the cerebral life." He regarded speech errors as evidence that behavior can only be accounted for by positing "a series of hierarchies of organization: the order of vocal movements in pronouncing the word, the order of words in the sentence, the order of sentences in the paragraph." Disordering of these hierarchical units, he said, may occur at any stage, which would account for the diversity of observed speech errors.

In spite of the universality of various types of speech error, it was not until the 19th century that scholars began to pay serious attention to such utterances as evidence for psychological and linguistic theories. Hermann Paul, a German philologist, was probably the first linguist to suggest that an examination of speech errors might provide important clues to one cause of language change. Other linguists have been interested in slips of the tongue as a means of finding out what it is we learn and store in our minds when we learn a language.

A person's knowledge of a language cannot be equated solely with the words and sentences he utters and understands. If all the utterances of a person, or a number of persons, were recorded for an hour, a day, a week, a month, a year or even a lifetime, the corpus of these utterances would not in itself constitute the language he speaks. No one book can contain a complete human language. It is highly unlikely that this English sentence will have been printed before: "The Watergate scandal was caused by green-skinned, three-headed, cloven-footed Martians dressed in pink tights who penetrated the top-secret files of the Pentagon." Whether or not it is true, the preceding sentence is a grammatical English sentence that can be understood by any person with a knowledge of the language, yet it could not have been included in an English-language book before I had written it.

What makes it possible for a person to produce and understand novel sentences? If we are to understand the nature of language, we must be able to explain this ability. It cannot be accounted for simply by listing all possible sentences; in principle the number of sentences is infinite. For any sentence of length n one can produce a sentence of length $n + 1$. For example: "This is the house that Jack built. This is the malt that lay in the house that Jack built. It is questionable that this is the malt that lay in the house that Jack built. I know that it is questionable that this is the malt that lay in the house that Jack built."

Given the finite storage capacity of the brain, one cannot store all possible sentences of a language. We can of course store the words of a language because they are finite in number. In no language, however, are sentences formed by putting words together at random. "Built Jack that house the is this" is not an English sentence. Furthermore, although the number of words in a language is finite, the speakers of a language have the ability to create and adopt new words, for example Brillo and Kleenex. But just as there are rules for well-formed sentences, so there are rules for well-formed words; "Glooper" could

© 1973 SCIENTIFIC AMERICAN, INC

be an acceptable word for a new product, but "nga" would never be used in English even though it is a perfectly good word in the Twi language of the Ashanti in western Africa.

Knowledge of a language must therefore include rules for the formation of words and sentences. In order to account for a speaker's ability to form a potentially infinite set of sentences and for his linguistic judgments concerning the well-formedness of words and sentences, linguistic theorists posit that what is learned in language acquisition is a grammar that includes a finite set of basic elements and a finite set of rules for their combination, including a recursive element to allow the formation of sentences of unlimited length [*see illustration on next page*]. Furthermore, there must be a hierarchy of such elements: discrete elements of sound (phonemes) combine in restricted ways to form syllables, which combine to form meaningful units (morphemes or words), which are combined to form phrases, which are combined into sentences [*see top illustration on page 113*].

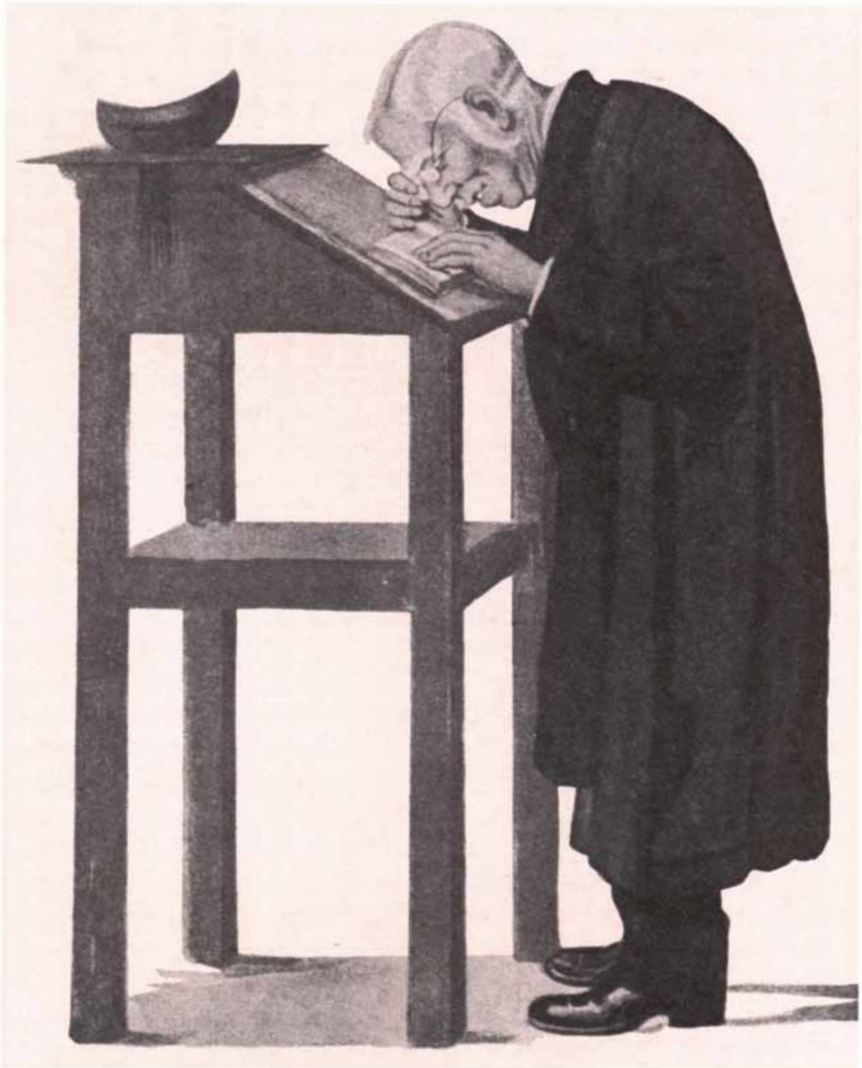
All attempts to describe language and to account for our linguistic abilities assume the discreteness of each of these linguistic units. Yet the sounds we produce and the sounds we hear when we are talking are continuous signals, and examination of the physical properties of these acoustic signals does not reveal individual discrete sounds, words or phrases [*see bottom illustration on page 113*]. It has been impossible, however, to account for our linguistic abilities without positing a grammar consisting of discrete units and rules. This has always been intuitively accepted, as is indicated by the ancient Hindu myth in which the god Indra is said to have broken speech down into its distinct elements, thereby creating language. The classical Greeks also recognized the difference between the continuous nature of speech and the discrete nature of language. The messenger of the gods, Hermes, is also the god of speech because he was always on the move. In Plato's *Cratylus* dialogue (the oldest extant philosophical essay dealing exclusively with language) one of Hermes' namesakes, Hermogenes, asks Socrates if language can be analyzed by taking it apart. Socrates answers that doing so is the only way one can proceed.

The reality of the discrete elements of language and their rules of combination cannot be found by looking into the brains of speakers. It is here that systematic errors of speech can yield useful evidence.

Looked at from the viewpoint of linguistic behavior or performance, speech can be considered a communication system in which the concept to be conveyed must undergo a number of transformations. The message is generated in the brain of the speaker, encoded into the linguistic form of the language being spoken and transformed into neural signals that are sent to the muscles of the vocal tract, which transform the message into articulatory configurations. The acoustic signal must then be decoded by the listener to recover the original message. Thus the input signal that presumably starts as a string of individual discrete sounds organized into phrases and words ends up as a semicontinuous signal that the receiver must change back into the original string of discrete units. The grammar that represents our knowledge of the language allows us to encode and decode an utterance.

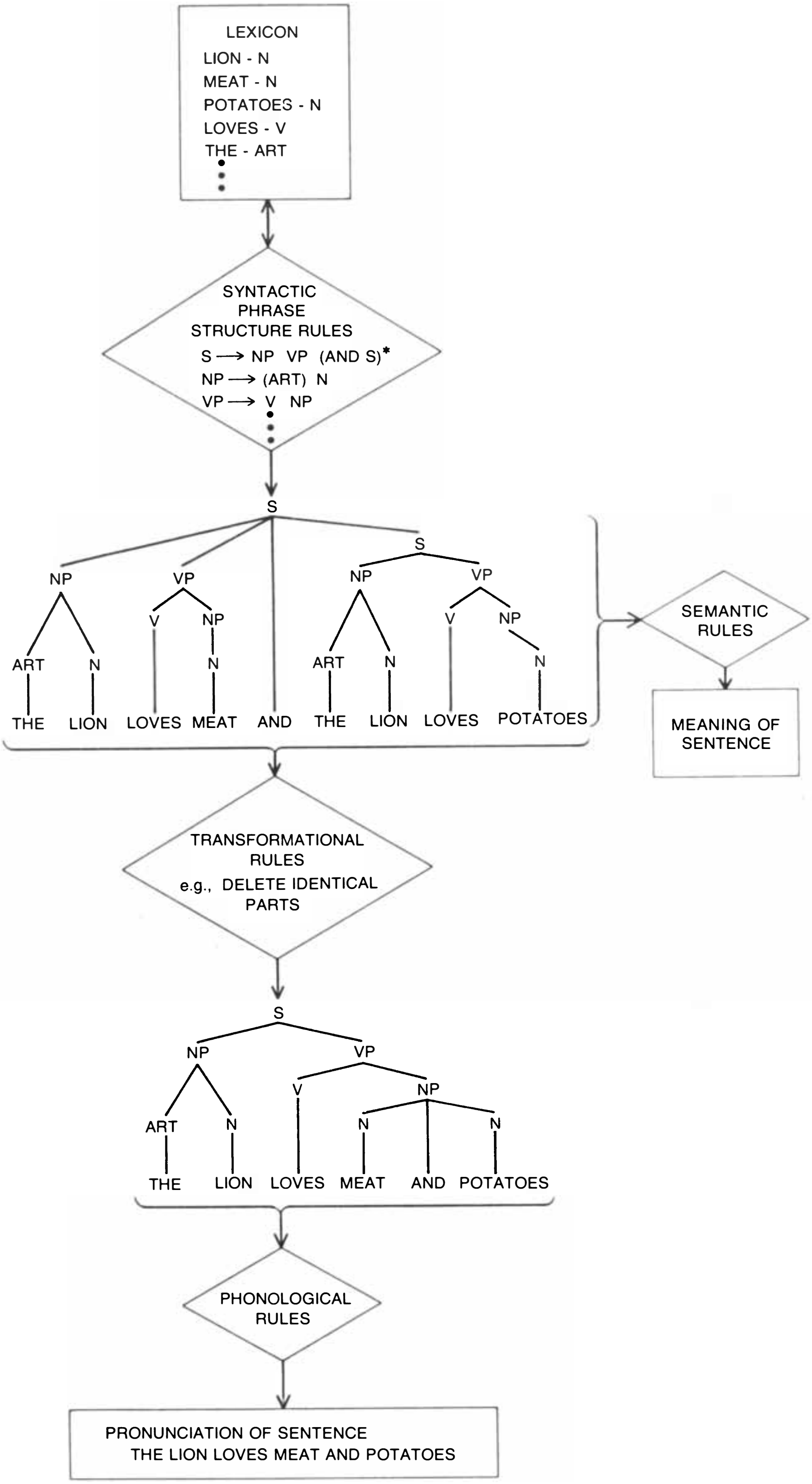
Difficulties are encountered in attempts to model the actual behavior of a speaker because the only phenomena in this communication system that can be examined are the semicontinuous muscular movements of the vocal tract, the dynamic articulatory configurations and the acoustic signals. As in other communication systems, however, noise in any of the stages or connecting channels involved in speech can distort the original message. Most errors of speech would seem to be the result of noise or interference at the stage of linguistic encoding. Such errors can tell us something about a process that is not otherwise observable, and about the abstract grammar that underlies linguistic behavior.

Over the past five years I have re-



WILLIAM A. SPOONER was famous for his reputed lapses of speech, in which he would transpose two or more sounds, for example "blushing crow" for "crushing blow." Such speech errors are now called spoonerisms. This caricature of Spooner is by Sir Leslie Ward, whose work appeared in *Vanity Fair* under the pseudonym of Spy. Spooner was born in 1844 and died in 1930. A clergyman, he served as dean and warden of New College, Oxford.

© 1973 SCIENTIFIC AMERICAN, INC



GRAMMAR OF A LANGUAGE consists of a finite set of basic elements (lexicon) and a finite set of rules for combining the basic elements such as nouns (*N*), verbs (*V*), articles (*ART*) and so forth. In order to generate a sentence (*S*), noun phrases (*NP*) and verb phrases (*VP*) are combined according to syntactic rules. The semantic rules determine whether or not the sentence generated is meaningful. Transformational rules enable a speaker to permute the sentence without altering its meaning. Phonological rules determine how the sentence is articulated. Errors at various stages can result in production of a deviant sentence, for example "The meat loves lion and potatoes" or "The lion loves peat and motatoes."

corded more than 6,000 spontaneous errors of speech. In order to prevent the inclusion of errors of perception each item has been attested to by at least one other person. The deviant utterances that I give as examples hereafter are taken from this corpus.

According to all linguists who have analyzed spontaneous speech errors, the errors are nonrandom and predictable. Although one cannot predict when an error will occur or what the particular error will be, one can predict the kinds of error that will occur. Such predictions are based on our knowledge of the mental grammar utilized by speakers when they produce utterances. For example, many errors involve the abstract, discrete elements of sound we call phonemes. Although we cannot find these elements either in the moving articulators or in the acoustic signal, the fact that we learn to read and write with alphabetic symbols shows that they exist. In addition, if these discrete units were not real units used in speaking, we could not explain speech errors in which such segments must be involved. Substitution of one segment for another occurs: a later phoneme may be anticipated ("taddle tennis" instead of "paddle tennis"); a phoneme may persevere ("I can't cook worth a cam" instead of "I can't cook worth a damn"), or two segments may be transposed ("Yew Nork" instead of "New York"). Such segmental errors can involve vowels as well as consonants ("budbegs" instead of "bedbugs"). Moreover, two consonants that form a cluster can be either split or moved as a unit ("tendahl" instead of "Stendahl" and "foon speeding" instead of "spoon feeding") [*see top illustration on page 114*]. Such errors demonstrate that even though we do not produce discrete elements of sound at the stage of muscular movement in speech, discrete segments do exist at some earlier stage.

It is not the phonetic properties of sounds alone that determine the more abstract representation of phonemes. Sounds such as those represented by the "ch" in "church" and the "j" and "dge" in "judge" are clusters of two consonants on the phonetic level. This is shown by the fact that in the regular tempo of conversation the following two sentences will be pronounced identically by most people: " 'Why choose,' she said" and " 'White shoes,' she said." Yet linguists have posited that in words such as "choose," "church," "chain" and "judge" these phonetic clusters are single phonemes. The fact that the "ch" and "j" sounds in such words are never split in

© 1973 SCIENTIFIC AMERICAN, INC

SENTENCE	[THE WILLOWY LIONESS LOVES THE WIRY LION]
PHRASES	[[THE WILLOWY LIONESS] [LOVES [THE WIRY LION]]] NOUN PHRASE — VERB PHRASE — NOUN PHRASE
WORDS	[[[THE] [WILLOWY] [LIONESS]] [[LOVES] [[THE] [WIRY] [LION]]]] ARTICLE ADJECTIVE NOUN VERB ARTICLE ADJECTIVE NOUN
MORPHEMES	[[[THE] [WILLOW + Y] [LION + NESS]] [[LOVE + S] [[THE] [WIR + Y] [LION]]]]
PHONEMES	TH + E + W + I + LL + OW + Y + L + I + O + NN + E + SS + L + O + VE + S + TH + E + W + I + R + Y + L + I + O + N

HIERARCHY OF LINGUISTIC ELEMENTS is depicted. A sentence is composed of noun phrases and verb phrases. Phrases are made up of phrases or individual words and words in turn consist of morphemes, the basic units of meaning. Morphemes are made up of discrete elements of sound called phonemes. Spelling of the phonemes does not represent their sounds in a one-to-one fashion.

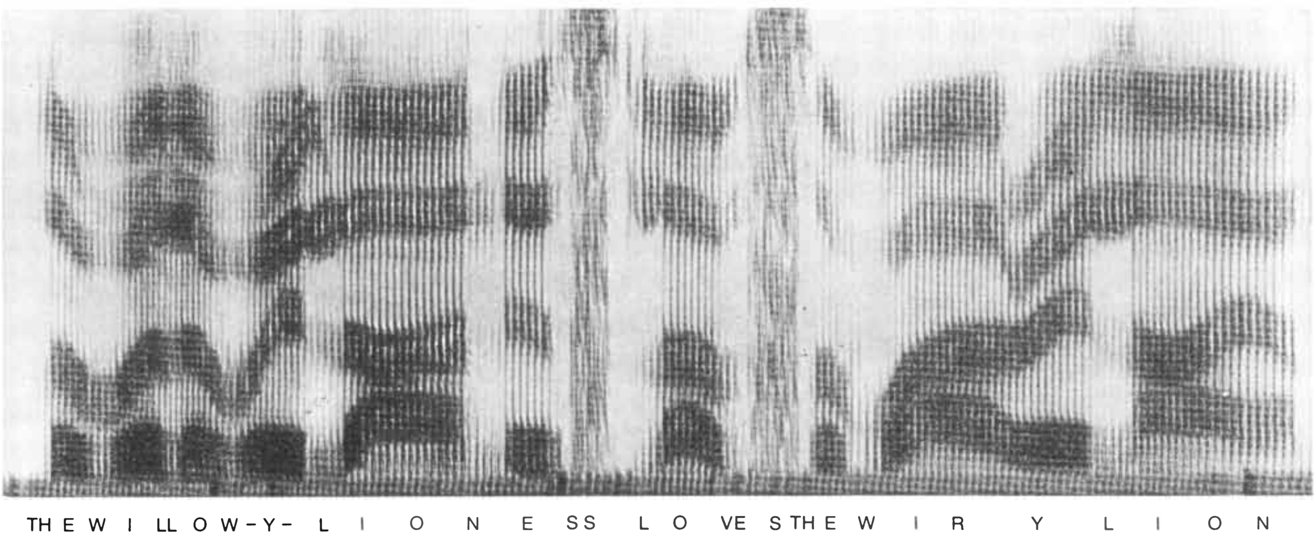
speech errors, although other consonant clusters such as "sp" and "gl" are, bears out this analysis. When these sounds are involved in speech errors, they always move as a single unit, as in "chee cane" instead of "key chain" and "sack's jute" instead of "Jack's suit." In cases where they represent two discrete phonemes, however, they can be independently disordered as in "Put the white boos in the shocks" for "Put the white shoes in the box." Speech errors therefore support the abstract analysis of linguists.

Segmental errors are constrained by rules of grammar that dictate the allowable sequence of sounds. Although "slips of the tongue" can be incorrectly uttered as "stips of the lung," it cannot be uttered as "tlip of the sung" because the sound "tl" is not allowed as the beginning of an English word. It is not the inability to say "tl" that inhibits such errors; we can say it easily enough. Rather it is a grammatical constraint in the English language. It is in this sense that speech errors are predictable and nonrandom.

Phonemic segments have been classified into intersecting sets dependent on shared properties. Thus the sounds that are produced by a closure of the lips, such as /p/, /b/ and /m/ (the diagonals are used to distinguish the sounds from the alphabetic letters), are classified as labials. The sounds produced by raising the tip of the tongue to the top of the teeth, such as /t/, /d/ and /n/, are alveolars. The sounds produced by raising the back of the tongue to the soft palate, such as /k/, /g/ and the /ng/ in "sing," are velars.

Such classes have been used to describe the sounds of all languages, but they had no basis in linguistic theory until recently. Roman Jakobson suggested a set of universal features that could be used to describe the sound system of all languages. These features, somewhat revised, were then incorporated into the theory of generative phonology by Morris Halle, who developed them further in collaboration with Noam Chomsky. It was shown that if segments are not viewed as being composites of features in the grammar of a language, certain regularities would be obscured, and the grammar written by the linguist would fail to correctly model a speaker's linguistic knowledge.

There has been some debate in linguistic circles over whether or not these universal phonetic features have any psychological reality. Some argue that they merely provide an elegant description of the sound system and do not exist as elements in the mental grammar of speakers. Just as speech errors show that discrete segments are real units, so also do they attest to the reality of phonetic features. Among the features posited in the universal set are the binary-valued features: voiced/voiceless and nasal/oral. Sounds produced with vocal-cord vibrations are voiced; sounds produced with an open glottis are voiceless. Nasal sounds are produced by lowering the soft palate to allow some air to escape through the nose while making a sound; oral sounds are produced by raising the soft palate to block off the nasal passage. In speech errors a single feature can be



SOUND SPECTROGRAM of the utterance "The willowy lioness loves the wiry lion" shows the speech sounds as a series of bands with the lowest sound frequencies at bottom and the highest frequencies at top. Note that the acoustical signal is semicontinuous.

© 1973 SCIENTIFIC AMERICAN, INC

ERRORS	EXAMPLES	
CONSONANT ERRORS		
ANTICIPATION	A READING LIST	A LEADING LIST
	IT'S A REAL MYSTERY	IT'S A MEAL MYSTERY
PERSEVERATION	PULLED A TANTRUM	PULLED A PANTRUM
	AT THE BEGINNING OF THE TURN	AT THE BEGINNING OF THE BURN
REVERSALS (SPOONERISMS)	LEFT HEMISPHERE	HEFT LEMISPHERE
	A TWO-PEN SET	A TWO-SEN PET
VOWEL ERRORS		
REVERSALS	FEET MOVING	FUTE MEEVING
	FILL THE POOL	FOOL THE PILL
OTHER ERRORS		
ADDITION	THE OPTIMAL NUMBER	THE MOPTIMAL NUMBER
MOVEMENT	ICE CREAM	KISE REAM
DELETION	CHRYSANTHEMUM PLANTS	CHRYSANTHEMUM P ANTS
CONSONANT CLUSTERS SPLIT OR MOVED	SPEECH PRODUCTION	PEACH SEDUCTION
	DAMAGE CLAIM	CLAMMAGE DAME

SEGMENTAL ERRORS IN SPEECH can involve vowels as well as consonants. Some typical types of substitution of sounds are shown. Such errors provide evidence that the discrete phonetic segments posited by linguistic theory exist in the mental grammar of the speaker.

	VOICED ORAL	VOICED NASAL	VOICELESS ORAL
LABIALS	BAT	MAT	PAT
	TAB	TAM	TAP
	BEAT	MEAT	PEET
	BEST	MESSED	PEST
	LIB	LIMB	LIP
	CAB	CAM	CAP
	AMBLE	AMBLE	AMPLE
ALVEOLARS	DIP	NIP	TIP
	CAD	CAN	CAT
	CANDOR	CANNER	CANTOR
	DOLE	KNOLL	TOLL
	DOOR	NOR	TORE
	RAID	RAIN	RATE
	RIDE	RHINE	RIGHT
VELARS	GIRL	*	CURL
	GREASE	*	CREASE
	GUARD	*	CARD
	LUG	LUNG	LUCK
	SAG	SANG	SACK
	ANGLE	ANGLE	ANKLE
	FINGER	SINGER	SINKER

LANGUAGE SOUNDS are categorized by certain universal features such as voiced/voiceless and nasal/oral. Some examples of voiced, oral, nasal and voiceless sounds are shown here. In speech errors a single feature may be disordered while the other features remain as intended. For example, when a person says "cedars of Lemadon" instead of "cedars of Lebanon," the nasality features of the /b/ and the /n/ are reversed. The intended oral labial /b/ becomes a nasal labial /m/ and the intended nasal alveolar /n/ becomes an oral alveolar /d/. Such reversal suggests that these features must also exist in mental grammars.

disordered while all other features remain as intended; for example, "clear blue sky" was transposed to "glear plue sky." There was a voicing switch: the voiceless velar /k/ became a voiced /g/ and the voiced labial /b/ became a voiceless /p/ [*see bottom illustration at left*].

Unless the individual features have an independent existence in the mental grammar such errors cannot be accounted for. Prior to or simultaneous with the stage in the production process when neural signals are sent to the appropriate muscles, the specifications for voicing or not voicing must have been disordered. Similar transpositions can occur with nasal/oral features.

Speech errors involve more than sound units. In all languages different meanings are expressed by different strings of phonemes. That is, knowing a language enables one to associate certain sounds with certain meanings. One learns the vocabulary of the meaningful units of a language by learning not only the sounds but also what the sounds mean. Since the words of a language can consist of more than one meaningful element, words themselves cannot be the most elemental units of meaning. "Tolerant," "sane," "active" and "direct" are all English words; so are "intolerant," "insane," "inactive" and "indirect." The latter set includes the meanings of the former plus the meaningful unit "in-," which in these instances means "not."

In learning a language we learn these basic meaningful elements called morphemes and how to combine them into words. Speech errors show that there can be a breakdown in the application of the rules of word formation. The result is an uttered word that is possible but nonexistent. For example, "groupment" was said instead of "grouping," "intervenient" for "intervening," "motionly" for "motionless," "ambigual" for "ambiguous" and "bloodent" for "bloody." It is clear from such examples that rules for word formation must exist; otherwise there is no way to explain the deviant word forms. Obviously we do not have such words stored in our mental dictionary. Speech errors suggest that we learn morphemes as separate items and the rules for their combination. This ability enables us to create new words.

Many morphemes have alternative pronunciations depending on their context. The indefinite-article morpheme in English is either "a" or "an" depending on the initial sound of the word that follows: a coat, a man, an orange coat, an old man. This rule of language depends

© 1973 SCIENTIFIC AMERICAN, INC

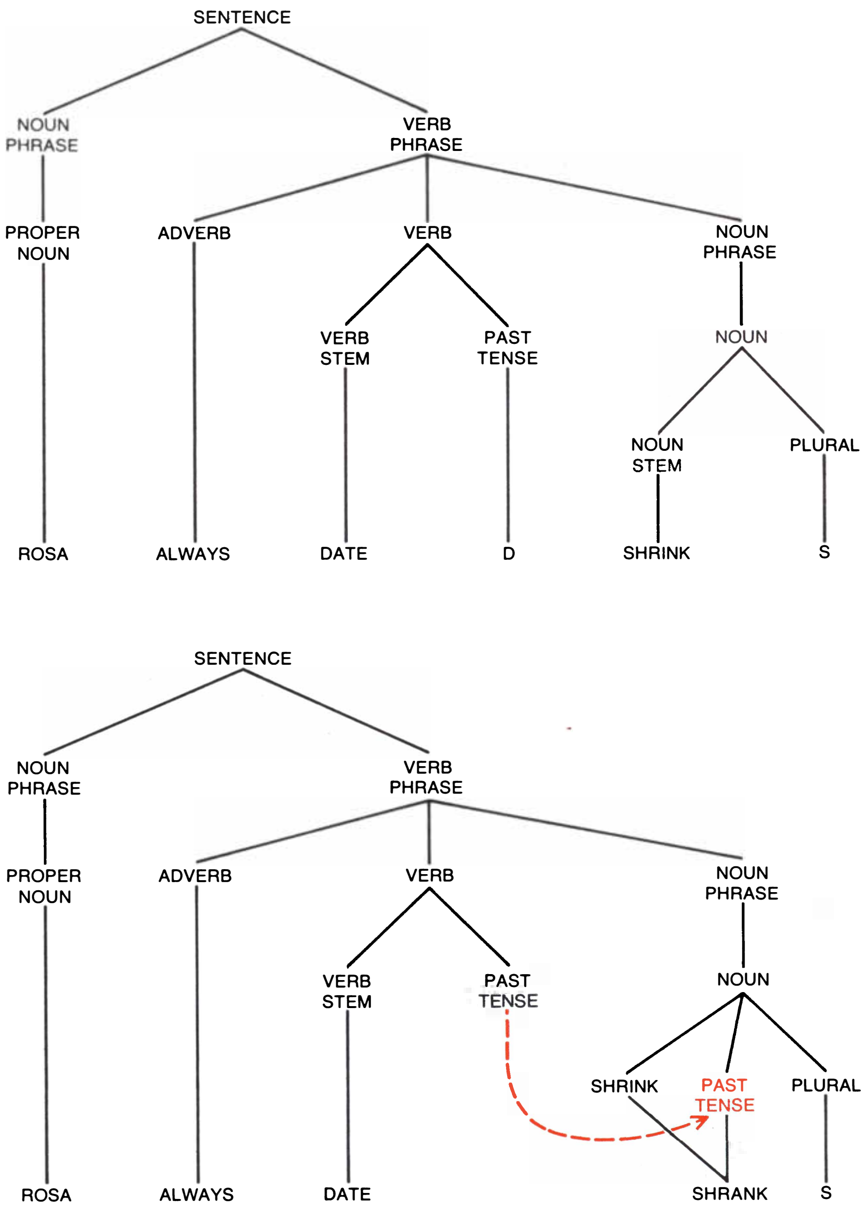
on the morpheme and not on the sound. We do make the "a" sound before a vowel ("America is") and the "an" sound before a consonant ("Roman court"). But errors such as "an istem" for "a system" or "a burly bird" for "an early bird" show that when segmental disordering occurs that changes a noun beginning with a consonant to a noun beginning with a vowel, or vice versa, the indefinite article is also changed so that it conforms to the grammatical rule. The rule also operates when entire words are disordered, as when "an example of courage" was produced as "a courage of example."

This operation is accomplished automatically, and such errors tell us something about the ordering of events in the brain. The disordering of the words or the phonemic segments must occur before the indefinite article is specified, or alternatively the rule that determines the indefinite article must reapply or feed back after the disordering has occurred. Furthermore, the monitoring function of the grammatical rule must specify the sounds of the indefinite article prior to the stage where neural signals are sent to the vocal muscles, since the rule does not change a structure such as "Rosa is" to "Rosan is." The existence of similar rules, called morphophonemic rules, and the ordering of their application are shown over and over again in speech errors.

The errors I have cited show that when we speak, words are structured into larger syntactic phrases that are stored in a kind of buffer memory before segments or features or words are disordered. This storage must occur prior to the articulatory stage. We do not select one word from our mental dictionary and say it, then select another word and say it. We organize an entire phrase and in many cases an entire sentence. This process can be demonstrated by the examination of errors in disordered phrases and sentences: "Nerve of a vergeous breakdown" instead of "Verge of a nervous breakdown"; "Seymour sliced the knife with a salami" instead of "Seymour sliced the salami with a knife"; "He threw the window through the clock" instead of "He threw the clock through the window"; "I broke the whistle on my crotch" instead of "I broke the crystal on my watch."

If these phrases had not been formed in some buffer storage, the transpositions could not have occurred. Furthermore, the intonation contour (stressed syllables and variations in pitch) of the utterance often remains the same as it is in the intended phrase even when the words are disordered. In the intended utterance "Seymour sliced the salami with a knife" the highest pitch would be on "knife." In the disordered sentence the highest pitch occurred on the second syllable of "salami." The pitch rise is determined by the grammatical structure of the utterance. It must be constructed prior to articulation and is dependent on the syntactic structure rather than on the individual words. Thus syntactic structures also are shown to be units in linguistic behavior.

When words are exchanged, they are usually exchanged with words of the same grammatical category; nouns are exchanged with nouns, adjectives with adjectives and so on. This phenomenon shows that words are represented in memory along with their grammatical characteristics. Indeed, when different grammatical classes are involved in a speech error, there is often a restructuring of the words to correct what otherwise would be syntactically incorrect. "I think it is reasonable to measure with care" was not transformed into "I think it is care to measure with reasonable" but rather into "I think it is careful to measure with reason." Such corrections



DISORDERING OF SYNTACTIC ELEMENTS can result in transformation of a sentence such as "Rosa always dated shrinks" into "Rosa always date shranks." The syntactical hierarchical structure of the intended sentence is shown in the top diagram. The error seems to have been caused by a disordering of the past-tense element, which mistakenly became attached to the noun node, as the bottom diagram illustrates. The shift probably occurred because "shrink" is a verb as well as a noun. After the disordering the phonological rules produced "shrank" and since the plural element was not disordered, "shranks" resulted.

© 1973 SCIENTIFIC AMERICAN, INC

Advice to youth on 1974 Science Fairs:

Winning a prize is more satisfying than not winning a prize.

Judges favor projects they can understand.

Well-planned photography may help them understand.

Now—not next spring—is the time to plan.

We offer helpful hints.
Write Dept. 841, Kodak,
Rochester, N.Y. 14650.

Kodak

Any questions?

The ADC-XLM.
A significant difference.

The phono cartridge, the smallest and perhaps the most critical element in a home music system, can make a significant difference in your perception of recorded music.

If it does its job well, it can convey a startlingly real sense of the original musical experience. If it doesn't, you end up with a pale, distorted imitation. Or worse, a permanently damaged record.

For only the cartridge comes into direct contact with the fragile record groove and translates its microscopic undulations into intelligible musical sounds.

For years, the experts, audio professionals, have relied upon ADC cartridges to provide faithful record reproduction and protect their valuable collections.

Today, more than ever, the choice of the experts is the new ADC-XLM, a cartridge of unmatched performance and reliability.

At a modest $50, it can make a significant difference in your own music system.

For complete information and reprints of independent test lab evaluations write: Audio Dynamics Corporation, Pickett District Road, New Milford, Conn. 06776.

Audio Dynamics Corporation

reveal that there is constant monitoring at different stages of the speech-production chain. Although some errors emerged, a compounding of errors does not usually occur. In speech errors we never find a total disruption of the permissible syntactic structure, such as "Breakdown nervous a of verge."

But syntactic rules can be broken or misapplied, and syntactic elements can be disordered. Misstatements such as "If he swimmed in the pool nude" and "The last I knowed about it" indicate that words are stored in a basic form. To produce a past tense we do not select a stored past-tense form of a word but apply the rule of past-tense formation to the elemental morpheme. The regular rule for past-tense formation must have been wrongly applied to produce "swimmed" and "knowed." In these two instances the mistakes recorded were made by university professors who do not regularly say "swimmed" or "knowed." The reality of such rules is also shown by the forms produced by children before they have learned that there are exceptions to the rules they have generalized. Children regularly say "swimmed," "knowed," "bringed" and "singed" even though they have never heard these words spoken. Language acquisition involves constructing rules rather than merely imitating what one hears. It is these rules that may be wrongly applied in speech errors [*see illustration on preceding page*].

The negation element in sentences is another example of mistaken rule application: "I regard this as imprecise" came out "I disregard this as precise." The error shows that in producing a negative sentence a speaker must generate an abstract negative element that is ordered in the string according to the rules of the language. The negative element in this sentence is independent of the particular words and can be disordered just as other units can be disordered. The sentence also shows that phonologically the negative element must be determined after the structure of the sentence is imposed. Only then can the negative plus "regard" be realized as either "do not regard" or as "disregard." A model of linguistic performance cannot posit a chain process of word selection; a hierarchical order exists.

Speech errors can involve entire words. A common type of error is a blend of two words: "shrig soufflé" for "shrimp and egg soufflé," "prodeption of speech" for "production and perception of speech." A more interesting blend, called a portmanteau word by Lewis Carroll, combines two words with sim-

© 1973 SCIENTIFIC AMERICAN, INC

ilar meanings into one: "instantaneous" and "momentary" into "momentaneous," "splinters" and "blisters" into "splisters," "shifting" and "switching" into "swifting" and "edited" and "annotated" into "editated." This type of error reveals that the idea of the message is generated independently of the particular words selected from the mental dictionary to represent these concepts. A speaker seems to match the semantic features of words with the semantic notion to be conveyed. When there are alternatives, synonyms or near-synonyms, the speaker may be unsure of what word will best express his thoughts and in the moment of indecision may select two words and blend them.

The involuntary substitution of one word for the intended word shows that the meaning of a word is not an indissoluble whole. The semantic representation of a word is a composite of hierarchically ordered semantic features. In word selection one finds that the substituted and the original word often fall into the same semantic class: "blond eyes" for "blond hair," "bridge of the neck" for "bridge of the nose," "When my tongues bled" for "When my gums bled," "my boss's husband" for "my boss's wife" and "There's a small Chinese—I mean Japanese—restaurant."

Some errors show that antonyms are substituted: "like" for "hate," "big" for "small," "open" for "shut" and "hot" for "cold." Whatever the psychological causes of such slips, they show the ways we represent language in our stored mental grammar. The person who substituted "dachshund" for "Volkswagen" apparently selected a word with the semantic features "small, German." In the selection he underspecified the features to be matched.

There are many other varieties of speech error. All of them must be accounted for in a model of speech production. By positing the same units and rules required in a linguistic grammar, many of the errors can be categorized and explained. Speech therefore does provide a window into the cerebral life. By carefully studying speech errors we can get a view of the discrete elements of language and can see the grammatical rules at work. We also can look into the mental dictionary and get some notion of the complexity of the specifications of words and how the dictionary is organized. Throughout history men have speculated, theorized and conjectured about the nature of human language. Speech errors provide good data for testing some of these theories.

He said:
I just want you to know that the bathrooms in this hotel are the nicest I've ever seen.

We said:
Did you watch the Today Show on the TV in your bathroom this morning while you shaved?

He said:
How did you know?

We said:
We made a very careful study of what businessmen really like, sir.

The Stanford Court.
Young, sentimental, graceful and human.
An original, just like San Francisco.

The STANFORD COURT on San Francisco's Nob Hill
(415) 989-3500

For reservations dial toll free in the U.S. (800) 227-4248, in California (800) 622-0812. Or call Quick Reservations in New York, Chicago or Los Angeles. *Hotel Representatives Inc. New York (212) 838-3110. *H.R.I.—the leading hotels of Europe and World Wide Associates.

FOR GREATER RELAXATION, CONCENTRATION,
... listen to your Alpha and Theta brainwaves!

Do it with an amazing biofeedback monitor. This ultra-sensitive sensor detects brain signals, lets you monitor (hear and **see!**) your Alpha and Theta brainwaves. Great aid to relaxation, concentration. This portable (8 x 3 x 4") lightweight (24 oz.) metal unit has a unique electrode headband to slip on or off in seconds without messy creams or solutions. Hooked to amplifier, it filters brainwaves, and signals an audible beep for each Alpha or Theta wave passed. You get both audio and visual (L.E.D.) feedback with this reliable, completely safe unit. It operates on two 9v transistor batteries, offers features comparable to many costlier models. A comprehensive instruction booklet is included.

Order No. 1635 S JUST $124.50 Ppd.

YOU MUST BE DELIGHTED!
EVERYTHING EDMUND SELLS HAS A 30-DAY MONEY-BACK GUARANTEE. Return it if you aren't delighted.

GIANT FREE CATALOG!
NEW! 164 PAGES—OVER 4500 UNUSUAL BARGAINS FOR HOBBYISTS, SCHOOLS, INDUSTRY . . . JUST CHECK COUPON!

EDMUND SCIENTIFIC CO
300 Edscorp Bldg., Barrington, N.J. 08007
America's Greatest Science • Optics • Hobby Mart
Helping to develop America's Technology for over 30 years.

COMPLETE AND MAIL COUPON NOW
EDMUND SCIENTIFIC CO.
300 Edscorp Bldg., Barrington, N.J. 08007
Send me: ____ Biofeedback Trainer(s) No. 1635 S ea. @ $124.50
Handling, ea. .50
Encl is ☐ check ☐ M.O. in amount of $ ____
( ) Send FREE 164-Page catalog "S"
Name ____
Address ____
City ____
State ____ Zip ____

© 1973 SCIENTIFIC AMERICAN, INC

MATHEMATICAL GAMES

On expressing integers as the sum of cubes and other unsolved number-theory problems

by Martin Gardner

In 1909 David Hilbert, the noted German mathematician, proved a lucky guess about numbers that had been made 139 years earlier by an English algebraist, Edward Waring. Hilbert's proof, one of his great achievements, has led to significant developments in number theory and has raised a myriad of fascinating related questions. Many of the questions, unsolved to this day, are so easy to understand, and so amenable to amateur empirical research by anyone with tables of powers and a desk computer, that perhaps a reader of this department will be the first to lay some of them to rest.

It all started in 1770 when Waring, in his book *Meditationes Algebraicae*, made the following conjecture: Every positive integer (he said in substance) can be expressed as the sum of no more than n positive kth powers, the value of n being a function of k. He stated that n equals 4 for squares, 9 for cubes and 19 for fourth powers, which is to say that every integer is the sum of no more than four squares or nine cubes or 19 fourth powers. It seems unlikely that Waring, a mathematician of middling ability, had any powerful, secret techniques for proving his conjecture even for squares and cubes. More likely the values he gave for squares, cubes and fourth powers were just plausible surmises supported by little empirical evidence.

At about the same time that Waring recorded his conjecture his value of $n = 4$ for squares was verified. Fermat had believed this "four-square theorem" to be true, but Lagrange was the first to prove it and Euler soon simplified Lagrange's proof. The proofs are elementary but not short. Readers interested in working through a proof will find one clearly explained in *The Enjoyment of Mathematics,* by Hans Rademacher and Otto Toeplitz.

Hilbert's 1909 proof of Waring's general theorem was merely an existence proof; it gave no procedure for calculating the minimum number of kth powers. The proof, ingenious but difficult, was later improved in many ways. The simplest version, by a Russian number theorist, Y. V. Linnik, is the last "pearl" in a marvelous little book by A. Y. Khinchin called *Three Pearls of Number Theory*. Linnik's proof is so elementary, Khinchin says, that any good mathematician can master it in a mere three weeks of concentrated study.

As soon as mathematicians were convinced by Hilbert that Waring's theorem was true, they began searching in earnest for a formula that would give the minimum number of kth powers. The symbol $g(k)$, or "little gee" as it became known, was adopted as the symbol for this set of numbers. Euler had easily shown that the formula,

$$[(3/2)^k] + 2^k - 2\,,$$

where brackets indicate that the inside expression is rounded down to the nearest integer, gives a lower bound for $g(k)$. Mathematicians had long suspected that this formula is also an *exact* expression for $g(k)$. The suspicion was strengthened soon after Hilbert published his proof, when it was shown that $g(3)$ is indeed 9, as the formula predicts and as Waring had correctly guessed. That $g(4)$ equals 19 has not yet been proved, but that $g(5)$ equals 37 was established in 1964 by Jing-jun Chen.

Since 1964 the value of "little gee" for $k = 6$ and all higher values has been shown to conform to Euler's formula for all k from 6 through 200,000. There are strong grounds for believing that no higher k values violate the formula. It has been known since 1957 that there is at most only a finite number of violations for k greater than 5, but the proof does not tell how to find such violations if indeed they exist. Most mathematicians today who have worked on Waring's problem are convinced that Euler's formula holds for all k even though it has not been completely proved.

Much harder to pin down are the values of "big gee," or $G(k)$, the symbol for the smallest number of kth powers needed to express an infinite class of positive integers. In the case of squares the value of "big gee" was well known in Euler's day. It is 4, the same as the value of "little gee." It is not hard to show that integers of the form $4^a\ (8x + 7)$, where a and x are any non-negative integers, require four squares to express them as a sum. The lowest such integer is 7, and the series continues 15, 28, 60, ...

For cubes the situation is enormously more complicated; indeed, the value of $G(3)$ is far from known. Number theorists had long been puzzled by the fact that 23 and 239 were the only integers they could find that required as many as nine cubes to express them. (For example, 23 is the sum of the cubes of 2, 2, 1, 1, 1, 1, 1, 1, 1.) In 1939 Leonard Eugene Dickson proved an astonishing fact that among the infinity of integers only 23 and 239 require nine cubes. All integers above 239 can be expressed as the sum of eight or fewer cubes. Hence $G(3)$ is no higher than 8.

The value of $G(3)$ was soon lowered to 7 or less when it was established that only 15 integers require eight cubes: 15, 22, 50, 114, 167, 175, 186, 212, 213, 238, 303, 364, 420, 428 and 454. Beyond 454 all integers are the sums of seven or fewer cubes.

"Big gee" for cubes is probably smaller than 7, but no one is sure. The largest number known to require seven cubes is 8,042 (the sum of the cubes of 19, 10, 4, 4, 3, 3, 1). It is known that at least four cubes are needed for every integer. The value of $G(3)$, therefore, is either 4, 5, 6 or 7. If the first figure is correct, as some number theorists hope, it means that there is a largest integer beyond which all integers can be expressed as the sum of no more than four positive cubes.

An infinite number of integers can, of course, be expressed as the sum of one, two or three cubes. Do you remember the famous story about G. H. Hardy and his Indian friend Srinivasa Ramanujan? When Hardy visited Ramanujan in a hospital and told him that he had been taken there in a taxicab numbered 1729, an "uninteresting number," Ramanujan promptly responded that it was by no means uninteresting. It was the smallest integer that could be expressed as the sum of two cubes in two different ways. (1,729 is the sum of the cubes of 10 and 9, and 12 and 1.)

Many generalizations and variations of Waring's problem have been proposed and the literature on such questions is voluminous. One of the oldest and most obvious variants is to allow negative powers as well as positive. The first im-

© 1973 SCIENTIFIC AMERICAN, INC

portant analysis of the problem was a 1934 paper by Hardy's associate E. M. Wright, now president of the University of Aberdeen. (He and Hardy coauthored the classic *Introduction to the Theory of Numbers.*) Wright titled his paper "An Easier Waring's Problem," and it has been called that ever since in spite of the fact that finding values for $g(k)$ turned out to be incredibly difficult. Wright called it "easier" because it is easier to prove that $g(k)$ exists. Of course this follows immediately from Hilbert's 1909 proof, but Wright meant that, aside from the proof of Waring's problem, the existence of $g(k)$ when negative powers are allowed is much easier to obtain directly. But calculating $g(k)$ for the "easier" variant is quite a different matter. To this day it is known only for squares, in contrast to Waring's problem, where it is known for all values of k through 200,000 except for the stubborn case of fourth powers. "I had thought myself of writing a short expository article sometime on the 'easier' Waring problem," Wright said in a letter when I wrote to him recently for information, "to acknowledge quite how absurd my title for it has turned out to be."

The case for squares is trivial. An elementary application of the calculus of finite differences is sufficient to establish that $g(k)$ equals 3 for the easier problem. As shown in the top illustration on this page, first put down a row of consecutive squares beginning with 1. The next row gives the differences between each adjacent pair of squares. Note that this row consists of consecutive odd numbers. It is clear that every odd number is the difference between two squares. Equally obvious is the fact that every even number can be expressed as the difference between two squares plus or minus 1. Since 1 is a square, we see that $g(2)$ equals 3. More formally, every number of the form $2x + 1$ (that is, every odd number) equals $(x + 1)^2 - x^2$, and every even number, $2x$, equals $x^2 - (x - 1)^2 + 1^2$, or $(x + 1)^2 - x^2 - 1$.

It is almost as easy to show that $G(2)$, "big gee" for squares, also is 3. Although some even numbers are themselves squares and others are the sum of or difference between two squares, there is an infinite class of even numbers (of the form $8x + 6$, where x is any non-negative integer) that require three squares (positive or negative) for their expression. These are numbers in the series 6, 14, 22, 30, ...

It is hard to believe, but the values of "big gee" and "little gee" for cubes in the easier Waring problem and for all higher powers are still unknown. It is conjectured, but far from proved, that if negative powers are allowed, all positive integers can be expressed as the sum of no more than four cubes.

SQUARES	1		4		9		16		25		36 . . .
FIRST DIFFERENCES		3		5		7		9		11 . . .	
SECOND DIFFERENCES			2		2		2		2 . . .		

Proof that $g(2) = 3$ for "easier" Waring problem

That five cubes suffice is easily demonstrated. Again we use the calculus of finite differences. The cubes provide the first row [*see illustration below*]. Calculate two rows of differences. Note that numbers in the third row, 12, 18, 24, 30, 36, . . . , are consecutive multiples of 6. Each of these numbers can be expressed by four cubes. Consider 18. The table shows that 18 is the difference between the two numbers above it, 19 and 37. Nineteen is the difference between the two cubes above it, 8 and 27, and 37 is the difference between cubes 27 and 64. It follows that $18 = (64 - 27) - (27 - 8) = 4^3 - 3^3 - 3^3 + 2^2$. Clearly this procedure provides a four-cube expression for any multiple of 6.

It remains to show that numbers that are not multiples of 6 can be expressed by five cubes. Consider the five numbers between 18 and 24. They are 19, 20, 21, 22 and 23. Each of these numbers differs by a cube from a multiple of 6. The two end numbers, 19 and 23, differ by 1 from a multiple of 6, so that we can express 19 by adding 1 to the four cubes that express 18, and express 23 by subtracting 1 from the four cubes that express 24. The remaining numbers are 20, 21 and 22. Twenty differs by 2^3 from 12, and 22 differs by 2^3 from 30, therefore we can express 20 by adding 8 to the four cubes that express 12, and express 22 by subtracting 8 from the four cubes that express 24. Only 21 remains. It differs by 3^3 from 48, therefore we can express 21 by taking 27 from the four cubes that express 48. This procedure applies to all the numbers that lie between multiples of 6. By adding or subtracting a suitable cube to or from a set of four other cubes, we can express every nonmultiple of 6 by five cubes.

Hardy and Wright, in their *Introduction to the Theory of Numbers*, give a shorter proof based on the fact that n^3 minus n equals 0 (mod 6). This leads to the following formula for expressing any number, n, with five cubes,

$$n = n^3 - 6x = n^3 - (x + 1)^3 - (x - 1)^3 + x^3 + x^3 ,$$

where x is a suitable positive integer. Neither this formula nor the previous procedure indicates how to express n with the fewest number of cubes; they show how to do it with five cubes. For instance, the procedure tells us: $15 = 8^3 - 7^3 - 7^3 + 6^3 - 3^3$. The Hardy and Wright formula leads to the more monstrous expression $15 = 15^3 - 561^3 - 559^3 + 560^3 + 560^3$. Actually 15 can be expressed with as few as three cubes: $2^3 + 2^3 - 1^3$.

The big question, still unresolved, is whether four cubes (allowing negative cubes) are sufficient for expressing every positive integer. No one has proved they are. No one has found a counterexample. The simplest expression known to me, with four or fewer cubes, for integers 1 through 99 are listed in the illustration on the next page. ("Simplest" means that the number of cubes is minimized and an expression is given with the smallest absolute value for the cube of largest absolute value.) The chart is based on information supplied by George Shombert, Jr., of Beaver, Pa. (who first called my attention to the easier Waring problem), supplemented by the results of two computer programs. In 1955 J. C. P. Miller and M. F. C. Woollett, using the EDSAC computer at the University of Cambridge, searched for three-cube expressions of integers 1 through 100 within a range of cubes through $3{,}200^3$. In 1964 the search was extended through integer 999 within a range of cubes through $65{,}536^3$ by V. L. Gardiner,

CUBES	1		8		27		64		125		216 . . .
FIRST DIFFERENCES		7		19		37		61		91 . . .	
SECOND DIFFERENCES			12		18		24		30 . . .		
THIRD DIFFERENCES				6		6		6 . . .			

Proof that $g(3) \leq 5$ for easier Waring problem

© 1973 SCIENTIFIC AMERICAN, INC

R. B. Lazarus and P. R. Stein, using the IBM STRETCH computer at the Los Alamos Scientific Laboratory of the University of California. (Miller and Woollett published their results in the *Journal of the London Mathematical Society*, Volume 30, 1955, pages 101–110. Gardiner, Lazarus and Stein summarized their data in *Mathematics of Computation*, Volume 18, 1964, pages 408–413.)

Note that four cubes are needed for every number with a digital root of 4 or 5. (The digital root of a number is obtained by adding the number's digits, then adding the digits in the result and continuing until one digit remains. It is the same as the value of the number modulo 9.) It is not hard to show that every number equal to 4 or 5 (mod 9) [*colored numbers in the illustration below*] requires at least four cubes.

One way to do it makes use of the old accountant's trick for checking addition by digital roots. The sum of any set of integers, positive or negative, has a digital root equal to the root of the sum of the roots of the same set of numbers. Every cube has a digital root of 1, 8 or 9. No pair of these roots (the possible pairs are 11, 18, 19, 88, 89 or 99), whatever their signs, has a sum with a digital root of 4 or 5. (To add a negative root, it is often convenient to change the minus sign to plus and the root to its complement with respect to 9. Thus $1 - 8$ is the same as $1 + 1$, giving the positive digital root of 2.) Consequently no integer equal to 4 or 5 (mod 9) can be expressed by two cubes.

Moreover, no triplet of digital roots 1, 8 or 9, whatever their signs, has a sum with digital root 4 or 5. Therefore no triplet of cubes can express a number equal to 4 or 5 (mod 9). We not only have established that $g(3)$ for the easier problem is at least 4 but also have found an infinite class of integers (those of form $9x + 4$ and $9x + 5$) that require at least four cubes. Both $g(3)$ and $G(3)$ are each at least 4.

We have learned still more. A check of the possible quadruplets of 1, 8 and 9 reveals just four patterns that give a digital root of 4. They are 1, 1, 1, 1; −8, 1, 1, 1; −8, −8, 1, 1, and −8, −8, −8, 1. Similarly, just four patterns give a digital root of 5: 8, 8, 8, 8; 8, −1, −1, −1; 8, 8, −1, −1, and 8, 8, 8, −1. Therefore, in searching for four-cube solutions of integers equal to 4 or 5 (mod 9), we need to consider only cubes with digital roots of 8 (cubes of 2, 5, 8, 11, . . .) or cubes with digital roots of 1 (cubes of 1, 4, 7, 10, . . .). All integers with roots *not* 4 or 5 have been shown to have expressions of four or fewer cubes, so that only numbers equal to 4 or 5 (mod 9) remain in doubt.

Observe that most of the numbers on the chart that are not equal to 4 or 5 (mod 9) have known three-cube expressions. Some were not easy to come by, notably the expression for 87 in which each cube has four digits. Miller and Woollett failed to find this expression, but it was trapped by Gardiner's more ambitious computer program.

The number 100 has an elegant four-cube expression: it is the sum of the cubes of 1, 2, 3 and 4. However, three three-cube expressions of 100 are known. In the simplest each cube is a digit. Can the reader find this expression before next month, when I shall give all three solutions?

Many number theorists believe, although it has not been proved, that all integers not equal to 4 or 5 (mod 9) have three-cube expressions. If so, the value of $g(3)$ for the easier Waring problem is settled. Do you see why? To obtain a four-cube expression for a number equal to 4 (mod 9) we have only to add 1^3 to a three-cube expression for the number just below it; to obtain a four-cube expression for a number equal to 5 (mod 9) we have only to subtract 1^3 from a three-cube expression for the number just above it. Perhaps readers can dis-

1 =	1^3
2 =	$1^3 + 1^3$
3 =	$1^3 + 1^3 + 1^3$
4 =	$1^3 + 1^3 + 1^3 + 1^3$
5 =	$2^3 - 1^3 - 1^3 - 1^3$
6 =	$2^3 - 1^3 - 1^3$
7 =	$2^3 - 1^3$
8 =	2^3
9 =	$2^3 + 1^3$
10 =	$2^3 + 1^3 + 1^3$
11 =	$3^3 - 2^3 - 2^3$
12 =	$-11^3 + 10^3 + 7^3$
13 =	$-11^3 + 10^3 + 7^3 + 1^3$
14 =	$2^3 + 2^3 - 1^3 - 1^3$
15 =	$2^3 + 2^3 - 1^3$
16 =	$2^3 + 2^3$
17 =	$2^3 + 2^3 + 1^3$
18 =	$3^3 - 2^3 - 1^3$
19 =	$3^3 - 2^3$
20 =	$3^3 - 2^3 + 1^3$
21 =	$16^3 - 14^3 - 11^3$
22 =	$16^3 - 14^3 - 11^3 + 1^3$
23 =	$2^3 + 2^3 + 2^3 - 1^3$
24 =	$2^3 + 2^3 + 2^3$
25 =	$3^3 - 1^3 - 1^3$
26 =	$3^3 - 1^3$
27 =	3^3
28 =	$3^3 + 1^3$
29 =	$3^3 + 1^3 + 1^3$
30 =	$3^3 + 1^3 + 1^3 + 1^3$
31 =	$52^3 - 44^3 - 44^3 + 31^3$
32 =	$2^3 + 2^3 + 2^3 + 2^3$
33 =	$3^3 + 2^3 - 1^3 - 1^3$
34 =	$3^3 + 2^3 - 1^3$
35 =	$3^3 + 2^3$
36 =	$3^3 + 2^3 + 1^3$
37 =	$4^3 - 3^3$
38 =	$4^3 - 3^3 + 1^3$
39 =	$4^3 - 3^3 + 1^3 + 1^3$
40 =	$4^3 - 2^3 - 2^3 - 2^3$
41 =	$8^3 - 7^3 - 4^3 - 4^3$
42 =	$3^3 + 2^3 + 2^3 - 1^3$
43 =	$3^3 + 2^3 + 2^3$
44 =	$8^3 - 7^3 - 5^3$
45 =	$4^3 - 3^3 + 2^3$
46 =	$3^3 + 3^3 - 2^3$
47 =	$-8^3 + 7^3 + 6^3$
48 =	$4^3 - 2^3 - 2^3$
49 =	$4^3 - 2^3 - 2^3 + 1^3$
50 =	$-49^3 + 41^3 + 29^3 + 29^3$
51 =	$-796^3 + 659^3 - 602^3$
52 =	$3^3 + 3^3 - 1^3 - 1^3$
53 =	$3^3 + 3^3 - 1^3$
54 =	$3^3 + 3^3$
55 =	$3^3 + 3^3 + 1^3$
56 =	$4^3 - 2^3$
57 =	$4^3 - 2^3 + 1^3$
58 =	$4^3 - 2^3 + 1^3 + 1^3$
59 =	$5^3 - 4^3 - 1^3 - 1^3$
60 =	$5^3 - 4^3 - 1^3$
61 =	$5^3 - 4^3$
62 =	$3^3 + 3^3 + 2^3$
63 =	$4^3 - 1^3$
64 =	4^3
65 =	$4^3 + 1^3$
66 =	$4^3 + 1^3 + 1^3$
67 =	$4^3 + 1^3 + 1^3 + 1^3$
68 =	$5^3 - 4^3 + 2^3 - 1^3$
69 =	$5^3 - 4^3 + 2^3$
70 =	$-21^3 + 20^3 + 11^3$
71 =	$4^3 + 2^3 - 1^3$
72 =	$4^3 + 2^3$
73 =	$4^3 + 2^3 + 1^3$
74 =	$4^3 + 2^3 + 1^3 + 1^3$
75 =	$4^3 + 3^3 - 2^3 - 2^3$
76 =	$-11^3 + 10^3 + 7^3 + 4^3$
77 =	$5^3 - 4^3 + 2^3 + 2^3$
78 =	$-55^3 + 53^3 + 26^3$
79 =	$35^3 + 33^3 - 19^3$
80 =	$4^3 + 2^3 + 2^3$
81 =	$3^3 + 3^3 + 3^3$
82 =	$14^3 - 11^3 - 11^3$
83 =	$4^3 + 3^3 - 2^3$
84 =	$4^3 + 3^3 - 2^3 + 1^3$
85 =	$7^3 - 5^3 - 5^3 - 2^3$
86 =	$-31^3 + 29^3 + 14^3 + 14^3$
87 =	$4{,}271^3 - 4{,}126^3 - 1{,}972^3$
88 =	$5^3 - 4^3 + 3^3$
89 =	$-7^3 + 6^3 + 6^3$
90 =	$4^3 + 3^3 - 1^3$
91 =	$4^3 + 3^3$
92 =	$4^3 + 3^3 + 1^3$
93 =	$7^3 - 5^3 - 5^3$
94 =	$7^3 - 5^3 - 5^3 + 1^3$
95 =	$-22^3 + 20^3 + 14^3 - 1^3$
96 =	$-22^3 + 20^3 + 14^3$
97 =	$5^3 - 3^3 - 1^3$
98 =	$5^3 - 3^3$
99 =	$4^3 + 3^3 + 2^3$

Simplest cube expressions known for numbers 1 through 99

© 1973 SCIENTIFIC AMERICAN, INC

cover three-cube solutions for eight numbers, 30, 33, 39, 42, 52, 74, 75 and 84, that may have three-cube expressions, none of which has yet been found. In particular, can anyone express 30 with three cubes or prove that it cannot be done? It is astonishing that this continues to be an open question. (I shall send a copy of *The Sixth Book of Mathematical Games from Scientific American,* with a congratulatory inscription, to the first person who sends me a three-cube expression for 30.)

The number 12 is also of special interest. It is the smallest integer known for which only one three-cube solution is known. Most integers with three-cube expressions can be expressed by three cubes in more than one way. For example, there are 19 known ways to express 90, and 23 known ways to express 2. On the other hand, no one has yet found more than two ways to express 3 (cubes of 1, 1, 1 and -5, 4, 4). There is a noticeable paucity of three-cube solutions for numbers with digital roots of 3 and 6. Six of the eight numbers listed above for which three-cube solutions have yet to be found are numbers of this form.

Number theorists distinguish between primitive and derived solutions. A primitive solution is one in which the cubes have no common factor. A derived solution is one in which they do. Derived solutions are obtainable from primitive solutions by multiplying each cube root by n and the number itself by n^3, where n is any integer greater than 1. Twelve solutions in the illustration on the opposite page are derived: 16, 24, 32, 40, 48, 56, 64, 72, 80 and 96 (by multiplying primitive solutions by 2), and 54 and 81 (by multiplying primitive solutions by 3). For example, the solution for 16 is obtained from the primitive solution for 2 by multiplying 2 by 2^3 and each cube root by 2. The solution for 54 is derived from the primitive solution for 2 by multiplying 2 by 3^3 and each cube root by 3. The derived solutions for 24 and 80 are the only known solutions for those numbers. Note that a derived solution is not always the simplest. From $11 = 3^3 - 2^3 - 2^3$ we can derive $88 = 6^3 - 4^3 - 4^3$, but the primitive solution on the chart is simpler.

I would be pleased to hear from anyone who simplifies any expression in the illustration, or who can report any computer work on the cube problem that has gone beyond Gardiner's program. I must thank Roger Deschner, W. H. J. Fuchs, Daniel Shanks, L. H. Skinner, P. R. Stein, Bryant Tuckerman and E. M. Wright for their help in locating the references I have consulted.

Do you want to observe in comfort; carry your "portable observatory" with one hand? or—

Photograph, in sharp detail, wildlife near at hand or at inaccessible distances?

Or have you an industrial requirement, a need for the finest optical system available built into special ruggedized equipment?

Other optical systems are performance-tested against Questar; why not come right to the source?

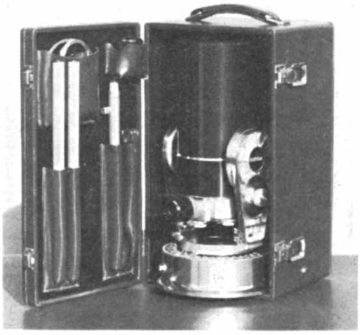
QUESTAR

DOES IT ALL

© Questar Corporation 1973
All rights reserved

Questar started out in life as a fine personal telescope in the days when you either ordered a conventional, custom-built refractor, or built a reflector yourself if you had happened to come across the wonderful book "Amateur Telescope Making" by the now-legendary A. G. Ingalls. But Questar's originator foresaw that we were entering upon a period which might almost be known as "the optical age," when this superfine optical system would be in demand not only as a multi-purpose telescope but for all sorts of modern engineering developments, to permit miniaturization and portability that would be otherwise impossible.

Because of its world-wide reputation for quality and versatility, Questar is the *specified* optical system, and it is on-the-shelf here, ready for many special applications. Our ruggedized versions save you engineering time and money. Why not let us help solve your problems?



QUESTAR, THE WORLD'S FINEST, MOST VERSATILE TELESCOPE, IS PRICED FROM $865. SEND FOR OUR BOOKLET IN COLOR WITH 150 PHOTOGRAPHS BY QUESTAR OWNERS. $1 TO COVER MAILING AND HANDLING COSTS ON THIS CONTINENT; BY AIR TO SOUTH AMERICA $2.50; EUROPE AND NORTH AFRICA, $3; ELSEWHERE, $3.50.

QUESTAR

BOX 520, NEW HOPE, PENNSYLVANIA 18938

© 1973 SCIENTIFIC AMERICAN, INC

THE AMATEUR SCIENTIST

A cold camera for astronomical photography and cardboard segments for big paraboloids

Conducted by C. L. Stong

The color photographs of the Great Nebula in Orion on the opposite page were made to demonstrate the performance of a remarkably simple and relatively inexpensive camera of the cryogenic type that was invented three years ago by Bill Williams of 2 Heather Lane, Mahwah, N.J. 07430. At the time Williams was 17 years old. He made the photographs on a muggy night near Key West. To make the top photograph on the opposite page he filled a compartment of the camera with dry ice that lowered the temperature of the film to approximately −75 degrees Celsius. He exposed the cold film to the nebula for 15 minutes. The bottom photograph was made soon thereafter with the same kind of film in the same camera but with an exposure of 20 minutes at a temperature of 25 degrees C. Notwithstanding the longer exposure, the higher temperature prevented the photosensitive emulsion from recording more than a fraction of the information that was caught in less time by the colder film.

The basic technique of photographing dim celestial objects by chilling photosensitive emulsions was developed for astronomical photography by Arthur A. Hoag of the Kitt Peak National Observatory. The method is simple in principle but somewhat complex in application. The emulsion can be cooled to the required temperature simply by pressing the film against the side of a metal box that is tightly packed with pea-size lumps of dry ice. The trouble is that the cold film causes moisture in the air to condense as fog that fills the interior of the camera.

The problem is solved by exhausting air from the interior of the camera with a vacuum pump. Now, however, the camera must be placed inside an airtight vessel reinforced sufficiently to resist the crushing weight of the atmosphere. The external controls of the camera and some parts of the vessel tend to collect frost, but this problem can be solved by recourse to electric heating units. The resulting hot spots give rise to new complications that lead to still other links in a growing chain of compensating gadgetry that suggests the design of a modern automobile.

The cost of such cameras exceeded the budget of most amateur astronomers. A few constructed somewhat less complex cameras by substituting liquid nitrogen as the refrigerant. The liquid was evaporated in an insulated boiler by an electric heating unit. Cold, dry gas from the vessel swirled past the film and swept the moisture-laden air from the assembly (see "The Amateur Scientist," Scientific American, August, 1969). This scheme did not catch on widely because liquid nitrogen is not readily available in most communities. Moreover, it is expensive, difficult to store and hazardous to manipulate in the dark.

That was the state of the art when Williams became interested in astronomy. He explains as follows how he solved the problem of making deep-sky photographs with limited funds.

"Like most beginners who develop an interest in astronomy, I tired rather quickly of looking at the moon and a dozen or so other 'easy' objects. After leafing through magazines that display spectacular deep-sky photographs, I decided to convert my telescope into a camera. The technical literature, however, was discouraging. It disclosed that the best astronomical photographs had been made by freezing the film in specially designed cameras that utilize vacuum chambers, actuating valves, O rings and liquefied gases.

"I could not help wondering why the film had to be so cold. The answer involved a property of photographic emulsions that I had not known about. Everyone who makes snapshots is familiar with the inverse relation between the speed of the camera shutter and the size of the lens opening. For a given amount of light to strike the photosensitive emulsion either the shutter speed is fast and the lens opening small or the shutter speed is slow and the lens opening large. The predictable response of the emulsion to this relation is termed the reciprocity rule.

"I did not know that the reciprocity rule fails when the light becomes so dim that exposures must exceed more than two or three minutes. I had always assumed that the speed at which film is rated by the manufacturer is valid under all circumstances. For example, high-speed Ektachrome film is assigned a speed rating of ASA 160. I was astonished to learn that this rating applies only to exposures of about .01 second. The rating does not change substantially even for exposures of a few minutes, but when the shutter must be kept open for two hours, the speed of high-speed Ektachrome falls to ASA 5! Tri-X emulsion, which is rated at ASA 400 for making snapshots, falls below the rating of Plus-X (ASA 125) in the case of time exposures that exceed 30 minutes. I also learned that some slow films, such as Eastman Kodak's spectroscopic emulsions, resist reciprocity failure and that emulsions of this kind are relatively unaffected by refrigeration.

"The latent photographic image that is created when photons dissociate silver halide molecules of the emulsion is not necessarily permanent. Given sufficient time, the ions tend to drift back together again at about the same rate at which they are formed. Thereafter no net gain in exposure results no matter how long light falls on the film.

"Lowering the temperature of the emulsion tends to suppress the recombination of the ions and hence to suppress reciprocity failure. Although cooling lowers the intrinsic sensitivity of the film, it disproportionately suppresses reciprocity failure. The result is a substantial net gain in the speed of refrigerated film for exposures lasting more than about a minute.

"The net gain in speed also improves

© 1973 SCIENTIFIC AMERICAN, INC

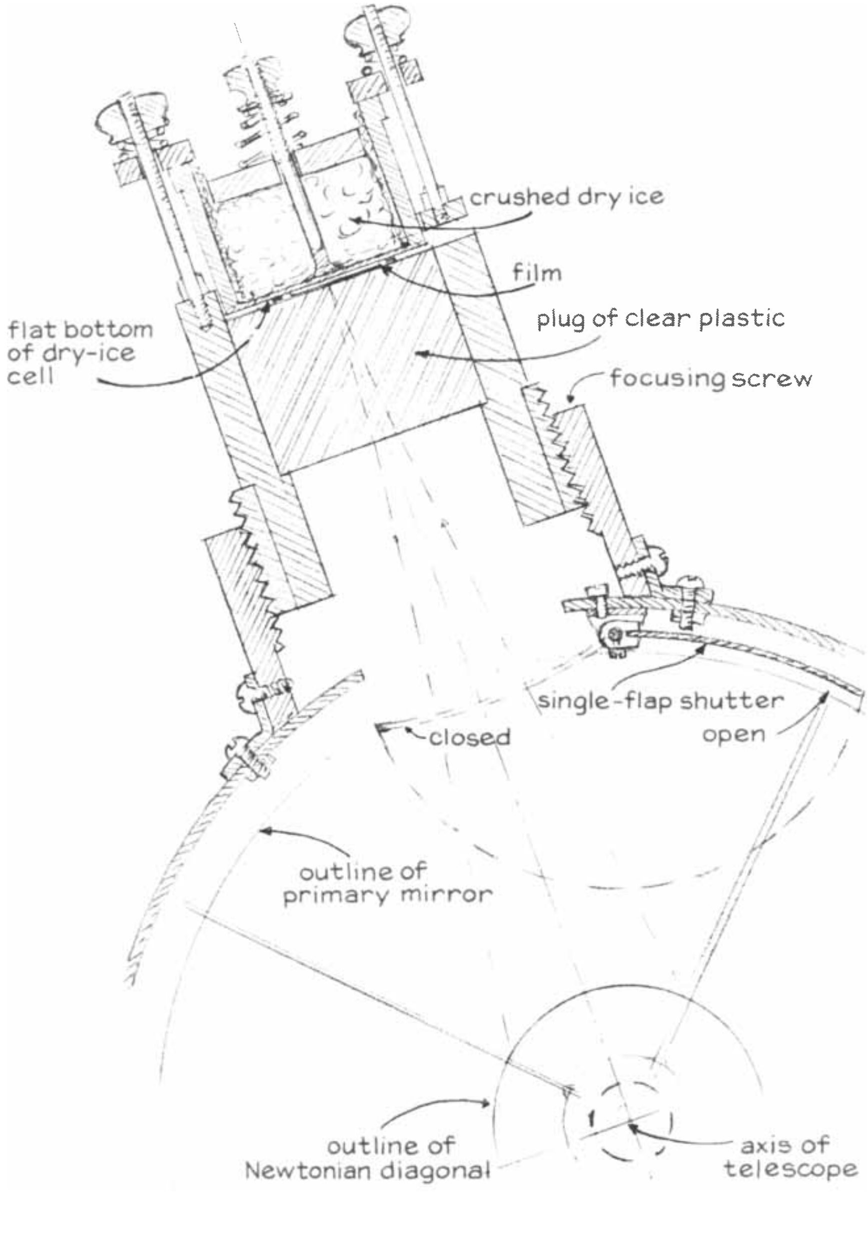
Bill Williams' chilled-film photograph of the Great Nebula in Orion

The nebula photographed with unchilled film

© 1973 SCIENTIFIC AMERICAN, INC

the resolution of deep-sky photographs by reducing the effects of guiding errors, which arise from the necessity of keeping the telescope pointed exactly at the celestial object as it apparently moves across the sky. The shorter exposure also reduces the interval during which the image jiggles as a consequence of atmospheric instability. It is much more likely that the atmosphere will be steady and that the observer can keep the cross hairs of the telescope centered on a star for 10 minutes rather than for an hour. Incidentally, I have observed that an accurately guided six-inch telescope makes far better photographs than a poorly guided 20-inch instrument.

"Cooling greatly reduces the required exposure intervals in the case of both black-and-white and color emulsions. It also improves the latitude of both kinds of film, meaning that it enables the emulsion to register dim features of the image without overexposing bright areas. In addition cooling restores the color balance that is ordinarily distorted by making long exposures in dim light. Color film consists of several layers of emulsion, each with a unique reciprocity characteristic. Cooling suppresses reciprocity failure disproportionately in the less sensitive layers of emulsion with the result that all colors register faithfully even in dim light. The effect is strikingly apparent in the first of my two photographs of the Orion nebula, which reproduces blues and greens that are not evident in the photograph made at ambient temperature.



Cross section of the camera assembly

"When I set out to make a conventional cold camera, I enlisted the help of a friend, Scott Usher. We tried to simplify the construction in a number of ways without much success until we observed that frost does not form on photographic film that is sandwiched tightly between flat surfaces chilled by subliming dry ice. The literature had given us the incorrect impression that the film had to be in a vacuum. Clearly all we needed was a transparent barrier of low heat conductivity. We got the idea of making a heat insulator in the form of a vacuum cell with opposing windows. We intended to press the film tightly against the external surface of one of the windows by a flat plate chilled to the required −75 degrees C.

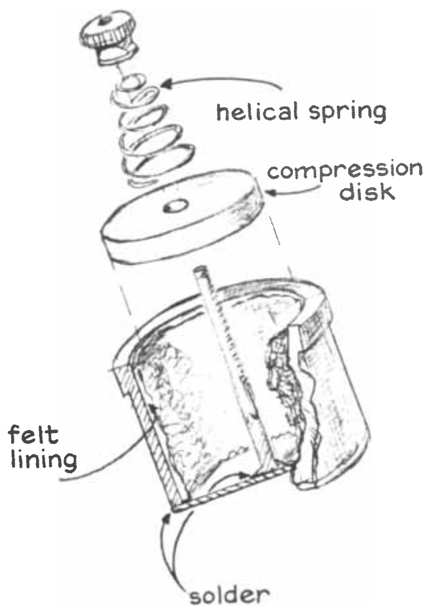
"Our vacuum cell proved to be faulty. While we were considering how to correct the design, it occurred to us that transparent heat insulators need not be based on a vacuum. Why not fill the cell with alcohol or a comparable liquid that freezes at a very low temperature?

"It also occurred to us that a transparent solid of low heat conductivity would doubtless work as well as a liquid. For example, a cylindrical plug of glass with flat, polished ends might do the job. The film could be pressed tightly against one end of the cylinder by a metallic container of dry ice. Light would be admitted through the other end of the cylinder.

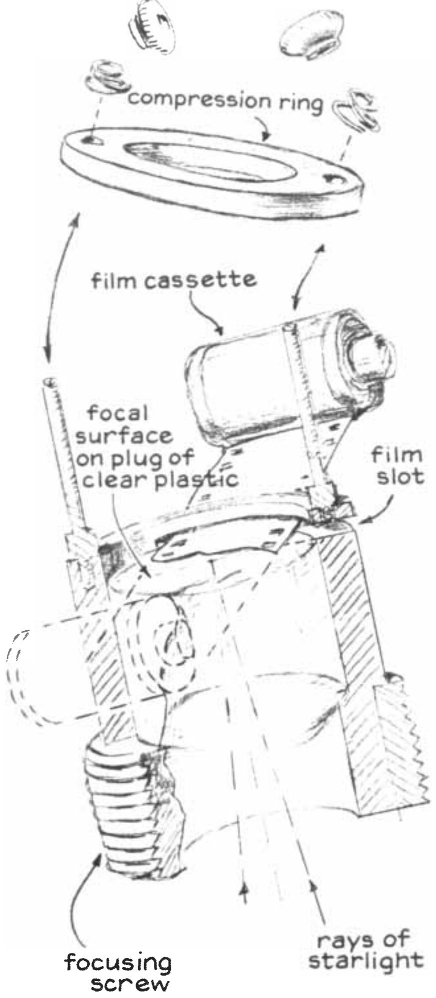
"The idea seemed promising. How long should the cylinder be so that frost would not form on one end until the other end had been cooled for a period of time greater than the longest exposure of interest? By experimenting we found that a plug about two inches long did not frost over for an hour.

"Next we learned that a clear plastic, such as methyl methacrylate (Plexiglas), can be substituted for glass if the ends of the cylinder are made reasonably flat, parallel and polished. We also wondered if a thick window would degrade the quality of the image. We knew that similarly thick plugs of glass have been used to correct spherical aberration of lenses of large aperture but short focal length. The focal ratio of our telescope was about $f/8$. For this reason we felt that

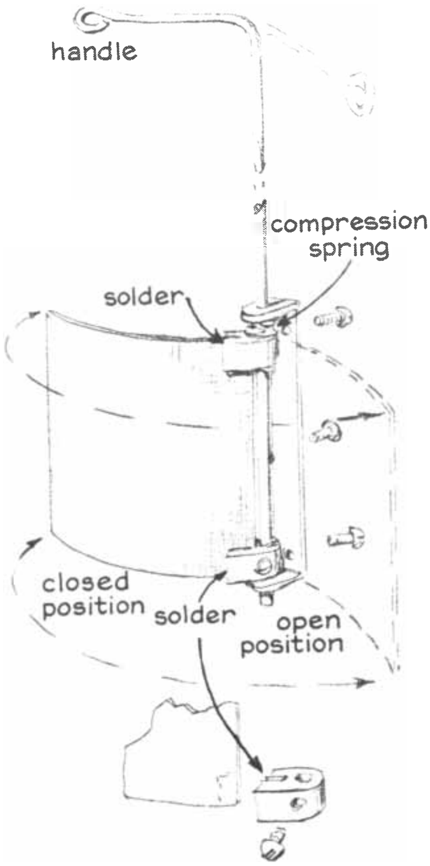
© 1973 SCIENTIFIC AMERICAN, INC



Dry-ice compartment



Method of loading film



Details of flap shutter

any possible overcorrection of spherical aberration would be trivial.

"We also investigated the question of how much light might be absorbed by two inches of plastic. Normally about 4 percent is lost by reflection at each surface. Our experiments disclosed that methyl methacrylate transmits approximately 92 percent of white light. Glass transmits slightly less light, is a somewhat better heat insulator and is more scratch-resistant than plastic. It is also more difficult to cut and polish.

"In its final form our camera consists of three principal subassemblies. We made the body of a thick-walled tube of opaque plastic, one end of which is externally threaded. The threads engage mating internal threads of a tubular bracket that attaches the camera to the telescope. Images of celestial objects are focused by screwing the body into or out of the mounting bracket. From the unthreaded end the internal wall of the body tube was bored to larger diameter to accept the plastic cylinder. The enlarged bore terminates in a shoulder somewhat more than halfway through the tube. The plastic cylinder rests against the shoulder [*see illustration on opposite page*]. The outer surface of the plastic cylinder extends to within about 3/8 inch of the unthreaded end of the body tube.

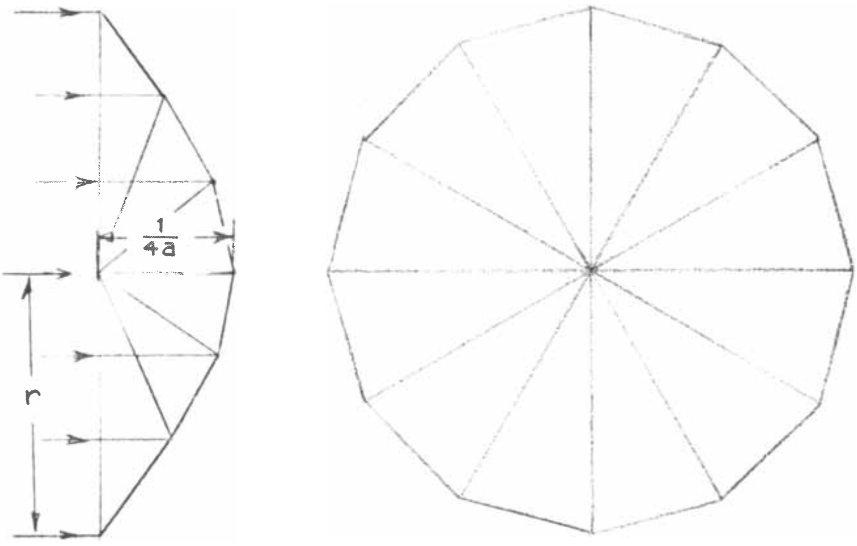
"A saw kerf that extends approximately three-quarters of the way through the body tube at the level of the outer end of the plastic cylinder admits 35-millimeter film to the camera. The film is pressed against the plastic by the flat bottom of a cylindrical box that contains lumps of dry ice. Pressure between the lumps of ice and the bottom of the box is maintained by a helical spring acting against a sliding disk that functions as the lid of the box. The box assembly is clamped to the housing by a retaining ring. Pressure between the bottom of the box and the film is maintained by stud bolts, which act through a pair of helical springs against the retaining ring.

"I use three interchangeable plastic cylinders. One is for focusing the telescope, an operation that subjects the plastic to abrasion and invites scratches. The other plugs, which are handled carefully to avoid scratches, are used alternately for making photographs. Frost forms on the cold plug immediately after it is removed from the camera. The plug warms and dries while the next exposure is made with the alternate plug.

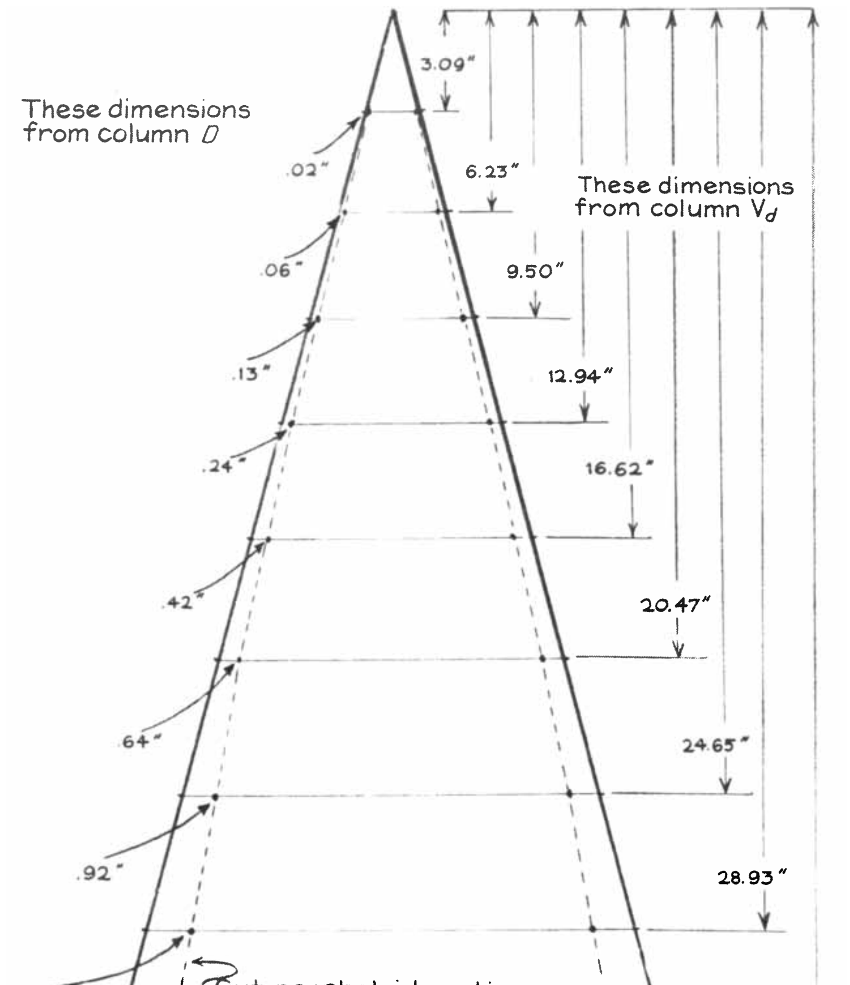
"I have worked with both cut and roll film. Initially I made a circular cutter—a small, sharp blade attached to a cylinder of plastic that turned on an axial shaft. The bottom of the shaft carried a rubber foot. Placing the film on a flat support, I set the rubber foot in the center of the desired disk of film, lowered the cylinder on the shaft so that the cutting edge of the knife made contact with the plastic and then rotated the cylinder to cut out the disk.

"Recently I devised a simple technique for using roll film. I push the leader of a new roll of 35-millimeter film into an empty cassette, which acts as a light-

© 1973 SCIENTIFIC AMERICAN, INC



Geometry of paraboloid designed by Alex McEachern and Paul Boon



Basic section of the paraboloid

tight storage compartment. Exposures are made on the strip between the cassettes. The film has to be removed from the camera after each exposure to exchange the plastic plugs and refocus and reset the telescope. During this time I put the cold, brittle film and cassettes in a lighttight box to warm and dry. I mark one cassette with a piece of adhesive tape so that I can identify it by touch in the dark.

"The cold, brittle film between the cassettes must be handled gently until it warms. Frost collects on the emulsion and wets the film when it melts. Part of the moisture can be wiped off without damaging the emulsion by using conventional darkroom techniques. Exposed portions of the film are pushed into the storage cassette after they have warmed and dried. The film can be transferred between the lighttight storage box and the camera on moonless nights without risk of exposure if one stays away from man-made sources of light.

"To make a photograph I line up the telescope, adjust the clock drive and focus an object, such as a bright star, in the plane that will be occupied by the film. The focusing can be done in either of two ways. A conventional eyepiece can be fitted with a short tubelike spacer. The end of the spacer lies in the focal plane of the image. To focus the camera place the end of the spacer on the surface of the plastic plug and screw the body of the camera in or out of the mounting bracket to the point at which the image of the star is smallest.

"The camera can be focused more accurately by the method used most frequently by professional astronomers. Place a dab of India ink, a razor blade or any similar sharp opaque edge on the surface of the plastic plug. Manipulate the telescope to the position at which the image of a bright star is bisected by the opaque edge.

"When the eye is placed close to the opaque edge, the observer sees a portion of a disk of light that represents the objective mirror. Part of the disk appears to be cut off by a dense, straight shadow. If the telescope is now moved so that the straightedge cuts deeper into the image of the star, the shadow will move either in the same direction as the telescope or in the opposite direction, depending on whether the plane of the straightedge lies inside or outside the focal plane of the telescope.

"Screw the camera into or out of the bracket to the point at which the entire disk of the objective mirror appears as a uniform pattern of light and shade that

© 1973 SCIENTIFIC AMERICAN, INC

changes form but not position when the straightedge cuts deeper or less deep into the image. The camera is then exactly focused. Telescope makers will recognize this focusing technique as a variant of the familiar Foucault knife-edge test. Exposures are then made by opening a flap shutter [*see illustration at right on page 125*].

"I have patented the camera and granted an exclusive license for its manufacture and sale to Celestron Pacific of Torrance, Calif., but permission is hereby granted to amateurs to make a duplicate camera for their own private use. I have now worked with the camera for three years in California, Vermont, Florida and New Jersey. It is light, portable and easy to use. It enables anyone who owns a telescope that can be kept pointed toward a selected star to make deep-sky photographs of professional quality."

row number	x	y	y_1	z	V_d	D
1	3	.19	.75	3.09	3.09	.02
2	6	.75	1.64	3.14	6.23	.06
3	9	1.64	3.00	3.27	9.50	.13
4	12	3.00	4.68	3.44	12.94	.24
5	15	4.68	6.74	3.64	16.62	.42
6	18	6.74	9.17	3.85	20.47	.64
7	21	9.17	11.99	4.12	24.55	.92
8	24	11.99	15.18	4.38	28.93	1.29
9	27	15.18	18.70	4.62	33.55	1.71
10	30	18.70	—	—	—	—

$I = 3''$ $R = 27''$ $a = .0208$ No. of sections = 12 $z = [I^2 + (y_1 - y)]^{\frac{1}{2}}$

$D = (V_d - x)(3.1416)/$no. of sections.

Base of triangle $= 2(V_d \text{max})(\sin [180°/\text{no. of sections}])$

Table for calculating sections of paraboloid

Amateur astronomers have had great fun with paraboloidal mirrors of metallized glass during the half-century since Albert G. Ingalls first explained in these columns how to make a simple reflecting telescope. Now two Californians, Alex McEachern of Manhattan Beach and Paul Boon of Garden Grove, call attention to the fun that can be had by making roughly paraboloidal structures of metallized cardboard. A big cardboard paraboloid is easy to make with very small focal ratios: $f/.25$ and less. It can concentrate an impressive amount of energy from a large area, but its relatively crude curvature is incapable of reflecting the intercepted rays to a sharp focus. Even so, it can be made to pick up ordinary speech sounds from distances of up to 100 yards and the songs of certain birds from more than five times that distance.

A cardboard paraboloid only four or five feet in diameter, covered with aluminum foil, can easily gather enough infrared rays from the sun to broil (and even burn) a hamburger within a couple of minutes. An aluminized paraboloid of this size is ideal for running a hot-air engine that operates on the Stirling cycle. When a big aluminized paraboloid is fitted with dipole antennas, it can pick up strong signals from otherwise weak radio sources such as distant ultrahigh-frequency television stations and broadcasts of the earth's pattern of cloud cover and surface temperature from weather satellites.

"In the interest of simplifying the design of the paraboloid," write McEachern and Boon, "we resort to two approximations. First, we assume that a continuous curve can be formed by joining together a series of short straight lines. Second, we assume that a dish-shaped curve can be made by joining the edges of a series of approximately triangular sections.

"To design the parabola decide on the value of a constant that we call an increment and abbreviate with the letter I. The increment should approximate the size of the target you have in mind—three inches, say, for a hamburger, two inches for a microphone or for the heated surface of a hot-air engine. Next decide on the radius R of the parabola—say 27 inches for a fairly large structure. Now decide how far from the bottom of the dish at its middle you want to position the target. We designate this distance d. If you want to broil a hamburger at a point 12 inches from the bottom of the dish, d equals 12. Finally, decide how many sections you want in the paraboloid. The accuracy of the curvature increases with the number of sections, but so does the difficulty of making the paraboloid. A disk of 12 sections is sufficient for concentrating solar energy.

"To calculate the shape of the required sections draw a chart or a table [*see illustration above*]. In the example the increment is three inches and the radius 27 inches; the paraboloid will have 12 sections. Number consecutively the column headed 'Row number.' The corresponding numbers for the column headed x are the product of the increment multiplied by the number of the row (3, 6, 9, 12 and so on in the example). Continue to fill in the x column until the product of the increment and the number of the row exceeds the sum of the radius plus the increment (in this example 27 plus 3). The algebraic equation for a parabola states that y is equal to the product of a constant a multiplied by the square of x. It turns out that the constant a is equal to the reciprocal of four times the distance to the bottom of the dish, or 12 inches in this example. The constant a is therefore equal to $1/(4 \times 12) = 1/48 = .0208$. Therefore $y = .0208 \times (x)^2$.

"For the first row y is equal to $.0208 \times 3 \times 3 = .187$, for the second row $.0208 \times 6 \times 6 = .749$ and so on. Entries in the column headed y_1 are equal to the value of y in the succeeding row. For example, the value of y_1 in row No. 1 is .75, which appears as the entry for y in row No. 2. The value for the next column, which is headed z, involves a bit of arithmetic. First multiply I by itself. In this example $I^2 = 3 \times 3 = 9$. Next subtract the value of y in each row from the value of y_1 in that row. Add the difference to the square of I. For example, in row No. 1, $y_1 - y = .75 - .19 = .56$. Add this difference to the square of I: $9 + .56 = 9.56$. Finally, the equation at the lower right of the table states that the desired value of z is equal to the square root of this sum: $(9.56)^{1/2} = 3.09$. Similarly, the value for column No. 2 is equal to $[9 + (1.64 - .75)]^{1/2} = (9.89)^{1/2} = 3.14$, and so on.

"The first entry in the column headed V_d is equal to the first entry in the preceding column. In this example the value is 3.09. Succeeding entries, however, are equal to the sum of z in the row plus the value of V_d in the preceding row. For example, the value of V_d for row No. 2 is equal to the sum of 3.14

© 1973 SCIENTIFIC AMERICAN, INC

Springer-Verlag
New York Heidelberg Berlin

New Journal—1974

Immunogenetics

Editor-in-Chief
George D. Snell, Bar Harbor, Maine

Managing Editor
Jan Klein, Dallas, Texas

Immunogenetics publishes original full length articles, brief communications and reviews on research in the following areas:
Immunogenetics of cell interaction
Immunogenetics of tissue differentiation and development
Phylogeny of alloantigens and of immune response
Genetic Control of immune response and disease susceptibility
Genetics and biochemistry of alloantigens

Volume 1 (6 issues) will appear in 1974.
$55.00 including postage.
Sample copies available.
Personal rate available.

Released in September

The Ribonucleic Acids
edited by *P. R. Stewart* and *D. S. Letham*
closes the gap between the rather general approach of biochemistry texts and the bewildering diversity of research reports on the role of RNA. It presents modern concepts of cell differentiation and describes the key role of RNA in the transfer and decoding of genetic information.

1973. xv, 268p. 56 illus. 14 tables. cloth **$18.70**

Scheduled for November

Regulation of Transcription and Translation in Eucaryotes
edited by *E. Bautz*

represents the proceedings of the
24th Colloquium Mosbach
April 26-28, 1973.

Recent experimental data and current views on the structure and function of chromatin as well as on the mechanism of protein synthesis in eucaryotes were presented by leading international specialists.

1973. approx. 300p. 86 illus. cloth. **$27.90**

Please tear off coupon below and return with prepayment to

Springer-Verlag New York Inc.
175 Fifth Avenue
New York, NY 10010

Please send me
☐ **Immunogenetics**—Sample Copy
☐ **Immunogenetics**—Subscription
______copies **The Ribonucleic Acids**
ISBN 0-387-06190-8 $18.70
______copies **Regulation of Transcription and Translation of Eucaryotes**
ISBN 0-387-06472-9 $27.90

Prices are subject to change without notice.

Enclosed is my check for $______
(including New York sales tax where applicable)

Name ______

Street ______

City/State/Zip ______ SA

(the value of z from row No. 2) plus 3.09 (the value of V_d from row No. 1 of V_d), or 6.23. A similar calculation shows that the value of V_d for row No. 3 is equal to $3.27 + 6.23 = 9.50$.

"Values of the last column, headed D, must also be found by doing a bit of arithmetic. For each row subtract from the value in that row of V_d the value in that row of x, multiply the difference by 3.1416 and divide the product by the number of sectors in the paraboloid. In this example the divisor is 12. The value of D for the first row is equal to $(3.09 - 3) \times 3.1416/12 = .02$. The largest value in the column headed V_d specifies in inches the length of the sides of an isosceles triangle from which the sectors of the paraboloid will be cut. In this example that length (from row No. 9) is 33.55 inches.

"One final calculation must be made to determine the length of the base of the triangle. The base is equal to twice the length of a side multiplied by the trigonometric sine of an angle that is equal in degrees to 180 divided by the number of sections. In this example the base is equal to $2 \times 33.55 \times \sin 180/12$; $180/12 = 15$ degrees. Trigonometric tables list the sine of 15 degrees as .259. Therefore the base of the triangle is $67.10 \times .259 = 17.37$ inches.

"Draw the isosceles triangle full scale, with sides of 33.55 inches and a base of 17.37 inches, on a sheet of cardboard. Beginning at the apex, mark off a series of intervals along both sides of the triangle that are equal in inches to the entries in column V_d. For instance, beginning at the apex make marks at 3.09 inches, 6.23 inches, 9.50 inches and so on to the base of the triangle. Draw straight lines across the triangle to connect equivalent pairs of intervals.

"Next, beginning at the first interval (3.09 inches), measure inward along the straight line from both of its ends a distance equal in inches to the entry in column D. For example, measure inward from both ends of the line that is 3.09 inches from the apex a distance of .02 inch. Place a prominent dot on the line at this distance from each side of the triangle [*see bottom illustration on page 126*]. Proceed to the next line (at 6.23 inches) and place a similar dot at distances of .06 inch from each side of the triangle. After dots have been placed on all lines interconnect all dots on each side by broken lines. Finally, cut off the sides of the triangle along the broken lines. Use the resulting pattern for cutting 11 identical pieces of cardboard.

"The edges of all 12 triangular pieces of cardboard, when they are joined with adhesive tape or an equivalent material, automatically bend into the desired paraboloid. We leave to the experimenter the fun of designing a suitable framework for supporting the structure."

STATEMENT OF OWNERSHIP, MANAGEMENT AND CIRCULATION (Act of August 12, 1970: Section 3685, Title 39, United States Code). *1.* Title of publication: Scientific American. *2.* Date of filing: October 1, 1973. *3.* Frequency of issue: monthly. *4.* Location of known office of publication: 415 Madison Avenue, New York, N.Y. 10017. *5.* Location of the headquarters or general business offices of the publishers: 415 Madison Avenue, New York, N.Y. 10017. *6.* Names and addresses of publisher, editor and managing editor: Publisher, Gerard Piel, 415 Madison Avenue, New York, N.Y. 10017. Editor, Dennis Flanagan, 415 Madison Avenue, New York, N.Y. 10017. Managing Editor, none. *7.* Owner: Scientific American, Inc., 415 Madison Avenue, New York, N.Y. 10017; Atwell & Co. (for Edwin H. Baker Pratt), United States Trust Co. of New York, 45 Wall Street, New York, N.Y. 10005; Janet R. Becker, c/o The Chase Manhattan Bank, P.O. Box 1508, Church Street Station, New York, N.Y. 10008; Buckley & Co. (for Elinor Gottlieb Manucci), c/o Fiduciary Trust Co. of New York, P.O. Box 924, Wall Street Station, New York, N.Y. 10005; Cudd & Co. for (a) Helen R. Snellenburg, Morris Duane and Raymond J. Armstrong, Trustees u/a 2/17/66 F.B.O. Helen R. Snellenburg and (b) Fred Grossman, Successor Trustee u/a 10/15/51 F.B.O. Robert L. Rosenwald, The Chase Manhattan Bank, 1 Chase Manhattan Plaza, New York, N.Y. 10015; Martin M. Davidson, 11 River Lane, Westport, Conn. 06880; Richard E. Deutsch, c/o The Chase Manhattan Bank, P.O. Box 1508, Church Street Station, New York, N.Y. 10008; Bayard Ewing, c/o Industrial National Bank, Trust Department, 100 Westminster Street, Providence, R.I. 02903; Dennis Flanagan, c/o Scientific American, Inc., 415 Madison Avenue, New York, N.Y. 10017; Sidney R. Garfield, M.D., Kaiser Foundation Hospitals, 1924 Broadway, Oakland, Calif. 94612; Nathan W. Levin, c/o The Chase Manhattan Bank, P.O. Box 1508, Church Street Station, New York, N.Y. 10008; Frasier W. McCann, Room 726, 10 Rockefeller Plaza, New York, N.Y. 10020; Donald H. Miller, Jr., c/o Scientific American, Inc., 415 Madison Avenue, New York, N.Y. 10017; Gerard Piel, c/o Scientific American, Inc., 415 Madison Avenue, New York, N.Y. 10017; Barbara K. Rosenwald, P.O. Box 3235, Norfolk, Va. 23514; Julius Rosenwald II, c/o The Chase Manhattan Bank, P.O. Box 1508, Church Street Station, New York, N.Y. 10008; Lessing J. Rosenwald, c/o The Chase Manhattan Bank, P.O. Box 1508, Church Street Station, New York, N.Y. 10008; Rowe & Co. (for Rhode Island Charities Trust), c/o Industrial National Bank of Rhode Island, Trust Department, 100 Westminster Street, Providence, R.I. 02903; Stanley Schaefer, c/o W. H. Freeman and Company, 660 Market Street, San Francisco, Calif. 94104; I. M. Scott, c/o The Chase Manhattan Bank, P.O. Box 1508, Church Street Station, New York, N.Y. 10008; Joan R. Scott, c/o The Chase Manhattan Bank, P.O. Box 1508, Church Street Station, New York, N.Y. 10008; Dorothy D. Spivack, 921 Bergen Avenue, Room 804, Jersey City, N.J. 07306; John Hay Whitney, Room 4600, 110 West 51 Street, New York, N.Y. 10020. *8.* Known bondholders, mortgagees, and other security holders owning or holding 1 percent or more of total amount of bonds, mortgages or other securities: none. *9.* For optional completion by publishers mailing at the regular rates (Section 132.121, Postal Service Manual). 39 U.S.C. 3626 provides in pertinent part: "No person who would have been entitled to mail matter under former section 4359 of this title shall mail such matter at the rates provided under this subsection unless he files annually with the Postal Service a written request for permission to mail matter at such rates." In accordance with the provisions of this statute, I hereby request permission to mail the publication named in item 1 at the reduced postage rates presently authorized by 39 U.S.C. 3626. (Signature and title of editor, publisher, business manager, or owner) Donald H. Miller, Jr., Vice-President and General Manager. *10.* Not applicable to this organization. *11.* Extent and nature of circulation: *A.* Total number of copies printed (net press run): average number of copies each issue during preceding 12 months, 558,506; actual number of copies of single issue published nearest to filing date, 585,000. *B.* Paid circulation: *1.* Sales through dealers and carriers, street vendors and counter sales: average number of copies each issue during preceding 12 months, 90,158; actual number of copies of single issue published nearest to filing date, 86,350. *2.* Mail subscriptions: average number of copies each issue during preceding 12 months, 421,274; actual number of copies of single issue published nearest to filing date, 450,784. *C.* Total paid circulation: average number of copies each issue during preceding 12 months, 511,432; actual number of copies of single issue published nearest to filing date, 537,134. *D.* Free distribution by mail, carrier or other means: *1.* Samples, complimentary, and other free copies: average number of copies each issue during preceding 12 months, 17,-625; actual number of copies of single issue published nearest to filing date, 16,500. *2.* Copies distributed to news agents, but not sold: average number of copies each issue during preceding 12 months, 24,832; actual number of copies of single issue published nearest to filing date, 28,650. *E.* Total distribution (sum of *C* and *D*): average number of copies each issue during preceding 12 months, 553,889; actual number of copies of single issue published nearest to filing date, 582 284. *F.* Office use, leftover, unaccounted. spoiled after printing: average number of copies each issue during preceding 12 months, 4,617; actual number of copies of single issue published nearest to filing date, 2,716. *G.* Total (sum of *E* and *F*—should equal net press run shown in *A*): average number of copies each issue during preceding 12 months, 558,506; actual number of copies of single issue published nearest to filing date, 585,000. I certify that the statements made by me above are correct and complete. Donald H. Miller, Jr., Vice-President and General Manager.

© 1973 SCIENTIFIC AMERICAN, INC

Other airlines fly as fast as we do. And their aircraft have the same range as ours. How can we then offer faster services and fewer stops between Europe and

S.E. Asia, Japan, N. America, West.

And between S.E. Asia and N. America, East.

How, indeed?

The answer is simple: *Copenhagen*. Or, more precisely, the geographical position of Copenhagen, the main gateway of our inter-continental routes.

Look at a globe. Or, better still, stretch a string over its surface between points within the areas above.

In many cases you will find that the string runs straight over Copenhagen (try, for instance, Paris-Tokyo, or London-Sydney, or Berlin-Seattle, or Glasgow-Singapore).

In other cases, Copenhagen will at least be closer to the stretched string than any other major airport in Europe (like Bangkok-New York, which makes the string run as far north as Spitsbergen).

So it's as simple as that: it's shorter via Copenhagen. And flying via Copenhagen is like running the inner track: a way to save distance and time.

And Copenhagen is the only major airport in Europe, from which nonstop flights to Bangkok, Los Angeles, Tokyo and Seattle are all within the reach of long-distance aircraft.

When you're going far east or far west you have two alternatives:

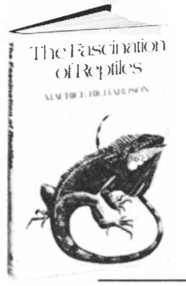
FLY VIA COPENHAGEN – OR FACE A DETOUR

SAS SCANDINAVIAN AIRLINES
General Agent for Thai International

© 1973 SCIENTIFIC AMERICAN, INC

From our treasure house of books on the natural sciences, pick a few treasures for yourself (or as gifts)

Superb books for reading and reference that belong in your library—books you will dip into often, refer to, treasure. Books that



examine every fact and facet of nature and the environment. Useful, enjoyable, mind-chilling—and quite often beautiful books for all who enjoy the thrill of scientific discovery. The chances are that you'll find a number of

books on this page you've been wanting to read and to own. Indulge yourself. No reason to wait any longer.

Take any 3 books
(values to $44.95)
only 99¢ each
as a member of the
Natural Science Book Club
(You simply agree to buy only 3 more books—all at handsome discount—over the next 12 months.)

(Retail prices shown)

38940. THE CLOSING CIRCLE. *Barry Commoner.* The man who has been called "the Paul Revere of ecology" analyzes our steadily worsening environmental dilemma and offers some cogent prescriptions for change **$6.95**

39731. COMMON INSECTS OF NORTH AMERICA. *Lester A. Swan and Charles S. Papp.* This first major one-volume survey of American insects to appear in nearly half a century will delight the naturalist, prove indispensable to the amateur collector and fascinate the interested browser. **$15.00**

47340. EXPLORING THE OCEAN WORLD. Revised and Expanded Edition. *Edited by C. P. Idyll.* Richly illustrated volume is the ideal introduction to oceanography. Explains continental drift, marine ecology, exotic underwater life, man's future in the sea, much more **$14.95**

58830. THE LONG AFRICAN DAY. *Norman Myers.* A breathtaking natural history of African wildlife, accompanied by 300 stunning photos of birth, play, conflict, death. *Counts as 2 of your 3 choices.* **$25.00**

36141. BEYOND STONEHENGE. *Gerald S. Hawkins.* The internationally famous astronomer assesses the astronomical significance of the temples of the Nile, Mayan ruins, enormous linear drawings in the Peruvian desert, and huge geometrical earth-works of the U S. **$10.00**

53870. THE HUDSON RIVER. *Robert H. Boyle.* Best-selling account of the destruction of one of America's mighty rivers. An eye-opener! **$7.95**

57540. THE LAND BEYOND THE MOUNTAINS: Siberia and its People Today. *Leonid Shinkarev* Russia's outstanding journalist paints a compelling portrait of this mysterious land six times the size of the USA. **$7.95**

56530. ISLAND AT THE CENTER OF THE WORLD. *Father Sebastian Englert.* Easter Island's mysterious giant statues, the islanders' puzzling past, their lost language — new light is shed on them all here. Lavishly illustrated in full color **$15.00**

63191. THE MOUNTAIN PEOPLE. *Colin M. Turnbull.* A compellingly readable account of Uganda's strange Ik people — an isolated tribe forced into inhuman cruelty by an inhospitable environment, and by an indifferent government. **$7.95**

44350. ELEMENTS OF CARTOGRAPHY: Third Edition. *Arthur H. Robinson and Randall D. Sale.* Comprehensive volume covers choice of scale and projection, flow maps, vector maps, graduated symbol maps, problems of three-dimensional rendering, *plus* the arts of design and lettering. Techniques of reproduction and air mapping. **$12.75**

How the Club Operates

The Book Club **News,** describing the coming Main Selection and Alternate Selections, will be sent to you 15 times a year at three to four week intervals. • If you wish to purchase the Main Selection, do nothing and it will be shipped to you automatically • If you prefer one of the Alternates, or no book at all, simply indicate your decision on the reply form always enclosed with the **News** and mail it so we receive it by the date specified. • The **News** is mailed in time to allow you at least 10 days to decide if you want the coming Main Selection. If, because of late mail delivery of the **News,** you should ever receive a Main Selection without having had the 10-day consideration period, that Selection may be returned at Club expense. • After completing your trial membership, you will be entitled to take advantage of our fabulous bonus plan which offers savings up to 70% and more. • (Offer good in Continental United States and Canada only Prices are slightly higher in Canada.)

85960. IN THE WAKE OF THE SEA-SERPENTS. *Bernard Heuvelmans.* Builds a *scientific* case to show that the legends of the Great Sea-Serpent have their origins in "chance sightings of a series of large sea-animals that are serpenti-form in some respect." A spell-binding scientific detective story. **$10.00**

50610. GREAT CITIES OF THE ANCIENT WORLD. *L. Sprague de Camp.* Gives a bird's-eye panorama of fourteen cities of the ancient world including Jerusalem, Rome, Constantinople. Crammed with fascinating facts and little-known details about ancient life. **$12.95**

34710. AT THE TURN OF THE TIDE: A BOOK OF WILD BIRDS. *Richard Perry.* Engrossing accounts, both dramatic and amusing, of shore birds. Graphic descriptions of the "languages" and personalities of each species — heron, kestrel, cormorant, the charming puffin. **$7.50**

52050. A GUIDE TO KENYA AND NORTHERN TANZANIA. *David F Horrobin.* Vicarious, thrilling armchair trip to East Africa in a guidebook of 300 pages with 48 handsome color photographs. **$12.50**

86841. WHAT YOU NEED TO KNOW ABOUT FOOD AND COOKING FOR HEALTH. *Lawrence E. Lamb, M.D.* An eminent cardiologist and author of *Your Heart and How to Live with It* offers a new and scientific approach to nutrition and how it can improve health through diet. **$10.00**

55620. IN THE SHADOW OF MAN. *Jane van Lawick-Goodall.* A fascinating account of some of the decade's most spectacular discoveries in animal research — Brilliant photographs. **$10.00**

49110. FROM THE LAND AND BACK. *Curtis K. Stadtfeld.* Subtly perceived and warmly recollected memories of the author's farming forefathers in central Michigan. **$6.95**

48400. THE FASCINATION OF REPTILES. *Maurice Richardson.* A colorful and handsomely illustrated appreciation of these scientifically neglected and often maligned animals. **$10.00**

Membership Application

Natural Science Book Club
Riverside, New Jersey 08075

4-57W

Please accept my application for membership and send me the three volumes indicated billing me only 99¢ each. I agree to purchase at least three additional Selections or Alternates during the first year I am a member, at special members' prices Savings range up to 30% and occasionally even more My membership is cancelable any time after I buy these three books. A shipping and handling charge is added to all shipments

Send no money. Members are billed when books arrive.

Indicate by number the 3 books you want

[ ] [ ] [ ]

Some expensive books count as 2 selections

Name______________________

Address______________________

City & State______________ Zip__________

Book selections purchased for professional purposes may be a tax-deductible expense. (Offer good in Continental U S and Canada only. Prices slightly higher in Canada).

© 1973 SCIENTIFIC AMERICAN, INC

BOOKS

Books about science for the younger reader: an annual Christmas survey

by Philip and Phylis Morrison

The crop is large this year. Standards are rising, so that otherwise mediocre works are acceptable as to intention and accuracy; still, outstanding books do not increase in number. We are particularly pleased as users of books to see that even a slender book for young readers can have a valuable index at the proper level. The sensitivity of the marketplace is high: we see a noticeable decrease in the number of titles in physics and mathematics, which seems a pity.

Mathematics and Physical Sciences

About Computers, by Craig Fields. Winthrop Publishers, Inc., Cambridge, Mass. ($2.95). A small bargain of clear and knowledgeable writing (the cute jacket design is its one trifling flaw), this paperback manages to say a great deal about computers as they are, without superficiality and without superfluous detail. Neither equations, photographs nor long bit strings mar the straightforward and convincing exposition of the whats and whys of computers and their programs. The book does not teach computer language; rather it gives a reader the confidence to begin to learn a language or to use one particular computer or to take on deeper computer mathematics. In particular it makes plain the architecture of programming at a very useful degree of detail. Accumulators, subroutines, macros for an assembler, plotters, batch processing and buffers all come to be understandable parts of the task of computation. FORTRAN occurs to the tune of a few instructions, but only as an example. This plain-language text, with a dozen or so line diagrams, gets one closer to the heart of the program and its substratum than any other introductory work. It is not light reading, but the serious beginner will find it a first-rate quick guide to the land of the list. Meant for undergraduates, it should be useful to kids from junior high up who really want to understand the computer.

Altair Design, developed by Ensor Holiday. Pantheon Books ($1.95). Eight designs make up this original and beautiful book. Each one is a lightly printed gray network spanning an entire marginless page (printed on one side of the page only to prevent color strike-through interference). Markers, colored pencils, pastels, watercolors or crayons will enable children and adults to exploit these remarkable traceries.

The simplest to describe is a square lattice of regular octagons. Around each octagon is a ring of four hexagons and five pentagons. The space is then cunningly filled with four heptagons around a square. Repeat, repeat, repeat. The other patterns are less simple: they suggest cut glass, Gothic windows, tartans, fantastic birdcages. Each one occupies the eye as well as the plane.

Ensor Holiday is a British biologist "whose hobby is geometry." These enticing empty bottles cry to be filled with designs, worked out in color and shape according to personal choice. Each pattern is supplied in eight copies, on perforated pages, with a few pages prefatory to the entire book.

Bigger and Smaller, by Robert Froman. Illustrated by Gioia Fiammenghi. Thomas Y. Crowell Company (95 cents). For young readers, this slim paperback presents simple, colorful wash paintings and black-and-white drawings dealing with the physical relationship of large and small. The frontispiece says it well: on the back of a behatted elephant a child strong man stands, holding overhead a horizontal beam that bears the full load of a brave mouse. How do you know the small girls in your class are small or the big boys big? Consider whales and pygmies and the giant of Fishhook, Ill., who weighed in at 1,069 pounds, dinosaurs and squirrels, sequoias, white mice, ants and newborn babies. The point comes clear, and there is something of texture to support it. The last page displays the starry sky.

Safe and Simple Electrical Experiments, by Rudolf F. Graf. Dover Publications, Inc. ($2.50). In more than 100 big pages this excellent paperbound beginner's guide details 101 electrical experiments investigating static electricity, magnetism and electric currents. They are realizable by grade school children who have enough internal energy and the ordinary resources of a household, plus a lantern battery, a bar magnet, a toy compass and a few feet of insulated copper wire. Weather permitting, the young experimenter can expect to make "respectable sparks" with a candle, a jar top, an old LP record and a piece of flannel, which combine to make a modern version of Volta's electrophorus. All the work is absolutely safe—except perhaps for experiment No. 35, meant for a "cool and clear winter day," in which one starts a spark from the betrayed nose of the just-stroked family cat!

Two clever little "motors" that require no current source, only a bar magnet to mediate rotation, are most unexpected designs. The current section includes a transformer and a somewhat tricky buzzer-relay-sounder that is based on the mechanical virtues of paper clips. Three-dimensional field patterns made visible with salad oil and steel wool are a little messy but marvelous.

The Secrets of Houdini, by J. C. Cannell. Dover Publications, Inc. ($2.50). A period piece, this is a paperbound republication (with newly added Houdini photographs of the time, decorated with Gloria Swanson and Jenny biplanes) of a 1931 memoir of Houdini by a friend and profound admirer who was himself a devoted amateur magician in London. The complex personality of the magician-prince is present but not central. Most of the book is devoted to reconstructions (generally, although not always, plausible ones) of how the hero managed his remarkable escapes and il-

© 1973 SCIENTIFIC AMERICAN, INC

lusions. How to break out of the "enormous new safe" delivered onstage by the proud London makers and locked by them in the presence of a committee of watchers? Houdini was, moreover, stripped and searched by a physician just within the half-open safe, while an umpire from the audience watched. Easy: get the safe delivered 24 hours in advance. Working with a crew of expert mechanics, replace the stiff springs of the locks with easily moved ones and prepare a special tool to pry the springs from within. How to carry that tool? Easy: shake hands with the doctor and the umpire before the door slams shut. The "umpire" is an old friend and the gadget is clipped to his ring. Restore the safe that night. To get free of an iron boiler riveted together on the stage, merely substitute soft locking bars for the tool-steel ones specified and delivered earlier, conceal about you a fine saw and cut your way through the bars behind the screen as the band plays. The skilled boiler inspectors won't notice the steel substitution; they are too busy looking after their rivets, and the mild steel bars can be told from the originals only by some kind of cutting test. Replace the original bars you kept concealed in the screening cabinetwork and let the local steelmen wonder. (They were certainly not implicated.) "Houdini specialized in employing... materials... above suspicion. His whole life appeared to be directed towards finding a flaw in honest craftsmanship, or, even if no such defect existed, to create one." Seances, disappearances, handcuff escapes, even card tricks, all are here. The style of analysis that is implied—a step-by-step analysis of both the physical and the human situation in detail, in bizarre circumstances that only the imagination of a Houdini could invent—is full justification for placing this how-he-done-it narrative here among the physical sciences. Plausible but erroneous assumptions are the downfall of those the magician deludes; with theorists it is the same.

LET'S PLAY MATH, by Michael Holt and Zoltan Dienes. Walker and Company ($6.95). An experienced writer for children here teams up with a widely known innovator in schoolroom mathematics to produce a volume of some 80 games and puzzles for children up to kindergarten or a bit beyond. The motif is struck by the phrase "Math *can* be child's play," but it would be no less clear to say child's play can be math. Math here is of course not mere number facts; the entire span of relationships—in space, logic, language and quantity—is touched by these games, whose devices include dances and cards, flags and mazes. Equipment of a simple symbolic kind is used, but substitutes are not difficult to find for nearly any part of it. To take one example, a child is asked to draw houses that are all the same shape and to color them according to a code card that specifies the colors for roof, wall, window and door. Then the colors permute by rotation. Next he may try the same game, now coloring to taste but with the shapes permuted among a small given set.

The first activity is to ask the child "what he is *not*." (One imagines that a long game with some kids!) These mathematical folk regard the recognition "I'm not my nose" as deep; it shows that a finite set is not the same as part of itself. Here is the strength and the weakness of their approach. The clear sense of how children learn in action and of how important a playful exploration of model relationships is to the forming mind (pre-math, or pre-language, or pre-life) we owe to pioneers such as the authors. They make it plain here too, in a helpful way. Yet not every parent or teacher will find it easy to set going games that flow not out of the child's wishes or experience but mostly out of a strong a priori structure. The essential improvisation, feedback and sensitivity to the opportune cannot be learned out of any book, even a good one such as this, which nevertheless provides excellent raw material for the serious teacher.

SPLASH AND FLOW, by Ruth Howell. Photographs by Arline Strong. Atheneum ($4.95). The evocative black-and-white photography and the simple text will help an early reader and interest a young listener as well. The first picture shows the sky on a rainy day: the source. There follow about 50 more pictures: umbrellas, seals, fish, snowflakes and icicles, an ocean tug and a bathtub one, a class cooking chestnuts and a girl blowing bubbles. There is an overshot turbine wheel made of pastry cups clipped between two picnic plates, a fountain, a manhole cover, a reservoir. The two final text pages are a bit too moralizing; the book ought to have ended with the contented young fellow at the fountain: "When you get thirsty, take a long cold drink."

Heavens and Earth

THE PLANET JUPITER AS IT APPEARED ON JUNE 1, 1971, by Ralph C. Turner. Rock Creek Experimental Station, Sheridan, Ore. ($15). MARS, by Patrick Moore and Charles A. Cross. Crown Publishers Inc. ($7.95). Globes and atlases can be less geocentric these days. Space buffs and skillful model-builders can celebrate *Pioneer 10*—which is scheduled to send us our first close views of Jupiter during the first week of December—by making up Turner's meticulous and handsome "globe" developed as a complex polyhedron, each hemisphere on a flat sheet of heavy paper. Master the cuts and the light scoring of the 288 triangles that build the near-sphere and you can view a 10-inch Jupiter, whose red, olive and yellowish markings represent the planet as it was at the epoch named. The drifting features were accurately rendered by projecting onto a white globe actual color slides made of Jupiter with the 61-inch reflector of the Catalina Station of the University of Arizona, copying the colors in pastels and reproducing them by color separation. The Great Red Spot is strong, two inches across, its color between fire red and copper red but one shade grayer. (Parents who are less dexterous with a sharp blade could frame the sheets and have striking geometric Expressionist prints.)

The Mars book seems almost familiar: it is a slim volume of large format, a good modest atlas showing place-names with carefully detailed features in realistic relief on a scale such that the U.S. would be about as big as your hand. But there is no U.S., no oceans, no lakes. This is the planet Mars, drawn from *Mariner 9* photomosaics by Charles A. Cross, a British engineer. Instead we can find the shield volcano Nix Olympica, the great equatorial rift valley, the cratered plains and the dry polar caps. Many good *Mariner 9* photographs document the maps, displaying dunes, stream beds and the little moons Deimos and Phobos, like two potatoes with craters for eyes. One section treats historical exploration, the voyages entirely sedentary and optical, of course. There are supporting charts and texts of aerographic facts and figures.

HOW THE WORLD WILL END, by Daniel Cohen. McGraw-Hill Book Company ($5.95). Henny Penny was misled: the sky will not fall. But the end of the planet, or merely of our species, is a probable event, one that has engaged thought for a long time. A simple upstate New York farmer, William Miller, thought he had winkled out the very year from a clue given in *Daniel* 8:14; reading years for the text's days, he put the end by fire in A.D. 1843. The meteors of 1833 were a portent, the comet of 1843 a terror. The Millerites became a mass movement in most of the cities of

© 1973 SCIENTIFIC AMERICAN, INC

the northeastern U.S. They prepared. When the year 1843 passed, a new seer among them set the very day: October 22, 1844. It too went by, the earth still firm. From that sect, however, grew vigorous Adventist groups still active today all over the world, although they are less clear about the date of the Second Coming.

This story of myth-making in everyday surroundings is capped by remoter visions: Ragnarök, the Apocalypse and Atlantis. Then too there have been the real explosion of Santorini, the little comet of the Siberian forest, the San Andreas fault—plenty of ends, or part ends, to place next to the more fanciful fears of comets' fiery tails. Maybe the earth's magnetic field is our shield; when it reaches a minimum in a few millenniums, something might happen. Or perhaps a supernova outburst, or a passing asteroid, will mean our end. More dangerous by far are war, famine and pestilence. Even if we humans and our progeny find the love and wit to survive all that, we shall not, save perhaps by emigration, long survive the death of our sun, charring the earth by fire as it evolves to a red giant. There are at least five billion years to go before we need flee the swelling sun. This admirable book, a broad exposition of eschatology past and present for ready young readers, with excellent photographs and a good reading list, ends in eloquence by citing from St. John the Divine "one of the most enigmatic and unsettling phrases in the entire Bible": "And when he had opened the seventh seal, there was silence in heaven about the space of half an hour."

A Book of Flying Saucers for You, by Franklyn M. Branley. Illustrated by Leonard Kessler. Thomas Y. Crowell Company ($4.50). Cheerful, appealing wash drawings full of point, looking rather like the paintings on the schoolroom walls, and a clear, brief text to match make up this small book for young grade school readers. There are photographs of flying hats and a Mars crater and useful lists of the dates of bright planet apparitions and meteor showers. The whole vexed topic—hoaxes, the will to believe, Ezekiel, balloons, St. Elmo's fire and all—is spelled out in simple language without either rancor or credulousness. If there are saucers (and there is no good evidence for them), they would have to come from the stars. Who knows? So the book ends. Although the most severe skeptics might not accept even this faintly agnostic air, the experienced astronomical author has made a model of honest approach and genuine content. The starship shown in one double spread should inspire a number of followers: one expects a farm, perhaps a barnyard—but an interstellar swimming pool?

From Afar It Is an Island, by Bruno Munari. World Publishing Company ($3.95). The beach is covered with stones. A child picks one up. "She shows it to us, all rust-colored and bare. So close it is just a stone like all the others. But if we hold it as if it were far away in the sea, it is an island. So many stones, all different." This small book of remarkable photographs, with a couple of lines of text to a page, is an artist's book, but Bruno Munari's eye sees the real world. Here it is stones he sees: rounded pebbles, glossy or matte, smooth or rough, yellow or sparkling—or in "black suits bulging out of white belts. The belts seem much tighter, but it is just that the white part is more tender and wears away much faster in wind and water." He draws on a stone, catching a monkey clinging to white vines in the jungle of the veined stone, and he tells you how to draw on stones too. Can you see a stone grow into a mountain? The first stone, three inches high, is as cliffed and blocky as an island. Put it near a tiny ship model, and it grows to gigantic heights. A real island that looks very like that stone is presented too. It is not easy to tell them apart. A tour de force of imagination, sensitivity and taste, this is a way into clear-sighted view of the world, an artist's pleasure and a beginner's natural history, a slight but real fusion of the outlooks of art and of science.

The World of Minerals, by Vincenzo de Michele. Photographs by Carlo Bevilacqua. World Publishing Company ($5.95). The yellowish rough diamond is lustrous in its blue kimberlite matrix. The green andradite garnets stud the asbestos fibers, natural jewels on a raveled beige cloth of rock. So, in 200 glowing color photographs as large as life (or a few times larger), you see splendid mineral specimens from the fine collection of the Museo Civico di Storia Naturale in Milan. The book is in fact a compact introductory text to the most important standard minerals. About 600 of them, arranged in familiar classes by chemical composition, are briefly characterized; their main occurrences are mentioned, and they are indexed by name of mineral species. The pictures present the showiest of the lot, the ones familiar to collectors. In this way the book, itself a handsome specimen of Italian bookmaking, unites two genres: the splendid picture book and the detailed guide to mineral identity. It is a real bargain for the crystal fan and a trap for the still uncommitted—down to the last full page, with its enlarged crystalline wreath of "pseudo-cubic individuals of white chabazite with pink apophyllite" against the green-brown matrix from the Alps near Bolzano.

City Rocks, City Blocks, and the Moon, by Edward Gallob. Photographs by the author. Charles Scribner's Sons ($5.95). "Gravity pulling stones from walls and cliffs," says the sharp, simple text. Equally sharp and even more vivid, the view the lens caught shows a brick wall in some waste lot, the bricks fallen away from a big patch. The magnified penny in another shot gives scale to the small curled shells there in the builder's limestone; still another picture shows the dark, fine-grained trap basalt, ballast among the railroad ties. So, through 40 photographs with their connecting text, this author-artist leads a young big-city reader into a sense of material and of change; into the continuity between a city and its mineral substances, some man-made rocks and some natural ones; into its processes of change and the main ideas and experiences of field geology. Gallob is sensitive of eye and thought; he knows the fossil places of the city—muddy playgrounds, soft asphalt, wet pavements—and he has seen its history. He understands collectors too, and he properly connects the moon rocks with the fun of real collecting open to a small child in the city. Again the author gives children a winning book, a small work of art and an open door to wonder and understanding out of the cramped city streets themselves. The gulf in time scale is not quite plain, but perhaps something needs to be left to grow toward.

Technologies

The Amateur's Guide to Caves and Caving, by David R. McClurg. Drawings by LaRhee Parker. Stackpole Books ($5.95). Dive: The Complete Book of Skin Diving, by Rick and Barbara Carrier, newly revised by Charles Berlitz. Funk & Wagnalls ($6.95). The Art and Technique of Soaring, by Richard A. Wolters. McGraw-Hill Book Company ($14.95). Our restless species occupies environments wholly alien to our evolution; we do so for the pleasure and excitement of the experience and for the sake of the challenge, and we call it sport. Here are three serious introduc-

© 1973 SCIENTIFIC AMERICAN, INC

tions to sporting entry into the dark caverns, the deep blue sea and the high, silent atmosphere. They belong to technology, since no unprepared adventurer can succeed in voyages to such new worlds; they beckon no less to the hopeful planner and dreamer than to the reader equipped and ready for the challenge. Any adventuresome young reader with an interest in one or another domain will gain from any of these books, even if the risks and costs of actual practice remain the "music of the future."

The most social and the least specialized of the three is caving. Caves are limited, although vast; they demand strict conservation. "Take nothing but pictures; / Leave nothing but footprints; / Kill nothing but time," reads a caver's motto. Cavers go in joined parties. Most of the book details the fascinating means of mountain climbing upside down in the dark, among the inorganic flowers that grow over the millions of years that mark the age of solution caverns. Vertical caving has developed particularly in the U.S. Southeast and Southwest, bringing with it climbing techniques little known under the sun. New forms of nylon rope without stretch (a braided sheath around a monofilament core) are used for the long, dark climb, with the beam of the headlamp lighting a mere fraction of the distance. The fastest way to climb a rope is with climbing cams that sling the climber to the rope by his right foot and left knee. The cams slide upward but grab tightly once a downward force sets in. The caver simply walks up the rope, a record rate of 1971 being 100 feet in 35.5 seconds!

The diver lives in a still more precarious world. Free natural dives, without any form of breathing equipment, are held the only sporting way to spear fish. (Breathing gear is reserved for longer stays below.) Free divers have gone down to 170 feet and speared fish weighing hundreds of pounds. The human body at rest requires about five cubic centimeters of oxygen per second (the women divers of Japan can get by with less than 3 c.c. per second after the first minute), and a diver starts down with a store of a liter or a liter and a half in his lungs. A face mask, fins and a snorkel are the essentials. A wild and ingenious technology has extended diving range and duration (at the price of cautious decompression after five minutes or so below 35 feet) and has given the diver weapons, watches, cameras, lifting power and—more or less—safety. The book is replete with proprietary products and their uses; this is a consumer's market, albeit a fascinating one.

Gliding became soaring once it was recognized that convective energy was available in the natural thermal currents of the atmosphere; mankind became as the great hawks. That was in the 1930's. Today the high-soaring pilot can ride the lee wave downstream from a mountain range, under the right conditions, to rise beyond where he can breathe. The champion has gone past 46,000 feet, "a celestial experience" even while wearing an oxygen mask and an electrically heated suit. This fine book, meticulous in both practice and theory, takes you soaring from the tow plane to the lee wave. Dynamic, shifting, lonely, the high air is even more demanding than the cave or the sea, and the amateur enters it only when he can bring still more knowledge and more advanced equipment. The cockpit panel of a serious sailplaner shows 10 dials, plus radio, oxygen gear and cameras. You can start out with a great deal less.

THE SIGHTS AND SOUNDS OF FLYING, text, photographs and sound recordings by Henry Humphrey. Little, Brown and Company ($7.95). People who dream of flying not simply as passengers crowded into a long aluminum tube but up front, with the wide view and the heavy responsibility, will enjoy this book. It begins in *two nine Romeo,* a little Cessna, while you take your first flight lesson. The camera and text together point out the instruments and the controls and describe the takeoff, a few effects of deliberate stall and spin and landing again. The landscape below you is Long Island Sound off Bridgeport, Conn. The second episode, a little inland, takes you on an hour's sailplane flight on a day with fluffy cumulus. The flight is quiet: no engine, and also no radio with a crisp and careful tower contact steering the traffic; this time you have to look out for yourself as you land downwind, floating in like a soap bubble. The third sequence takes a 747 jet to London. This time you are the planner and commander, not just your own pilot. Start with weather and dispatch a couple of hours before takeoff from Kennedy; walk into the cabin, and with your copilot start punching the navigational data into the flight computer. The flight engineer checks his dials; you watch startup with great care and give the engines all 17,000 horsepower with the four large throttle handles as you speed down the lighted runway. At early dawn you land at Heathrow. The return flight allows the text to pay attention to the radar traffic-control center at Islip on Long Island, which watches over all the planes in the busiest air-traffic region in the world. The radar screen is a spider web of changing bright lines.

The small stereo record that comes with the book samples all of this as it really sounded to the ear; it is convincing, if brief.

HOW A HOUSE HAPPENS, written, designed and illustrated by Jan Adkins. Walker and Company ($4.50). Hand-lettered and sharply drawn, the 29 big pages carry the reader fondly through the "happening" of a split-level frame house. The story begins with a crowded scene: family and pets in an old house. The Purlins decide to move. First they find a bank and a mortgage. ("Houses are not paid for in the same way hot dogs are.") Then a site. Now we meet Alexander Pushpin and Associates, four very informal architects. The plans —a picture language—are cleverly explained. First one learns about the three views by seeing the plan, elevation and section of a peanut, an apple pie and a sandbox. The contractor enters; his men excavate, pour footings, build foundation walls, erect the framing (two-by-fours, joists, rafters and all), sheathe the walls, insulate and shingle; install wiring, plumbing, air ducts and windows; put up the dry-wall interior; paint and finish, build cabinets and lay tiles and carpets. Finally the furniture comes. The house is a place to live in once the family arrives; it takes the family to make the house.

The visual style is attractive but the matter-of-fact subject matter somewhat cramps Adkins' familiar flair for romance, and he has allowed his whimsy rather heavy play with dress, pets and names. A family brave enough to buck the current interest rates will find this book good reading for all, particularly for children in the early grades.

A SKYSCRAPER GOES UP, by Carter Harman. Random House ($4.95). Just five years ago they were blasting a hole 60 feet deep into the Manhattan schist on the west side of the Avenue of the Americas between 49th and 50th streets. Three and a half years later a steel-framed skyscraper, the Exxon Building, stood there, 54 floors high, the walls straight limestone columns between vertical strips of windows. This book tells in genuinely interesting language and spirit just how that structure grew, from needs and plans to footings, to columns, to concrete and topping out, and how it lifts its tenants and supplies them with air, water and warmth, making connections with the

© 1973 SCIENTIFIC AMERICAN, INC

mains and lines that are the capillary system of Manhattan life. Now 225,000 deadweight tons of structure holds by day more than 4,000 working people; by night the cleaning crews finish up floor by floor, until only maintenance and security men are left; "the building itself never sleeps." The building is one element of a city such as New York; the text does not go much beyond the single tower, its parking and supplies, but within those limits it is a most readable and informative narrative. Costs are treated sketchily; "as much as a million dollars per floor" is about all we learn. Floor plans, block maps, sections, elevator schemes and a good set of photographs made over a period of time add to the verisimilitude of this witness's account of a skyscraper's growth.

SIMPLE PRINTMAKING WITH CHILDREN, by Harvey Daniels and Silvie Turner. Van Nostrand Reinhold Company ($6.95). PHOTOGRAPHY WITHOUT A CAMERA, by Patra Holter. Van Nostrand Reinhold Company ($8.95). Not many of us can draw Giotto's round, round *O;* kids might not even try. But a printing technique, the form now mediated by something more than a shaky hand, can lure a three-year-old to create a minor work of art. The richly illustrated Daniels-Turner book proves it. The pages are crowded with the ingenious, wry, witty or beautiful work of children, plus some by such heavies as Matisse and Picasso. How to print? Paper and ink you really need; the rest is at option. The simplest press is made by placing a board on your block and paper and standing on it. Your hand prints wonderfully well; other methods are stamping with a comb or an orange, or with a block marked by a toy train track and pressed into a surface of Elmer's glue. Rubbings from a hubcap will do, or a magazine halftone wet with solvent, a Styrofoam block cut and scraped away, a wrench or a hand used as a stencil or a wooden surface painted and printed. What it takes is originality, and that the children bring. The text, by two experienced teachers, is a literal eye-opener. Children and their teachers will find that these pages overflow with starters.

The Holter book, more formal in text and argument but about as rich, uses light-sensitive surfaces, mostly photographic printing papers of many kinds, to make images without a camera. The method is older than the camera itself; its first adepts were Niepce, Daguerre and Fox Talbot. They would be proud of the children who follow them. With or without a darkroom, grade school children (eight- or 10-year-olds and up) can produce striking results by painting papers with developer, fixer or toner; by exposing papers dotted with marshmallows or matches or macramé; by working on film and then printing on paper; by painting ink and cement on glass—by all these ways and many more. Works in the medium by Corot and Man Ray and Moholy-Nagy and contemporary hands are shown as examples of what schoolchildren can aim at and sometimes hit. Full process details and what and where to buy are made explicit.

These two books are kin: in each, art itself is close behind the mastery of simple but protean techniques, which give pleasure in themselves. What a counterpoint is here played out for art's sake with the transformations—positive to negative, concave to convex, rotations, translations and mirroring, an entire crystallography of the image plane!

People and Place

SHIMMY SHIMMY COKE-CA-POP! A COLLECTION OF CITY CHILDREN'S STREET GAMES AND RHYMES, with piano arrangements, by John Langstaff and Carol Langstaff. Photographs by Don MacSorley. Doubleday & Company, Inc. ($4.95). The streets of Boston and New York and Rapid City, no less than the more homogeneous districts of the Old World, sound to the gibes and rhythms of all kinds of children, forever newly recruited to a culture as old as the harvest and newer than yellow submarines. This feast for eye and voice presents name-calling ("Eddie Spaghetti with the meatball eyes" and "Ringo, Ringo, Ringo Starr") and ball, tag, rope, circle, action, drawing, dramatic and follow-the-leader games, all transcribed in our land and in our time. Tune and handclap rhythm are noted for many, such as the trochaic little rhyme, "I don't want-a let you go. / Just be-cause I kissed you once doesn't mean I love you so." Vigorous, as authentic as the rearing bike and the kicked can, the text and photographs are full of life and action, by no means prettified. The book is both a record and a guide to emulation, provided that the way is genuinely freed and that the adults, forever alienated by the years, manage to stay far off on the sidelines. No fights! The collectors, incidentally, come from the world of music theater, dance and film.

THE VICTIM IS ALWAYS THE SAME, by I. S. Cooper, M.D. Harper & Row, Publishers ($6.95). The freshman medical student "fell in love with the brain." As an intern he saw his first cases of dystonia: a rare genetic disease that, from the age of six or eight on, induces constant, lifelong spasms and tremors of the victim's uncontrollably contorted back, neck or limbs. A standard text admits: "It is, in truth, not a pleasant disease, and possibly in the end, death is welcomed gladly." Grim to read, but Dr. Cooper has by now operated on close to 400 dystonic children (out of his 7,000 surgically similar cases in all) and some 60 percent have had full relief of symptoms. The operation consists in destroying a bundle of cells in the thalamus, a walnut-size data-processing center lying deep within the brain, by touching them with a liquid-nitrogen-cooled probe.

The narrative is firsthand. It centers on operations performed on two young girls—both on the events themselves and on the surgeon's conversations with the patients and their parents. "Though victims, Janet and Susan were superior, stronger, and wiser than those about them." This is a brief, tender and profound book. It is not merely a glimpse of the hero-surgeon, although it is that. It is not an effort at popular neurology, although it succeeds in transmitting a sense of clinical science. It is an essay in humanity, an attempt to make honest exposure of the risks and fears of the surgeon who sees the suffering of the patients who lie under his drill, listening to him, conscious, fearful, fragile, innocent victims. It is a search for values threatened by facelessness, a search informed by Albert Camus—from whom the title comes—and some contemporary theologians. Readers of teen age and beyond will find in its plain language and concrete situations a smooth path to an ethical discussion as deepgoing as the dilemmas of life and death.

POPULATIONS: EXPERIMENTS IN ECOLOGY, by A. Harris Stone and Stephen Collins. Illustrated by Peter P. Plasencia. Franklin Watts, Inc. ($5.95). The faith of publishers in word magic has brought to stillborn existence many a small volume with the magic word "ecology" in its title. This one seems, among a dozen, the most honest and useful for young readers. It is organized around a number of tasks in the wide domain of population studies among humans and other living forms, each of them readable, pointed and practical for many children of school age. They are mostly counting, interviewing, weighing or modeling tasks. Only two (one with lima beans and the other with fruit flies, and both far from easy because of time span or tech-

© 1973 SCIENTIFIC AMERICAN, INC

nique) involve the use of living forms whose husbandry the experimenter must first master. These are real experiments just the same: weighing one's own meals (and finding their gross equivalents), counting human sex ratios at supermarkets, movies and construction sites, totting up the floor space in one's own house, counting heads in a fine photograph of the stadium during the Rose Bowl game, sampling marble populations and so on. The experiments are not dramatic on the surface, but they cut to the real problems of a science. Children —or any group of people who are serious about this weighty topic—will enjoy and profit for a long time from this book by an experienced author-artist team.

FLOOR OF THE SKY: THE GREAT PLAINS, by David Plowden. Sierra Club Books ($19.75). THE SUN DANCE PEOPLE: THE PLAINS INDIANS, THEIR PAST AND PRESENT, written and photographed by Richard Erdoes. Alfred A. Knopf ($4.95). In the year of the ironies of Wounded Knee and of wide public concern for wheat and beef the Great Plains must be attended to. The rolling steppe that extends from a little east of the 100th meridian to the wall of the Rockies is not the valley across the Sangres that Willa Cather wrote about: "Elsewhere the sky is the roof of the world; but here the earth was the floor of the sky." Her wonderful phrase fits anyway, and Plowden's quiet, wide pictures breathe of the plains and sky.

He is a photographer of prairie and plain who lives in Sea Cliff, N.Y., and in his book one can see the silent battlefield of the Little Big Horn, twilight across the Sandoz homestead in the sand hills of Nebraska, a pensive cowboy foreman, the elevators, combines and freight cars by which the Great Plains feeds so many of us—always on that sky's floor. His text begins with Precambrian bedrock and ends with the issues of our day, like the doubled wheat yield per acre on Bill Stramer's North Dakota five sections, won "not by love alone. He is constantly at war."

Plowden includes the Indian story fairly, if briefly, but the Plains Indian does not himself appear, except implicitly in the small tablets where Custer's cavalrymen lie buried. The Erdoes book, written and illustrated for young readers, is devoted to the Plains Indians, from the days when they hunted on foot with their dog travois until wealth and power came to them with the escaped horses of the Spanish (probably not Coronado's two mares but the outcome of the Pueblo Revolt of 1680) and left them to the badlands and the oppression of the dusty reservations. Their sun dance is here in detail, recent photographs matching a painting from 1832, an ordeal dance that at Wounded Knee still requires the bravest dancers to pierce their flesh with eagle's claws.

Bestiaries

HOSIE'S ALPHABET, pictures by Leonard Baskin, words by Hosea, Tobias and Lisa Baskin. The Viking Press ($4.95). THE ZOO CONSPIRACY, by Betty Levin. Illustrated by Marian Parry. Hastings House, Publishers ($5.95). ANIMALS IN ARCHAEOLOGY, edited by A. Houghton Brodrick. Praeger Publishers ($15). The bestiary is one of the oldest literary forms; for a long time we humans have delighted in representing some of the other links of that great chain of organic being. Here are three excellent and wonderfully distinct examples of the ancient form.

The Baskin book is for those young people who still have to learn the letters and for their fortunate elders who get to show it to them. The meticulous, deeply colored washes of this distinguished American artist present real beasts from *A* to *Z*, with a demon, "a ghastly garrulous gargoyle," an (almost) invisible violet unicorn and a grand, multicolored, befeathered *X* of a dragon thrown in to represent the artistic imagination. The choice was Hosie's when he was three; he got his mother and his brother to help with the big words. The furious fly is a half-inch beauty, and the omnivorous swarming locust is orange-eyed and apocalyptic in his green armor. *The Zoo Conspiracy* is a small novel, usually cheerful, sometimes a bit tense (but it ends happily), for readers in the grades. It is fiction, plainly, since it presents animals as actively thoughtful characters talking to people, particularly to an unhappy little girl named Lena, who doesn't seem at all as ghastly as she thinks she is. It is the diversity of animal characters that makes the book: a New Zealand tuatara, platypuses, an endearingly furry ball of a slow loris, an aye-aye, a kinkajou, a honey badger and a boa. All these beasts are presented in elegant line drawings so simple you'd think you could do them. Even the silent, ugly coelacanth stops shedding his round, oily underwater tears when the evolutionary moral is finally struck on one of Lena's gum wrappers: "You are the Crossroads of something new." Off she goes, a little more content. The endpaper bears a fine family tree from Crossopterygian to primates. (Don't touch this book if anthropomorphism pains you; otherwise enjoy it.)

Adults young and old will value the Brodrick volume, which displays the tradition of animal art from the very beginning. Seven archaeologists and art historians discuss the place of animals in ancient art, one for each period or culture: the Old and New Stone ages, Mesopotamia, Egypt, the Aegean, India and China. This catholic approach is uncommon and welcome. André Leroi-Gourhan presents some fascinating remarks about the cave bears, whose strange ossuaries leave "a curiously ordered impression," the random work of "innumerable generations of ambling, digging cave-bears." The painted caves are here, the first human art and already, he asserts, associated in a complex metaphysical framework. For the rest let a sample of the figures merely represent the generally excellent and informative essays: a figurine from the Siberian Neolithic, a bronze onager from Ur, the griffons in the throne room at Knossos, a peacock from Bharhut and two symmetrical horse skeletons flanking the buried chariot and the skeleton of their charioteer in the tomb at Anyang.

INSECTS AS PETS, by Paul Villiard. AMPHIBIANS AS PETS, by Georg and Lisbeth Zappler. With photographs and drawings by Richard Marshall. Doubleday & Company, Inc. ($4.95 each). These two volumes of a larger series are manuals of husbandry for unusual pets. The insect book includes beekeeping in rather limited detail (for pet purposes, not honey yield). Its other pets cover a considerable range: ant lions, butterflies, fruit flies, some beetles, the mantis, crickets and half a dozen more. There are commercial sources for most of these, as eggs or in other stages, but some, such as the ant lion and the dragonfly, need to be collected in the wild state. The know-how is included. Villiard has obviously done most of the work he describes. His favorite is the praying mantis, which comes "nearest of all insects to being a pet." This beautiful and fearsome creature with the inscrutable gaze need not be caged; given the freedom of the house, it will clear the premises of all bugs and insects. It is clean and neat. The mantis can bite, but the bite is "a feeble thing, and not painful." Still, it will eat a hole in your finger if you let it: "I suppose, if you stand and wiggle your finger while they chew at it, they will eat it all, leaving the nail and the bones." Good luck!

The amphibians are a more demanding group. Woodland and marsh varie-

© 1973 SCIENTIFIC AMERICAN, INC

ties can be taken in the wild with some care by methods that are described. Many foreign kinds are available from pet dealers. The easiest to rear is the Japanese newt, with its black back and red belly; it will quickly eat raw meat from your hand, and it lives for years with a minimum of attention. The task is clearly more arduous for many species, however, since "the healthiest food for amphibians is crickets." The cricket itself is a pet recommended in the first of these books. Here, crystal clear, is the meaning of the food chain. Crickets can be bought commercially, however; we are given the address of a large cricket ranch in Memphis.

THE WEB IN THE GRASS, by Berniece Freschet. Illustrated by Roger Duvoisin. Charles Scribner's Sons ($5.95). THE SPIDER WORLD, written and illustrated by Penelope Naylor. Franklin Watts, Inc. ($3.95). TRACKS BETWEEN THE TIDES, by Elizabeth Shepherd. Illustrated by Arabelle Wheatley. Lothrop, Lee & Shepard Co. ($4.25). LIFE IN A BUCKET OF SOIL, by Richard Rhine. Illustrated by Elsie Wrigley. Lothrop, Lee & Shepard Co. ($4.25). THE BUG CLAN, by Ross E. Hutchins. Dodd, Mead & Company ($4.25). These are varied but parallel books. The first is aimed at an audience that is read to but is free to look a long time at the colorful paintings; the others are successively more difficult; the last will engage readers old enough to collect knowingly for themselves. All deal with some group of small animals, no single animal larger than your hand and most of them smaller than your finger.

The Web in the Grass presents a simply poetic text of a few lines per page that tells an endless cyclical tale. On the first page a little spider spins a shiny thread. On the last page "somewhere in a meadow . . . in a forest . . . in a garden . . . a little spider hides, and waits." In between, spread across a couple of dozen glowingly colorful paintings, the life story of a spider is told: web, prey, predators, egg sac—and a blue sky stitched with the silky skeins that waft spiderlings to the wind.

The Spider World casts a wider web. Meant for the curious in the fourth grade and beyond, it tells about spider anatomy generally, about their webs simple and complex, about spider courtship, life cycles and enemies. A fair number of groups of spiders are briefly characterized: trapdoor spiders and jumpers, tarantulas and daddy longlegs, spiders that spit and spiders that throw sticky balls. Not much space is spent on identification, which is sensibly surrendered to more detailed and more local guides. Although this is mostly a sober and matter-of-fact account, imaginative material is not omitted entirely: the book includes two tales of the West African spider-hero, Anansi. The black-and-white toned paintings are convincing and attractive renderings with a sense of style.

The next two books, one about the beach and the other about the backyard, are both guides to actual exploration and capture. In the sandy beach there live, more or less hidden, a variety of remarkable forms: mud snails, worms of many kinds, clams, pea crabs. Identifying them by common name and formal name, giving both Atlantic and Pacific examples where they differ, Elizabeth Shepherd makes it seem exciting and not very difficult to find these curious creatures on your own beach. The writing is full of life and wit. If you leave a piece of bait as big as a broken clam in two inches of water, walling it with sand to keep it from washing away, you can watch the mud snails gather. Some of these voracious scavengers will appear at once, and before long "snails from six or more feet away have picked up the scent. I wonder if this mass of hungry snails will frighten you too." The tools of the trade are magnifier and salad fork, eyedropper and sieve, pail and jars, and a face mask for close watching in shallow water.

The bucket of soil from garden or yard is, like the sandy beach, home for many special and important forms. None here are as small as bacteria or protozoa, but they may be only as big as a sand grain, repaying the use of a hand lens. None, on the other hand, are larger than worms; the bigger, rarer dwellers below, such as moles and woodchucks, are omitted. In the range between the careful searcher can find plenty of worms and snails, springtails and centipedes, wood lice, ants, beetles. The task is harder than the beach examination, and the book is a little more difficult. Soil is a darker jungle; the tools include strainers, specialized funnels, traps and tiny soil cages: recesses in moistened plaster of Paris, covered with glass slides. These are a step more special than the household devices the sandy world yields to, although they are not hard to make. A small team of young naturalists would work out very well in both environments. This book, like the one on sand creatures, ends with an account of what humans are doing to both of the ancient environments it describes. And each has a good reading list.

The final book describes the big insect order made up of animals that have sucking or piercing mouthparts with which to siphon out the sap of plants or the blood of animals. The true bugs rank after the beetles, the butterflies, the ants and bees and the two-winged flies in number of species. Ladybirds and aphids, spittlebugs and treehoppers, cicadas and scale insects all enter the text, and most appear in the remarkable photographs this expert writer-photographer knows so well how to make. The jacket has the only color photograph, a treehopper striped and studded with yellow and red, magnified thirtyfold. The cicada story is told here very briefly; it would be worth a volume of this size, not a mere dozen pages. The cicada nymphs shown here, a sixteenth of an inch long, enter the ground. There they live on the sap of underground roots until they grow to an inch or so, to emerge into the summer sun 17 years later, timed to a few days. The Chinese felt in this story the sense of immortality.

Flesh and Bone

BARE BONES: AN EXPLORATION IN ART AND SCIENCE, by Beverly Halstead and Jennifer Middleton. University of Toronto Press ($7.95). MUMMIES, by Georgess McHargue. J. B. Lippincott Company ($1.95). X-RAYING THE PHARAOHS, by James E. Harris and Kent R. Weeks. Illustrated in color and in black and white. Charles Scribner's Sons ($10). THE ILLUSTRATIONS FROM THE WORKS OF ANDREAS VESALIUS OF BRUSSELS, with annotations, translations, discussion and biographical sketch by J. B. deC. M. Saunders and Charles D. O'Malley. Dover Publications, Inc. ($4). What a lively bag of bones these books are! Readers from 10 up will find something in any one of them to fascinate, both in text and visually; no library can afford not to shelve at least the one on the list that is best suited to its clients. *Bare Bones*, the work of two British scientists, casts the widest net. Personal rather than comprehensive, it invites the reader (he must be no beginner) to a trip through the authors' world of bones. (The two of them appear, nose toward nose, in a double cranial radiograph in the first few pages. We see skulls there, minds in the rest.) How did bone originate? As a mitochondrial scheme to store seasonal phosphate excess, at the same time getting rid of the unused calcium. The volume is full of other surprises and insights, from the fact that the Neanderthal type specimen was a bent, infirm old man to the neat hole in the temple of Rhodesian man, no ancient alien cosmonaut's bullet mark but an old abscess. Dürer, da Vinci and Henry Moore fur-

© 1973 SCIENTIFIC AMERICAN, INC

3331 PAMe

Mercedes-Benz agrees with its competitors: You should drive their cars before you drive a Mercedes-Benz.

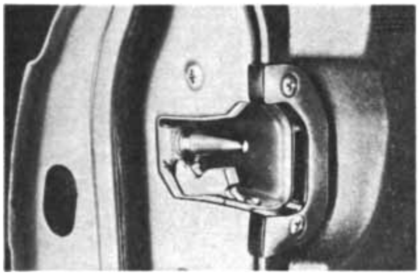
There are many good cars today. There are even some in which this feature or that is superb.

But one or two outstanding features do not make a great car. It is the sum total of all characteristics that counts.

Judged in this way, a Mercedes-Benz stands comparison with any car you can buy.

Progress is technology – not sheet metal.

Mercedes-Benz emphasizes the car under the skin – because first and foremost, an automobile is a machine. Its performance



The safety lock, which prevents the door from springing open or jamming shut.

can make your driving life safer and easier; its appearance cannot.

For instance, a car should not suddenly dart to the right or left in gusty sidewinds. And a Mercedes doesn't. It reacts gently to that "slamming" effect, deviating only gradually from its path.

Contributing factors: A low center of gravity; a wide track; a long wheelbase; balanced distribution of axle loads; aerodynamically sound body design.

Quick reflexes in a crisis.

The car must obey the driver, not the other way around – especially in a sudden emergency. The reflexes of a Mercedes are engineered to be as quick, as alert as possible.

The engineering formula includes a diagonal swing-axle with independent wheel suspension, precisely located wheels and tenacious roadholding. Firm suspension with gas-filled shock absorbers to prevent pitching. Anti-dive control to retard "nose-dive" in hard braking. Recirculating ball steering to eliminate the need for constant steering corrections. And a built-in steering shock absorber; it helps muffle the effects of bumpy roads before they can reach your hands on the wheel.

Buy a Mercedes-Benz and buy 30 years' worth of work on safety.

Mercedes safety is not tacked on. It comprises more than 100 design features and fittings, carefully integrated into a total safety design.

From the rigid "safety cell" body shell to a deformable instrument panel, built to yield under impact in progressive stages. From a laminated glass windscreen to patented safety locks on every door.

You will find four safety design features in the steering system alone. Padded steering wheel hub, impact absorber, telescopic column, and a steering box placed well behind the front axle.

Many cars boast comfort unsurpassed – when they're parked.

Automobile comfort is an exacting science, not just a matter of cushions and carpets.

What good are the softest seats when you squirm with a backache after a few hours? What's the use of a pushbutton radio if you can't hear it at 100 km/h? What's the point of elegant interior styling if you switch off the headlights instead of the wipers while driving at night?

A Mercedes is painstakingly engineered for driving comfort, even on marathon journeys.

With seats you can sit in comfortably after six hours. Quiet conversation, even at 180 km/h. And functional placement of every control.

The secret ingredient in every Mercedes-Benz: conscientiousness.

No car in the world surpasses a Mercedes in the care with which it is assembled and finished.

And designed. From the first stroke on the drawing board until series production, Mercedes invests from 5 to 6 years of development and tests. (Other makers usually need about 4 years.)

On top of a basic phosphate coat, each new Mercedes is lavished with up to five layers of paint. Underbody, wheel arches, longitudinal members and the underside of the luggage-compartment floor carry a thick coating of underseal. A special wax is sprayed into all cavities subject to corrosion.

Before a new seat can enter production, its suspension must survive 300,000

The rear light unit repels dirt, because of its ridget surface, developed in the wind tunnel.

load changes on a vibrating rig. This corresponds to a distance of 500,000 km.

The heating and ventilation system has passed wind-tunnel tests that can simulate outside temperatures from −40° to +40°C. Actual tests are conducted in Sweden and Africa.

Every engine, every rear axle, every gearbox is checked individually on the test stand.

Out of every ten Mercedes production workers, one is a quality controller.

Put this story to a test. Drive a few competitive cars. Then drive a new Mercedes-Benz.

Mercedes-Benz

© 1973 SCIENTIFIC AMERICAN, INC

© 1973 SCIENTIFIC AMERICAN, INC

The real
Through this area, in only one of the oil pipelines that lies beneath it, have moved 24 million gallons of energy in the past month. Energy that powers industry, homes, cars, planes, ships, trucks. Energy that sustains the life style Americans have come to take for granted.

We learned a long time ago that practical things needn't be ugly. That they needn't be seen at all. And that they needn't waste valuable land, divide neighborhoods, create an industrial feel in a rural atmosphere.

The ideal
Continuity of supply by responsible energy companies that have demonstrated their concern for the environment.

AtlanticRichfieldCompany

© 1973 SCIENTIFIC AMERICAN, INC

nish the visual accent to the final chapter of a genuine exploration, a book both deep and broad in small compass, a palpable bit.

The first of the two books about mummies, an inexpensive and enticing little paperback, belongs to a series dubbed "The Weird and Horrible Library." Granting the unusual nature of the subject, the reader is not horrified (although the standing row of naturally mummified poor citizens of Guanajuato, shown here in a halftone, did fill that bill when the reviewer visited their church a while ago) but edified and instructed. Mummies everywhere are discussed, from the mammoths of Siberia (caught in not a planetary convulsion but a very local trap: a layer of soil windblown across a crevasse in the buried edge of a receding glacier) to the social innovators Jeremy Bentham and V. I. Lenin, their remains still visible in London and Moscow. The second book centers sharply in Egypt. There an expedition from the School of Dentistry of the University of Michigan has been working with counterparts from the University of Alexandria and the experts of the great Egyptian Museum and the Egyptian Antiquities Department to X-ray the mummies of the dead kings and noblemen of Egypt. Modern equipment allows an intimate visual examination of mummies through their intact wrappings; no student of the past would destroy all those remarkable packages, so that only a few have been examined before. The medical purpose was to examine the development of human dentition over centuries. An ancient burial ground had been studied, as had the teeth of living Egyptians, but there remained the question of differences among ancient social classes: Did the better-fed share the commoner's dental problems? The pharaohs alone could give the answer, which seems to be yes. Not only decay but also heavy wear and frequent abscesses plagued the kings of Egypt. The diagnoses were literally revealing. Secrets appeared. The small mummy buried with the high priestess Makare, who died in childbirth or near to it, was not her baby but a baboon. Grave robbers were arrested and tried around 1000 B.C. and in A.D. 1900. (Some trial reports are cited.) The embalmer's art declined after the Twenty-first Dynasty, for the succeeding dynasties were foreigners and the techniques were poorly imitated. The early New Kingdom saw the art at its height; here are color photographs of the beautiful Thuya, with "long reddish-blond hair... astonishingly lifelike," and a black-and-white one of the "doll-like" Queen Nodjme, with artificial eyes and molded cheeks. The pharaoh of Moses' time and he who was Ozymandias are here as well, inside and out. This detailed but nontechnical report, written by an orthodontist and an Egyptologist, precedes the complete roentgenographic atlas the expedition will one day bring out to expose the pharaohs. Given any initial interest, no reader can easily put this book down.

The final book, a genuine reprint bargain, displays the wonderful anatomical illustrations of the first modern work of human anatomy. The bones and tendons appear against a changing landscape that is in each case harmonious with the state of the cadaver. These drawings are not merely examples of the glory of Renaissance science and art; they remain today first-class anatomical studies for school libraries. (The occasional deficiencies of 16th-century science are amply noted in the text.) Medical and premed students with any taste for the history of their art will find this large and inexpensive facsimile of a scholarly work first printed in 1950 an engaging gift.

To Find a Dinosaur, by Dorothy E. Shuttlesworth. Doubleday & Company, Inc. ($4.95). The Dawn of Life, by Giovanni Pinna. Photographs in color by Carlo Bevilacqua. World Publishing Company ($5.95). Dinosaur buffs in the early grades can start toward bigger books with a freshly seen and personal introductory book by a museum editor, excellently illustrated. The biology is there, the "family tree," names, reconstructions, tracks and the like, treated with lightness and accuracy. The book takes its reader out on a real fossil hunt by bus with a bunch of youngsters from the Newark, N.J., schools, led by an enthusiastic teacher of paleontology, Robert Salkin, dubbed "Mr. Fossil" by the students. It is a great day, even if he has to admit that no one has ever found a dinosaur fossil in New Jersey, since the children travel out to the Delaware Water Gap and there find plenty of trilobites and crinoids—*older* than dinosaurs. Ten thousand girls and boys have made such trips, and two high school boys—meet them here as Anthony Lessa and Paul Olsen—have found hundreds of dinosaur footprints, some made by animals that were among the smallest dinosaurs known, right in Livingston, N.J.

The encyclopedic Italian natural-history volume is a bargain introduction to invertebrate paleontology. The specimens are nearly all from Milan, beautifully presented in glowing color, and often bigger than (can one say?) life. The arrangement is systematic: the book reaches from radiolarians to some sea urchins that look very up to date indeed. No dinosaurs, or indeed any very large animals, appear; a hyena coprolite and a lizardly footprint alone represent our backboned kin. The twisted ammonites, the massive lobed trilobites and the clams shown big as your two hands should be the envy of shell collectors, modern or fossil.

Animals and Plants

What Do Animals Eat?, by Ruth Belov Gross. Pictures by Don Bolognese. Four Winds Press ($4.95). Readers in the early grades will enjoy this factual little book of 25 brief chapters, each with a sensitive line drawing of the animal eating, each made up of a number of direct questions and their answers. The text in lilac and the drawings in green give the small volume an unusually attractive look. Dinosaurs don't eat anything now, we read. When they were living, they ate many familiar things, such as eggs and insects and fruit and water plants, and "there was one thing that some dinosaurs ate that no animal can eat today—they ate other dinosaurs." The foods children like best are sketched and listed: spaghetti, watermelon and ice cream sundaes. Bears and bees and lions and dragonflies are included; one wishes automobiles had been given a chapter.

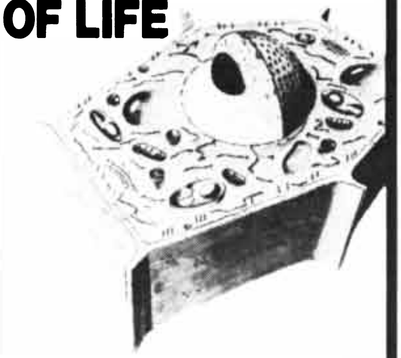
On Behavior: Instinct Is a Cheshire Cat, by Peter H. Klopfer. Illustrated by Martha Wittels. J. B. Lippincott Company ($5.25). The title reveals the nature of this highly unusual book: it is rich in content and sophisticated in interpretation, but it does not always make a point clear. Klopfer is an ethologist at Duke University; his own research and more are outlined in the text, complete with epistemological doubts and speculation on the biological bases for art and for altruism and on the role of language in knowing. Even the illustrations are unusual and demanding. They are mostly abstract black-and-white drawings that graphically suggest the logic of an experiment.

The central topic of this work is the nature of behavior development in animals reared in deliberately perturbed environments; that is the author's own research mode. The familiar imprinting story becomes far more intricate, and its implications unclear, once analysis asks details such as whether ducklings imprint the male or the female pattern of their parent models. Experiments are described with goats and lemurs and chip-

© 1973 SCIENTIFIC AMERICAN, INC

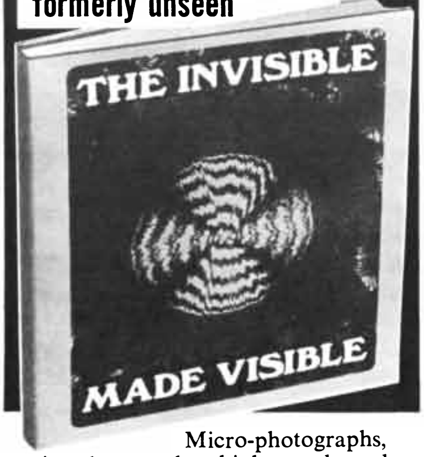
Ernest Borek, acclaimed for his achievements in both molecular biology and science writing, tells about: the truth behind the old wives' tale that children grow in their sleep; the hardy microbe that lives happily in nuclear reactors; the virus that beat Buckminster Fuller to an idea by several million years; the prospects for genetic engineering and human cloning. . . .

ERNEST BOREK
THE SCULPTURE OF LIFE



Hardcover $10.00, Paperback $2.95
At bookstores or from
COLUMBIA UNIVERSITY PRESS
136 South Broadway, Irvington, N.Y. 10533

Pictures of astonishing beauty that reveal the formerly unseen



Micro-photographs, time-lapse, ultra-high-speed, and other new techniques that have enlarged the limits of man's vision are thoroughly described and strikingly displayed.

THE INVISIBLE MADE VISIBLE THE EXPANSION OF MAN'S VISION OF THE UNIVERSE THROUGH TECHNOLOGY
By Ernst von Khuon. 39 color plates, 236 b & w ills. 300 pp. 10 x 11½ ins. $19.95 at all bookstores
NEW YORK GRAPHIC SOCIETY
Greenwich, Conn. 06830
A Time Incorporated Company

ping sparrows. The results are frustrating; the imprinted duckling preference changes, for example, in "some curious way" with the context. So the text runs. Few books for young readers (experienced reading is required) give such a strong and honest account of the depths of a science. At the same time one can fault the book for the depths it enters in so brief a space. The claim that our language misleads us because we say "It thunders" when there is no "it" is made in a couple of pages, with deference to the Hopi. This Whorfean claim seems far from established; what is missing is the idea of approximation: an attack on all nouns is a bit sweeping. This is a fine book, a hard one and a real challenge for the thoughtful.

PIGEONS AND PEOPLE, by Mildred and John Teal. Illustrated by Leslie Morrill. Little, Brown and Company ($4.95). "The most cosmopolitan of all birds, at home in all cities of the world, is the pigeon. The city seems made for him." *Columba livia,* the rock dove, has nested on cliffs since long before our strain came down from the trees. The species ranged from the British Isles to the Middle East and has been domesticated for 5,000 years and more; so many artificially selected tame birds have become feral that no pure wild pigeons exist. The cliff birds of Spearfish Canyon in South Dakota differ from city pigeons only in diet: the wilderness birds are seedeaters and the city pigeons live on the litter and handouts of people. The feral birds are both nuisance and companion, so well paired with people that they will be with us for a long time, eating our leavings, nesting in our structures; the bird is wary enough to escape those of us who dislike him and "winsome enough to get many of the rest of us to feed him." They breed fast, and they convert seeds alone into protein rich enough to feed the young ones in the nest from the protein-rich "pigeon milk," a curd formed in the parent bird's gut. It is true that men extinguished the passenger pigeon. (Audubon, encamped in Kentucky on the banks of the Ohio, saw a flight pass him for three days, in flocks that obscured the sun; he reckoned more than a billion pigeons in one flock, a thousand times the New York City number.) The passenger pigeons lived on hardwood seeds, and the clearing of the Eastern forests ended their support; the massive killings, homey slaughter by entire families to fill barrels for salting and to feed the hogs, only accelerated the end. What would St. Mark's be without pigeons? "This book does not take sides with pigeon-lovers or pigeon-haters." It explores the why and how.

TIGER HAVEN, by Arjan Singh. Edited by John Moorehead. Harper & Row, Publishers ($8.95). "One early morning in May 1959 I set out from my farm on my elephant Bhagwan Piari towards the forest which runs along the border of Nepal." So goes the opening sentence of this personal narrative and plea. That smashing sample should make it clear which readers will find this earnest story exactly what they want to read. Singh, shown in color riding with the mahout on the wise and devoted 70-year-old family friend Bhagwan Piari a few pages later, is a lifelong hunter, a member of a distinguished military family in India, who now devotes his energy and knowledge, both abundant, to preserving from the gun the noble tiger and other game of the vanishing Indian forests.

The plains stretch far north of Mother Ganges toward the Himalayan range. With the mountains in sight, the foothills support a vast monsoon forest dominated by the sal tree. Once a broad grassy belt separated the populous and cultivated plains from the wild forests, but now people and their farms press up to the Nepal border and the tigers' swampy home. There Arjan Singh cultivates some sugarcane, but even more he attends to the striped king of cats. He has browbeaten the state into making a gun-free sanctuary for the tiger, but the pressures of impoverished India bring into the shadowy preserve grazing cattle, honey collectors and timber cutters, all foes of the tiger. At the turn of this century India may have sheltered 40,000 of these great cats; today there are perhaps 2,000. How tigers live and hunt, how man and tiger can coexist, how the claims of greedy or hungry men can be weighed against the legacy of that resonant roll that echoes through the forest is the burden of this book. The hour is late, but it is not yet too late. Singh understands the thrill of the hunt but he argues persuasively that we cannot afford to indulge it; the photographer's chase is the more sporting, the more intimate and the more satisfying. It lacks only the communal nature of the shooting party. What the tracker with the camera brings home to display is far finer than the decaying pelt, whose sheen disappears as the whiskers fall out and the teeth crack. Tiger coats (at $10,000 each) are, of course, intolerable. The solution lies in true preserves, barred to all users save the tiger and its prey, along with the tourists whose fees provide an economic return for the fraction of the land

© 1973 SCIENTIFIC AMERICAN, INC

the wild forest must forever claim. Kenya has done it; can India?

A Natural History of Giraffes, pictures by Ugo Mochi, text by Dorcas MacClintock. Charles Scribner's Sons ($5.95). Ugo Mochi is a sculptor of animals. This book is distinguished by his work in the form of "graphic sculpture": cutouts from single sheets of heavy black paper, somehow suggesting motion and depth in a quite remarkable way. The text is brief, rich and clear, the work of a mammalogist who can write and who has seen giraffes in the savanna. Spots, form, function, motion, herds, calving, predators and other ills—these are the topics included, tersely but sharply.

Spots are inherited in some detail, it seems, but just why is not clear. Camouflage does not protect giraffes against the lion, their main predator, because the lion hunts mainly by scent; their good eyesight and high viewpoint are their chief protection. Telemetry has demonstrated that the giraffe does not have particularly high blood pressure; instead its elevated brain is supplied with oxygen by blood vessels that manage a lot of valving and pumping. A giraffe has two gaits, the pace and the gallop. The full gallop, head forward and low, is done at a slow yet graceful rhythm, tens of feet to a one-second stride. Man is its most dangerous enemy; 70 years ago the giraffe was on the way out. Protection came just in time, and now the giraffe is stalked mainly by camera.

The cutouts are no less than stunning; the giraffe silhouettes lie down, get up, sleep, nurse and run.

Watch Out, It's Poison Ivy!, by Peter R. Limburg. Drawings by Harris Petie. Julian Messner ($5.29). From Guatemala north across the continent to the Canadian pines, poison ivy is found everywhere, save only for California and Nevada. It is present wild on no other continent. This simply written and well-illustrated account is a good mix of practical lore and botanical background. Seven people in 10 possess a strong allergic reaction to the oily substance found in all parts of the plant: leaf, stem, berry, root, sap. Its relatives are poison oak, sumac, cashew, mango, pistachio and the lacquer tree, and many of these contain a similar irritant. Sections on how to get rid of the plant, how to treat (and how not to treat) the affliction and above all how to recognize the plant in its many forms and guises complete the little book, for readers and hikers up to the sixth grade or so—and any uninformed adult friends.

INDEX OF ADVERTISERS

DECEMBER 1973

© 1973 SCIENTIFIC AMERICAN, INC

ANNUAL INDEX

The following index lists all the authors and articles that appeared in SCIENTIFIC AMERICAN *during 1973. Also indexed are "Mathematical Games," "The Amateur Scientist" and an essay book review.*

AUTHORS

© 1973 SCIENTIFIC AMERICAN, INC

ARTICLES

© 1973 SCIENTIFIC AMERICAN, INC

In pursuit of the Titanothere, the Allosaurus, and the Eohippus, they braved the wrath of hostile Indians, rattlesnakes, and six-gun toting bandits. The bone hunters' race for the rich fossil finds of the Great West was as dramatic as any land rush or cattle stampede, and Url Lanham, Curator in the Museum of the University of Colorado, tells the tale with a connoisseur's appreciation of its color, excitement, and scientific importance.

THE BONE HUNTERS
Url Lanham

COLUMBIA UNIVERSITY PRESS
New York, New York 10025

AN INVITATION TO JOIN THE . . .

AMERICAN LITTORAL SOCIETY

- To learn about what lives in coastal waters, marshes, and estuaries, and why.
- To support the Littoral Society's coastal zone conservation projects.
- To receive Society publications — a quarterly journal, newsletters, conservation alerts.

Annual dues are $7.50 ($5 for students) and help support the Littoral Society's conservation projects.

AMERICAN LITTORAL SOCIETY
HIGHLANDS, NEW JERSEY 07732

To join the Littoral Society, please fill in the coupon below:

Please enroll me as a member of the American Littoral Society.
Enclosed is my check for $ ______ for first-year dues.

NAME ______
ADDRESS ______
CITY ______
STATE ______ ZIP ______

Dues are tax deductible.

MATHEMATICAL GAMES

© 1973 SCIENTIFIC AMERICAN, INC

THE AMATEUR SCIENTIST

BOOKS

To preserve your copies of SCIENTIFIC AMERICAN

A choice of handsome and durable library files—or binders—for your copies of SCIENTIFIC AMERICAN.

Both styles bound in dark green library fabric stamped in gold leaf.

Files—and binders—prepacked for sale in pairs only.

Index for entire year in December issue. *

FILES *shown at left*
Hold 6 issues in each.

Single copies easily accessible.

Price: $4.00 for each pair (U.S.A. only).

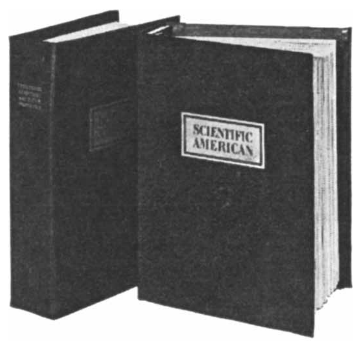
Address your order, enclosing check or money order, to: *Department 6F*

BINDERS *shown at right*
Hold 6 issues in each.

Copies open flat.

Price: $4.50 for each pair (U.S.A. only).

Address your order, enclosing check or money order, to: *Department 6B*



New York City residents please add 7% sales tax
Other NYS residents please add 4% state sales tax plus local tax

*Supply of back copies of SCIENTIFIC AMERICAN is limited. A list of back issues still in stock is available upon request.

SCIENTIFIC AMERICAN, 415 Madison Ave., New York, N.Y. 10017

© 1973 SCIENTIFIC AMERICAN, INC

BIBLIOGRAPHY

Readers interested in further reading on the subjects covered by articles in this issue may find the lists below helpful.

FLYWHEELS

COMPOSITE FLYWHEEL STRESS ANALYSIS AND MATERIALS STUDY. G. F. Morgan Thaler and S. P. Bonk in *Advances in Structural Composites: Vol. 12.* Society of Aerospace Material and Process Engineers, 1967.

NEW CONCEPTS IN MECHANICAL ENERGY STORAGE. David W. Rabenhorst in *1970 Intersociety Energy Conversion Engineering Conference Proceedings: Vol. I.* Society of Automotive Engineers, Inc., 1970.

DESIGN AND TESTING OF HIGH ENERGY DENSITY FLYWHEELS FOR APPLICATION TO FLYWHEEL/HEAT ENGINE HYBRID VEHICLE DRIVES. Louis J. Lawson in *1971 Intersociety Energy Conversion Engineering Conference Proceedings.* Society of Automotive Engineers, Inc., 1971.

GENETIC DISSECTION OF BEHAVIOR

BIOLOGY OF DROSOPHILA. Edited by M. Demerec. Hafner Publishing Co., Inc., 1965.

BEHAVIORAL MUTANTS OF DROSOPHILA ISOLATED BY COUNTERCURRENT DISTRIBUTION. Seymour Benzer in *Proceedings of the National Academy of Sciences of the United States of America,* Vol. 58, No. 3, pages 1112–1119; September, 1967.

CLOCK MUTANTS OF *DROSOPHILA MELANOGASTER.* Ronald J. Konopka and Seymour Benzer in *Proceedings of the National Academy of Sciences of the United States of America,* Vol. 68, No. 9, pages 2112–2116; September, 1971.

MAPPING OF BEHAVIOUR IN *DROSOPHILA* MOSAICS. Yoshiki Hotta and Seymour Benzer in *Nature,* Vol. 240, pages 527–535; December 29, 1972.

VIOLENT TIDES BETWEEN GALAXIES

MULTIPLE GALAXIES. F. Zwicky in *Ergebnisse der exakten Naturwissenschaften,* Vol. 29, pages 344–385; 1956.

GRAVITATIONSEFFEKTE BEI DER BEGEGNUNG ZWEIER GALAXIEN. J. Pfleiderer in *Zeitschrift für Astrophysik,* Vol. 58, No. 1, pages 12–22; August, 1963.

ATLAS OF PECULIAR GALAXIES. Halton Arp. California Institute of Technology, 1966.

GALACTIC BRIDGES AND TAILS. Alar Toomre and Juri Toomre in *The Astrophysical Journal,* Vol. 178, pages 623–666; December 15, 1972.

TIDAL INTERACTION OF GALAXIES. T. M. Eneev, N. N. Kozlov and R. A. Sunyaev in *Astronomy and Astrophysics,* Vol. 22, No. 1, pages 41–60; January, 1973.

THE TROPICAL RAIN FOREST

THE TROPICAL RAIN FOREST. Paul W. Richards. Cambridge University Press, 1952.

ECOLOGICAL STUDIES ON RAIN FOREST IN NORTHERN SURINAME. J. P. Schulz. North-Holland Publishing Co., 1960.

THE LIFE OF THE JUNGLE. Paul W. Richards. McGraw-Hill Book Company, 1970.

A TROPICAL RAIN FOREST: A STUDY OF IRRADIATION AND ECOLOGY AT EL VERDE, PUERTO RICO. Edited by H. T. Odum and R. F. Pigeon. U.S. Atomic Energy Commission, 1970.

ECOLOGY OF TROPICAL AND SUBTROPICAL VEGETATION. H. Walter. Van Nostrand Reinhold Company, 1973.

ON BIOMASS AND TROPHIC STRUCTURE OF THE CENTRAL AMAZONIAN RAIN FOREST ECOSYSTEM. E. J. Fittkau and H. Klinge in *Biotropica,* Vol. 5, No. 1, pages 1–14; 1973.

LASER SPECTROSCOPY

SPECTROSCOPY—A: NARROW RESONANCES AND PRECISION APPLICATIONS in *Fundamental and Applied Laser Physics,* edited by Michael S. Feld, Ali Javan and Norman A. Kurnit. Wiley-Interscience, 1973.

COPERNICUS AND TYCHO

ON THE REVOLUTIONS OF THE HEAVENLY SPHERES. Nicolaus Copernicus, translated by Charles Glenn Wallis in *Great Books of the Western World: Vol. 16,* edited by Robert M. Hutchins. Encyclopaedia Britannica, Inc., 1952.

TYCHO BRAHE: A PICTURE OF SCIENTIFIC LIFE AND WORK IN THE SIXTEENTH CENTURY. J. L. E. Dreyer. Dover Publications, Inc., 1963.

THE COPERNICAN REVOLUTION: PLANETARY ASTRONOMY IN THE DEVELOPMENT OF WESTERN THOUGHT. Thomas S. Kuhn. Harvard University Press, 1966.

THREE COPERNICAN TREATISES. Edward Rosen. Dover Publications, Inc., 1971.

A FRESH LOOK AT COPERNICUS. Owen Gingerich in *The Great Ideas Today,* edited by Robert M. Hutchins and Mortimer J. Adler. Encyclopaedia Britannica, Inc., 1973.

THE SOARING FLIGHT OF VULTURES

COMPETITION FOR FOOD BETWEEN VULTURES IN EAST AFRICA. Hans Kruuk in *Ardea,* Vol. 55, No. 3–4, pages 171–193; December, 1967.

NEW SOARING PILOT. A. Welch, L. Welch and F. Irving. John Murray [Publishers] Ltd., 1968.

SOARING BEHAVIOUR AND PERFORMANCE OF SOME EAST AFRICAN BIRDS, OBSERVED FROM A MOTOR-GLIDER. C. J. Pennycuick in *Ibis,* Vol. 114, No. 2, pages 178–218; April, 1972.

SLIPS OF THE TONGUE

THE NON-ANOMALOUS NATURE OF ANOMALOUS UTTERANCES. Victoria A. Fromkin in *Language,* Vol. 47, No. 1, pages 27–52; March, 1971.

LANGUAGE AND MIND. Noam Chomsky. Harcourt Brace Jovanovich, Inc., 1972.

SPEECH ERRORS AS LINGUISTIC EVIDENCE. Edited by Victoria A. Fromkin. Mouton, in press.

MATHEMATICAL GAMES

AN EASIER WARING'S PROBLEM. E. M. Wright in *The Journal of the London Mathematical Society,* Vol. 9, pages 267–272; 1934.

THE 'EASIER' WARING PROBLEM. W. H. J. Fuchs and E. M. Wright in *The Quarterly Journal of Mathematics,* Vol. 10, No. 39, pages 190–209; September, 1939.

WARING'S PROBLEM. W. J. Ellison in *The American Mathematical Monthly,* Vol. 78, No. 1, pages 10–36; January, 1971.

THE AMATEUR SCIENTIST

EXPERIENCES WITH COOLED COLOR EMULSIONS. Arthur A. Hoag in *Sky and Telescope,* Vol. 28, No. 6, pages 332–334; December, 1964.

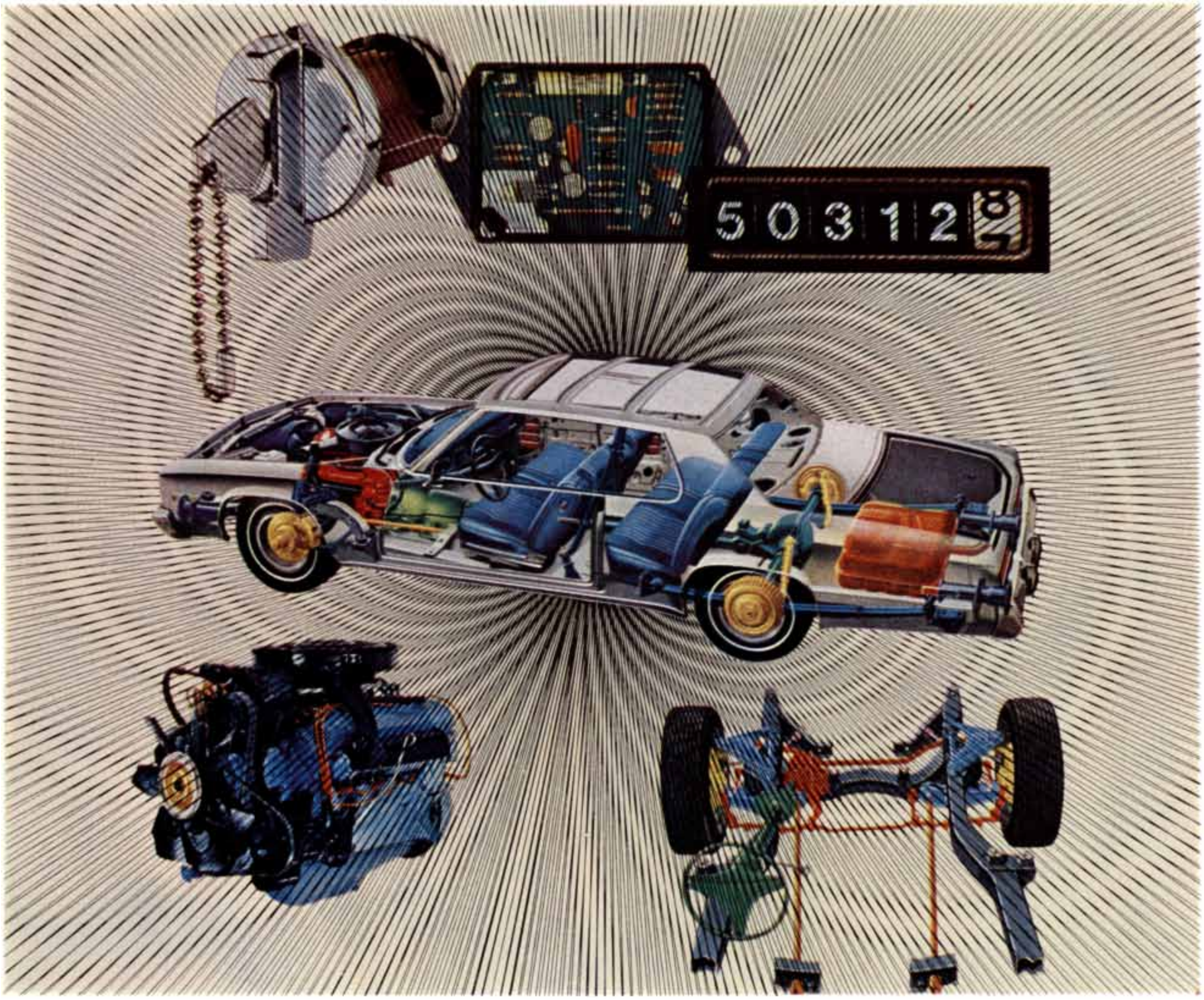
THE THEORY OF THE PHOTOGRAPHIC PROCESS. C. E. Kenneth Mees and T. H. James. Macmillan Company, 1966.

OUTER SPACE PHOTOGRAPHY FOR THE AMATEUR. H. E. Paul. Chilton Book Company, 1967.

© 1973 SCIENTIFIC AMERICAN, INC

EXTRA CARE IN ENGINEERING...IT MAKES A DIFFERENCE.

Chrysler Corporation offers 7 important engineering differences that could help you choose your next car.



There are important engineering differences in every Chrysler Corporation car made in this country. Differences that are basic to the way we build our cars. You should know about them before you buy your next car.

Difference #1: Electronic Engine Testing. Every one of our engine plants in this country uses Chrysler-engineered Electronic Engine Function Testers to help keep substandard engines out of your car.

Difference #2: Use of Electronics. Electronic Ignition and Voltage Regulator are standard on all our American-made cars. The Electronic Digital Clock and Security Alarm System are available on many.

Difference #3: Reduced Maintenance. Like other carmakers, we've worked to improve service. We've also reduced, even eliminated, service in certain areas. For example, Electronic Ignition has no points or condenser to replace.

Difference #4: TorqueFlite Transmission. It's rugged and dependable. With no recommended maintenance under normal driving conditions. TorqueFlite is standard on all our full-size cars, and it's available on all of our cars.

Difference #5: Electronic Ignition. Standard. It delivers up to 35% more starting voltage than conventional systems; works as good as new even after 50,000 miles.

Difference #6: Torsion-Bar Suspension. Our Torsion-Bar Suspension is a different way of obtaining a comfortable ride and is easily adjustable for height.

Difference #7: Unibody Construction. The body panels and structural members are joined by over 4,000 welds for strength, durability.

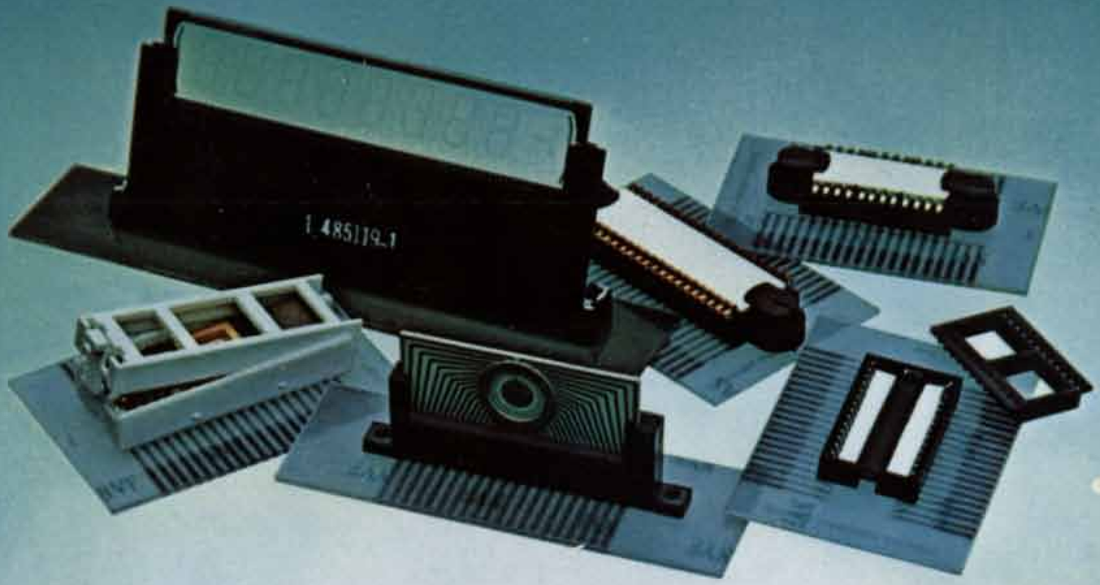
Compare Chrysler Corporation's engineering differences. See your Dodge or Chrysler-Plymouth dealer before you choose your next car.

CHRYSLER Plymouth Dodge Dodge Trucks

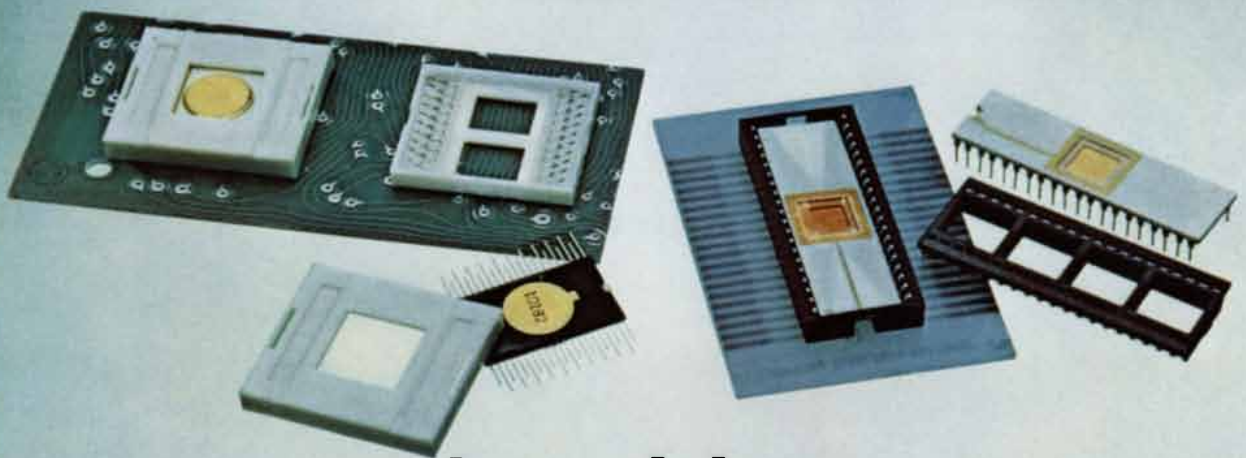
CHRYSLER CORPORATION

CHRYSLER • PLYMOUTH • DODGE • DODGE TRUCKS

© 1973 SCIENTIFIC AMERICAN, INC



AMP is making things smaller,



easier and denser for interconnecting MOS.

Take the 42-position connector in the foreground, for example. It's less than .250-inch high, with lid installed. And only .050-inch lead centers! Simple, easy to use. With zero entry force.

Then, there's our 40-position connector (far right, foreground). It's only .235-inch high, .100-inch lead centers and—with its snap-on adapter—converts in seconds to accept leaded as well as leadless packages. Also available for 24 and 28 package configurations.

We have others, too. Bottom metallized arrays, liquid crystal connectors, etc. But that's another story. To get the AMP microelectronics story, write AMP Incorporated, Harrisburg, Pa. 17105.

AMP microelectronics: doing small things in a big way.

AMP
INCORPORATED

AMP is a trademark of AMP Incorporated.

© 1973 SCIENTIFIC AMERICAN, INC