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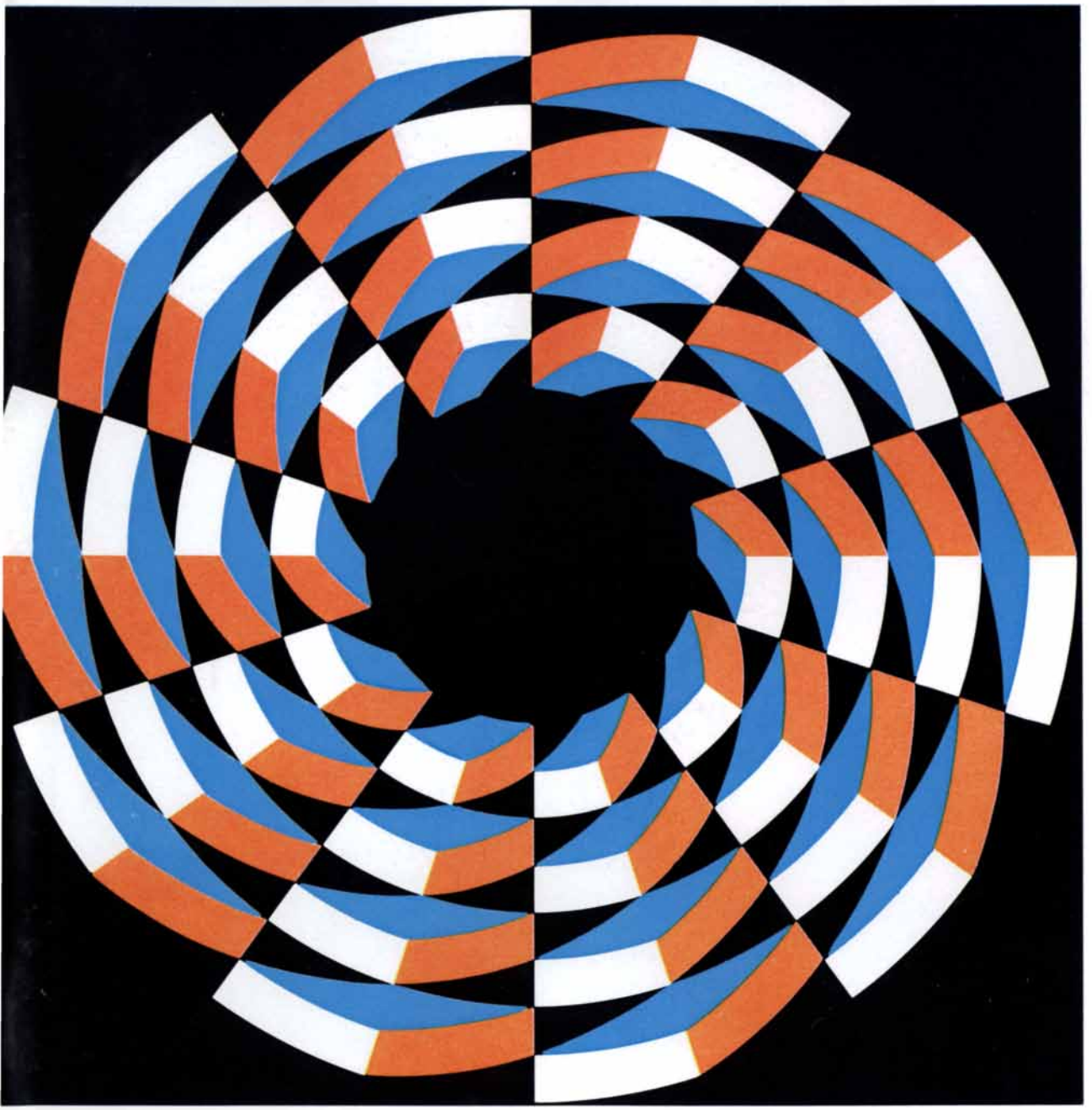

ANAMORPHIC ART

$1.25

January 1975

The fire started on the first floor...

...worked its way to the second floor where my Marantz 2270 was, and finally engulfed the third floor. The floors collapsed and fell into the basement where the Marantz remained buried in debris and water until March when the wrecking company came.

While the men were lifting the debris into trucks I noticed a piece of equipment I thought could be the Marantz. I asked the man to drop the load, and the receiver fell 20 feet to the ground.

Out of sheer curiosity, I brought the damaged receiver up to my apartment and after attaching a new line cord to it, I plugged it in. All the blue lights turned on. I connected a headphone and the FM played perfectly. I then tested it with my tape deck, and finally the turntable and speakers. They all played perfectly, too.

Francisco Espina*
Newport, Rhode Island

Unretouched photograph.

Mr. Espina's Marantz 2270 receiver still meets factory specifications. We design all Marantz equipment to perform under extreme conditions for unmatched reliability year after year after year. Like the new Marantz 2275—even better than its incredible predecessor. See the complete line of Marantz receivers, components and speaker systems at your Marantz dealer. He's in the Yellow Pages.

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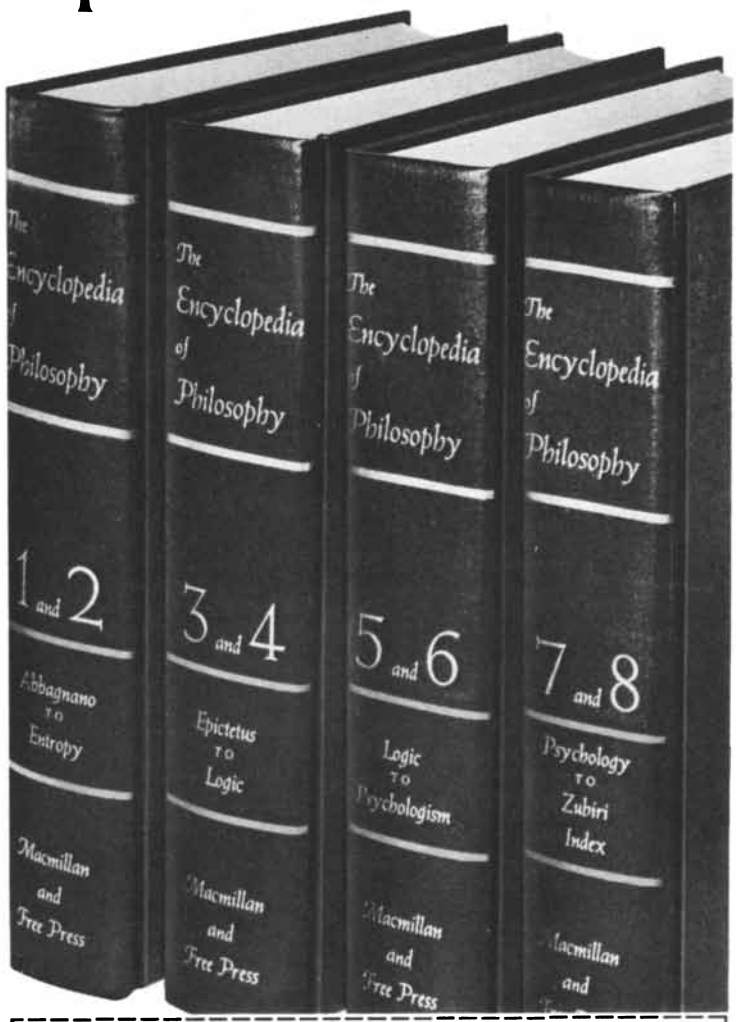

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An Evel's eye view of the Snake River Canyon

It commanded the world's attention. Some 30,000 converged on Idaho's Snake River Canyon to see it. Evel Knievel, daredevil motorcyclist, would attempt to jump the canyon in a steam-driven "sky cycle." Uncannily, it seemed a greater challenge than a moon shot.

How does it feel to be shot 3000 feet into the sky and gaze down into a canyon 600 ft. deep?

To find out, photographer Stu Allen bought the rights to mount remote-controlled cameras aboard the sky cycle, bringing back an Evel's eye view of the flight.

"With $70,000 and weeks of preparation invested in the project," says Allen, "I had to be able to recover my film — even if the sky cycle was blown all over the desert. I checked with NASA and found that their Nikons, similar to my off-the-shelf models, withstood impact tests of 0 to 50 G's in 5 microseconds — the equivalent of hitting a camera with a sledge hammer!"

The cameras would have to function in desert air, where humidity hovered at zero percent. The aft camera, mounted atop a pressurized tank of 485°F water, became so hot the film was seared.

At liftoff, the parachute opened prematurely, and the sky cycle crashed into the canyon wall with a force of 12.5 G's, tumbling down the precipice.

But Allen's Nikons worked perfectly throughout the flight, descent and afterwards, despite a smashed lens shade, cracked battery pack and scratches.

Like most photographers, you'll never send your cameras on a canyon jump. But if you're serious about photography, you'll want to be ready for that once-in-a-lifetime picture opportunity. A day when you'll need the camera so versatile, so reliable, it's the choice of about 90 percent of photojournalists. Write for Folio 10A. Nikon Inc., Garden City, N.Y. 11530. (Canada: Anglophoto Ltd., P.Q.)

Someday, you're going to need a Nikon.

Established 1845 **SCIENTIFIC AMERICAN** January 1975 Volume 232 Number 1

ARTICLES

DEPARTMENTS

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THE COVER

The pattern on the cover is an example of anamorphic art, an art form popular with European artists in the 17th and 18th centuries. When the objects in anamorphic illustrations are viewed with the unaided eye, they appear grossly distorted, but when they are viewed with the aid of a suitable reflector, the distortions disappear and the normal image is perceived. To view the pattern on the cover the reader is invited to remove the label from a juice or soup can, clean the metal surface of the can and place the can in the center of the pattern. When the can is moved somewhat off center, the curved pattern will be seen reflected in the side of the can as a repeating pattern of rectangular blocks. Further examples of anamorphic art are presented in Martin Gardner's department "Mathematical Games" (*page 110*).

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Keep Your Middle-age Young

It is not your age, it is knowing how to take care of yourself that counts!

executive health

the report that briefs you on what to watch

Alton Ochsner, M.D.:

ON "THE CHAIR DISEASE"...

Why blood clots in your veins are a little-realized occupational hazard of desk-bound executives

PUBLISHER'S NOTE: *Dr. Ochsner is one of the outstanding international leaders in modern medical progress. Now Emeritus Professor of Surgery at Tulane University School of Medicine, he maintains an active practice at the famed Ochsner Clinic in New Orleans. As a member of our Editorial Board we have asked him, out of his long personal experience, to explain this little-realized occupational hazard of your executive life*

—Richard Stanton

Until former President Nixon was first hospitalized for what was expected to be "routine" treatment of *thrombophlebitis*, the chances are you had never heard of the medical problem involved and could not care less. However when it was discovered that part of a blood clot that had formed in a vein in his left leg had broken loose and traveled up into his right lung, this potentially dangerous hazard (called a pulmonary embolism) created world-wide attention. The events that have followed, one after another, should be a warning to you of a little-realized occupational hazard of your own executive way of life. Why?

Thrombophlebitis is no uncommon medical happening and its possible end results hold a potential threat to any executive who spends his life SITTING . . . *sitting* at a desk, *sitting* at a conference table, *sitting* as he travels by car, train, or transcontinental plane . . . *sitting* at night reading, playing cards or viewing television . . . always *sitting, sitting, sitting!* I call it *"the chair disease"!*

According to the National Heart and Lung Institute, as many as 400,000 Americans suffer from a *pulmonary embolism* (one of the potential hazards of a blood clot within their veins) . . . and most of them do not even

Because you are not going to get out of this world alive, doesn't it make sense to learn how to live in it as long as you can? Never forget: *"Men's lives are chains of chances"* but as Euripides saw clearly so long ago: *"Chance fights ever on the side of the prudent."*

Your only insurance against tomorrow is what you do today! To put it bluntly, the mistakes you make in your younger years are drafts upon your older years, *payable with interest,* some 30 years later. The so-called *"diseases of old age"* are essentially the diseases of 50 to 70; *"the dangerous years."* Medical research now indicates that men who survive these dangerous years *without acquiring a chronic disease* (such as heart trouble or cancer) are likely to live on another *healthy* quarter of a century.

What keeps well people well? Medical men have long concentrated upon sick people and how to get them well . . . not upon well people and how to keep them well. Now many top research scientists are concentrating their efforts on *preventive medicine . . . how to keep well people well.*

May we suggest that you get the benefits of this new research for yourself? Do as so many thousands of executives do. Subscribe to Executive Health Report. The members of our Editorial Board are among the world's most distinguished authorities on *preventive medicine.* Their wise advice can help you not only live longer but enjoy those extra years!

Each month you are briefed on some one new research finding that can help you take better care of yourself and so stay healthy long years after other men your age are dead . . . or might as well be.

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We will be happy to send you with our compliments your choice of 3 of our reports already in print (back issues sold regularly at $1.50 each) if you will enclose a dollar to defray handling and mailing costs.

As you examine these 3 complimentary reports, written in clear, non-technical language, we believe you will see why our reports are used by so many of America's great corporations (such as Westinghouse, Boeing and Sears) to brief their executives on how to take better care of their health, and so **keep their middle-age young!**

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General Motors believes it has found the answer to the automotive air pollution problem...

...and the catalytic converter has enabled GM engineers to improve performance and to increase fuel economy.

Starting with the 1975-models, General Motors is installing catalytic converters on its cars. Our testing program shows that the converters reduce exhaust emissions to such a low level that as older cars not equipped with catalytic converters are gradually replaced, the automobile will cease to be a significant part of the air pollution problem in most areas of the country.

Catalytic Converter

Because it is a part of the 1975-model GM car you buy, we would like to tell you here about the catalytic converter and how it works.

What is a catalyst?

A catalyst is a substance, in this case a metal, that speeds up a chemical reaction but remains unchanged itself by the process. For example: some chemical reactions only happen quickly at very high temperatures. A catalyst can make them happen at lower temperatures.

Why do cars need catalytic converters?

Automotive exhaust is composed mainly of nontoxic or harmless gases, those that we find in "pure" air. The parts of the exhaust that are called pollutants occur in very small quantities. They are usually measured in "parts per million."

Automotive pollutants already are declining in the atmosphere because of the control systems we've been putting on cars for the past ten years. In most parts of the country, present controls are good enough to remove the automobile from the local air pollution problem. But some areas need more stringent auto emission controls—and that's where the catalytic converter comes in.

Why is GM using platinum and similar metals in its converter?

There are two basic demands made upon a catalyst: it must be efficient and it must be durable.

Nearly a thousand metals and combinations of metals were tested by GM scientists. Some needed very high temperatures in order to be efficient. Others were quickly rendered inoperable by the heat of the exhaust or some of the components of automotive exhaust. Platinum and palladium best met the specifications.

The next step then had to be to find a way to use these noble metals in the smallest possible quantities. GM scientists helped develop an extremely porous aluminum oxide bead. Because of the tiny hills and valleys on the surface of this bead *(shown actual size),* the real surface area of a single bead is over 25 sq. feet. The catalytic material is then spread on the great surface of the bead as sparsely as possible.

To give you an idea of how sparsely the catalyst is deposited on the beads, there are thousands of beads in a converter (actually 150,000 beads per GM converter) and all of them can be treated with 1/20 of a troy ounce of platinum and palladium.

How will the converter affect gas mileage?

In recent model years, we have had to compromise engine efficiency to "tune" the engine for low emissions. Since the catalytic converter treats the exhaust after it leaves the engine, we have been able to recalibrate the engine for improved efficiency and let the converter control emissions. Tests indicate that 1975-model GM cars with catalytic converters are more economical to operate than 1974-models.

Current-model cars tested by General Motors on a simulated city/suburban driving schedule have averaged about 10% more miles per gallon over their 1974 counterparts. In addition, where comparative data are available, the results of the Environmental Protection Agency urban test confirm this improvement in gasoline economy. In fact, the EPA has measured an average 28% improvement in 1975-model GM cars, compared with 1974-models.

How will the converter affect performance?

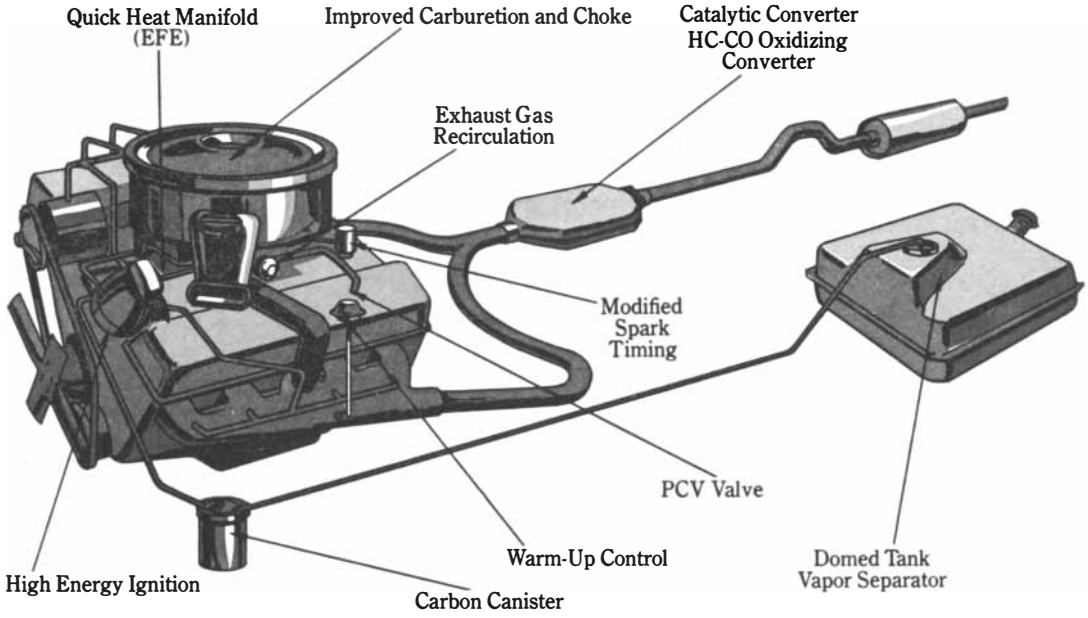
The engine recalibration allowed by the converter also results in a noticeable improvement in the performance qualities of GM cars. The responsiveness to driver demands of our 1975 cars is excellent.

The converter itself has very little effect on performance. Engine and drive train refinements, designs that are more aerodynamically efficient, even tires will play a role in the continuing improvement of the performance qualities of GM cars.

How long will a catalyst last?

If unleaded gasoline is used exclusively and normal engine maintenance is performed at recommended intervals, there is no reason why the catalytic converter should not last the life of the car. Lead in gasoline "poisons" the catalyst and therefore, our 1975-model cars have special fuel tank filler necks that allow only the smaller unleaded fuel pump nozzles to be used. However, in case of emergency, a motorist can use a few gallons of leaded fuel without significant or permanent effect on the converter, and of course, with no effect on engine operation.

In all, over 25 million miles of development testing have been completed, both at the GM Proving Grounds and in field experience. *Under normal circumstances, no maintenance or replacement of the catalytic converter is recommended.*



1975 Emission-Control System

Will the converter remove 100% of all pollutants from automotive exhaust?

The goal of anti-pollution systems is not perfection. It is to remove so much of the pollutants from automotive exhaust that the effect of the unremoved or unconverted pollutants on the atmosphere will be insignificant. *We believe GM cars equipped with catalytic converters will achieve that goal.*

What are hydrocarbons and carbon monoxide?

Hydrocarbons are the basis of all fossil fuel. An ideal engine would burn all of the hydrocarbons in gasoline. But there are no ideal engines. A very small part of the hydrocarbons in gasoline comes out of the engine unburned. The purpose of the catalytic converter is to oxidize (burn without combustion) these hydrocarbons.

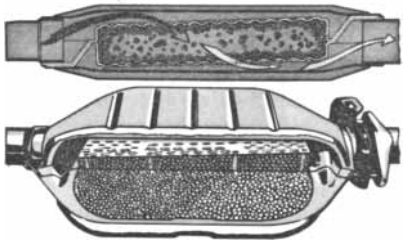
Carbon monoxide is a byproduct of the combustion of all carbon-based materials. Smoke, for example, has a high carbon monoxide content. As with hydrocarbons, the catalytic converter oxidizes the carbon monoxide in engine exhaust.

What happens to carbon monoxide inside the converter?

Oxygen comes into the converter along with exhaust gases as a result of excess combustion air or from air supplied by an auxiliary air pump. The oxygen sticks to the surface of the catalyst. As the carbon monoxide molecules pass over the catalyst, they also stick to the catalyst's surface and join together with the oxygen to form carbon dioxide, the gas you exhale when you breathe.

What happens to hydrocarbons inside the converter?

Hydrocarbons are more complicated than carbon monoxide. They are generally made of a chain of carbon atoms,



Catalytic Converter

each of which is attached to several hydrogen atoms. As the hydrocarbons pass through the converter, they meet the oxygen on the surface of the catalyst and begin to change. The oxygen pulls the carbon chains apart, forming carbon dioxide from the carbon atoms and good old-fashioned H_2O (water) from the hydrogen atoms.

The process by which certain hydrocarbons change into carbon dioxide and water is so complex that physical chemists still do not completely understand the exact order of the process. They can, however, measure what goes into the converter and what comes out, so they know it happens.

Will the catalytic converter be the ultimate answer to the automotive air pollution problem?

We're working with turbine engines, diesel engines, stratified charge engines, to name just a few of the projects now going on at the General Motors Technical Center.

There are mass-production problems with some kinds of engines. Vehicles powered by electricity stored in on-board batteries still require improvement. Other kinds of engines are low in one pollutant and high in another.

For the immediate future we believe the catalytic converter is the best answer to the problem of changing the very small amounts of hydrocarbon and carbon monoxide pollutants in automotive exhaust into harmless gases.

It is the practical answer. But the engineers and scientists at General Motors are looking for better answers all the time; that's their job.

GM cares about cars.

GM cares about people, too.

General Motors

Chevrolet, Pontiac, Oldsmobile, Buick, Cadillac, GMC Truck

LETTERS

Sirs:

I read with interest the article by Marianne L. Teuber in the July issue of *Scientific American*. The parallels she draws between the work of the Gestalt psychologists and the graphic work of my father, M. C. Escher, are striking, but suggestive as they may be I do not think they warrant Mrs. Teuber's conclusion: that a large portion of Escher's work is based on studies by him of Gestalt psychology. On one important point I do agree with her: Rubin's well-known vase, Schröder's stairs and Necker's cube did almost certainly provide the seed of inspiration for M. C. Escher's work on the regular subdivision of the plane and for many prints. These fascinating visual concepts came into his hands, however, not through psychological publications, in which he never showed interest, but more likely through the puzzle department of more prosaic periodicals of which I have vague recollections.

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NAME

NEW ADDRESS

OLD ADDRESS

Here are some of my reasons for disagreeing with Mrs. Teuber. In the first place I do not recognize the personality of the M. C. Escher that emerges from the article as being that of the M. C. Escher I knew all my life. Mrs. Teuber's study suggests a research- and psychology-minded man, searching for ready-made ideas in rather technical publications. There is little resemblance between him and the man I knew, not interested in psychology, doing, pencil in hand, his searching, slow and dogged work toward a vaguely defined visual goal, driven by the excitement of daily discoveries.

In the second place, M. C. Escher was a systematic and tidy person who kept files of letters, publications, illustrations and objects concerning his work. Many references can be found to other people's ideas on which he based prints, but nowhere, to my knowledge, is the work of a Gestalt psychologist mentioned. Thirdly, I have the impression that Mrs. Teuber's analysis is largely based on the written comments of M. C. Escher. It is instructive to read what he has to say on this subject in the closing paragraph of the introduction to *The Graphic Work of M. C. Escher* (Ballantine Books, 1971): "It is a fact... that most people find it easier to arrive at an understanding of an image by the roundabout method of letter symbols than by the direct route. So it is with a view to meeting this need that I myself have written the text [to the illustrations]." These texts were written many years after the completion of the prints, and in my opinion they reflect more than my father had in mind while he was creating the works.

Judging from experience I would explain the similarity between Escher's comments and the work of Gestalt psychologists as follows. After early brief contacts with visual concepts out of the psychologists' works, which established a number of trends, Escher went his own way, exploring visual, artistic and technical facets of these concepts. There are hardly any records of his thoughts during this period. For many years after his transition from Italian landscapes to his typical abstract prints he remained virtually unknown. Then in the late 1940's his work began to attract attention, and from that time on a lively discussion developed between him and perception specialists, psychologists and mathematicians. He found this exciting and told us with enthusiasm about new aspects or explanations pointed out to him. It was during this later period in his life that he began to write commentaries about his prints. It is little wonder that his words seem to indicate familiarity with psychological literature: not only do they deal with similar specialized subjects, they also reflect the language of his professional correspondents.

M. C. Escher is not with us anymore to arbitrate the matter, and any discussion of this type is doomed to remain largely conjectural. Nevertheless, I should like to have it on record that my memory and the available evidence indicate to me that his work was not, except in a restricted sense, influenced by the Gestalt psychologists.

George A. Escher

Mahone Bay, Nova Scotia

Sirs:

It may seem irreverent to take issue with a son's view of the work of his father, but sometimes the outsider can see things that an artist's own family may have overlooked. Besides, the disagreement between George Escher and myself is only partial: there is no argument that M. C. Escher knew devices from scientific studies of perception such as the reversible Necker cube, the Schröder staircase and the ambiguous Rubin vase-profile pattern and made these visual ideas topics of his fantastic and disquieting prints. Nor would anyone question the artist's later debt to the "impossible figures" of the Penroses (since he explicitly acknowledges that debt), and the visual evidence makes it undeniably clear that he must have had access to von Fieandt's variations on the crater illusion. I would also agree with George Escher that in the artist's earliest attempts in 1921–1922 puzzle pictures may have played a role. They were as popular with the public as with psychologists studying visual perception (before World War I).

What remains at issue between us is the question of what triggered the profound change in M. C. Escher's style in 1937–1938. Did he consciously apply Gestalt-psychologic principles in constructing his complex figure-ground designs at that time or did he encounter these concepts only later, when he had increased opportunities for discussing them with others and wrote the commentaries on his prints for the publication of *The Graphic Work of M. C. Escher?* I do not think that such a sharp contrast can be defended. The artist, I believe, would have been the last to say so; for him form was never devoid of meaning. Rather, I would say that in 1937–1938, when he was inspired by

the visual and intellectual analyses of the Gestalt school, he created his most beautiful works, *Sky and Water* and *Day and Night*. The visual evidence alone makes this clear, as I have shown in my article. The artist's writings and published interviews with him provide additional documentation. They support my thesis that it was in 1937–1938, soon after he had left Italy, that he was captivated by these new insights. As I noted in my article, these ideas may have been transmitted to him by a psychologist friend and not necessarily by direct reading.

It is my contention that the work of the Gestalt psychologists, increasingly fashionable through the later 1920's and early 1930's, and summarized in Kurt Koffka's *Principles of Gestalt Psychology* of 1935, fell into a prepared mind; it helped M. C. Escher to find his way back to his earlier preoccupations with figure-ground problems in 1921–1922 and in 1926–1927, when symmetry groups briefly appear in his work. These two themes, figure-ground relations and symmetry groups, became major foci in his mature achievement....

The reversal of figure and ground is of course a venerable decorative motif; it can be found around the world, in Greek vase painting and Roman mosaics, in the basket-weave patterns of American Indians, in 19th-century American quilts, in Art Nouveau. Yet in the hands of the Gestalt psychologists this ornamental device was elaborated into a method of testing fundamental issues of form perception. They asked, "Why do we see things and not the holes between them?" (Koffka, page 208); they varied figure-ground relations systematically in order to find out what sets a figure (or Gestalt) off against a background. What makes their patterns special is not the use of figure-ground motifs as such but the graded emergence of figures from a shapeless (or gray) ground (as in M. C. Escher's *Sky and Water* or *Development I*) and their subsiding into the ground again in appropriate stages. When I first saw the artist's striking woodcuts of 1937–1938, in the 1950's, I was amazed at the close visual parallels with the figure-ground experiments of the Gestalt school, as anyone familiar with that movement would be.

The artist explains his fascination with figure-ground constellations in exactly the same manner by saying that "our eyes are used to focusing on one particular object; when that happens, everything around it becomes background." Therefore, he continues, "we cannot see both black and white birds simultaneously" (for example in *Day and Night*), as Rubin had demonstrated for vase profiles. The artist recalled that he was 40 (1937–1938!) when he made these discoveries. He added, "It was a very productive time," and he "yearned to communicate these mental images to other people."

Additional visual concepts that entered M. C. Escher's work and vocabulary (my apologies to George Escher!), such as "closed contours," the "double function of line," the "transition from flat to spatial" (in the print *Cycle*, 1938; the *Metamorphosis* series, 1937–1939; *Reptiles*, 1943), the "development of forms and contrast" (in *Development I*, 1937; *Verbum*, 1942; *Liberation*, 1955), leave no doubt that he must have had some contact with the Gestalt-psychologic literature of his time, in particular Koffka's *Principles* of 1935 and the experiments of Koffka's student Molly R. Harrower, which were published in 1936. Escher's biographer, J. L. Locher, describes the mature work of the artist beginning in 1937 exactly in the above terms, and the question "Why did his style change in 1937?" runs like a refrain through the entire essay (*The World of M. C. Escher*, 1971). My article in *Scientific American* is an attempt to answer that question.

That Escher did not mention Koffka or Harrower by name should not surprise us. He does not cite any authors for the mathematical rules of symmetry groups either. Yet he referred by name to the mathematician H. S. M. Coxeter and to L. S. Penrose and R. Penrose, and it is obvious why he did so: he had met them in person.

Much has been written about the relationship between art and science in the 20th century, but the real links have remained elusive. They were established more by analogy than by uncovering historical connections. In M. C. Escher's case I believe these links can be demonstrated. They can also be shown for Albers, Vasarely and the "op" artists. However, as I have indicated in my article, Gestalt-psychologic experimentation cannot be seen in isolation either; it owes a debt to modern art. Nor do I find that pointing to an artist's intellectual background and special interests should take away from his stature. Quite the contrary, in this way the complexity of his work is revealed and new dimensions are added to our understanding of his artistic achievement.

MARIANNE L. TEUBER

Cambridge, Mass.

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Internal workings of the new 300D, the world's only 5-cylinder automobile.

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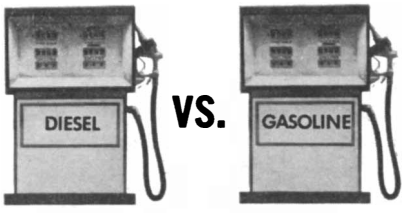

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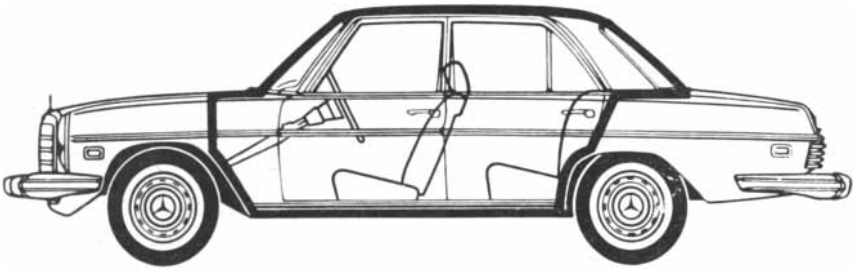

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50 AND 100 YEARS AGO

SCIENTIFIC AMERICAN

JANUARY, 1925: "Critics of Professor Robert H. Goddard's project for sending a rocket to the moon, who have taken the position that in a vacuum such as exists in space between the earth and the moon the gases emitted by the rocket would have nothing to impinge upon in order to propel the rocket, will be silenced by recent experimental proof that this criticism is a fallacy. Professor Goddard answered his critics by placing a revolver in a vacuum and firing a blank cartridge from it. Although the hot gases of the burning powder had no air to impinge against, the revolver recoiled on its prepared axis just as if it had not been fired in vacuum. Further experiments along this line were made with a small model of the rocket which it is planned to send to the moon. Professor Goddard never expected his rocket to get its kick from the impact of its escaping gases against air. On the contrary, its propulsion depends on Newton's Third Law, which states that, 'To every action, there is an equal and opposite reaction.'"

"What happens when we get out of breath or become exhausted? Dr. A. V. Hill, professor of physiology in University College London recently set out to answer this question. He discovered that there is a very close relation between the fatigue caused by exercise and the production of a certain chemical called lactic acid in the muscles that are being used. Dr. Hill has shown that fatigue is always accompanied by an increase in the amount of lactic acid in the muscles, whereas recovery from fatigue is always marked by a decrease in lactic acid."

"It is now generally agreed that the earth consists of an iron core surrounded by silicate rock. Earlier speculations proceeded on the assumption that the earth is essentially uniform in composition, but it is now certainly known that somewhere within the earth is a very considerable amount of material intrinsically denser than any known rock. The metallic core was until recently thought to be separated by a rather sharp boundary from the surrounding silicate shell, but it has now been suggested that between the core and the shell lies an intermediate zone of mixed iron and rock. The stony shell is supposed to be granitic near the surface and basic below."

"If you look up on a moonless night into the sky, you may be able to count one or two thousand stars. With modern telescopes astronomers reckon the total number of visible stars, clusters and nebulas as possibly one or two billion. This is as far into the depths of space as the eye of man has been able to penetrate, but theoretical physicists have begun asking themselves whether this is the end, and indeed whether there is any end. One attempt to answer this question has grown out of the idea of the 'radius of curvature' of the universe. We are in much the same position with regard to measuring the size of the universe as men were when they first began to suspect the roundness of the earth. They observed that the idea of its being round fitted quite well into what they knew of nature, but they lacked instruments to prove that the earth is round and to get an accurate idea of how much it is curved."

"California has a vast and thus far unused source of power on tap in the geysers of Sonoma County. Tests have recently been completed that show the tremendous possibilities in the use of the geysers for the purpose of power development. Borings have been made, and one steam well is already in use supplying power for the boring of other wells. The first two wells have a constant pressure of 30 pounds per square inch. Tests indicate that these two wells could supply at least 1,500 kilowatts."

SCIENTIFIC AMERICAN

JANUARY, 1875: "Among scientific puzzles is one that has long perplexed geologists, namely the existence of large areas of rock containing no sign of life side by side with formations of the same period that are full of fossils—relics of primeval life. There is now an answer to this important question in a paper written by Dr. Wyville Thomson, chief of the scientific staff on board the *Challenger*. The paper contains the results of deep-sea soundings that have revealed the existence of vast areas of barren clay at the bottom of the sea at depths varying from 2,200 fathoms to more than 4,000 fathoms. In shallower parts of the sea the bottom is composed of the remains of many tiny plants and animals that live near the surface and sink to the bottom when dead. Beyond 2,200 fathoms these tiny shells are dissolved by the water, so that in the greater depths the sea floor remains barren clay."

"The edge of the sun's visible disk is surmounted to an elevation of between 8,000 and 10,000 miles by an envelope of rose-colored gases to which Mr. Lockyer has given the name of chromosphere. It is a sheet of scarlet flame that clothes the whole surface of the sun and here and there rises in cloudlike forms that ascend to enormous heights. Occasionally an uprising jet attains a very great velocity and spreads out in the upper regions of the coronal atmosphere into precisely such forms as those assumed in our own air by smoke and vapors. For many years the composition of these clouds was subject to much discussion, but the spectroscope has now set the question at rest by showing that they are nothing but heated clouds of gas, largely hydrogen. Their spectrum exhibits conspicuously the bright lines of that element and another very prominent line as well. Many circumstances make it nearly certain that this line is due to some substance other than hydrogen, a congener in lightness and many other properties but as yet undiscovered by our terrestrial chemistry. To this hypothetical element the name of helium has been assigned by Lockyer and Frankland, though with rather doubtful propriety."

"The submarine cables that now keep continents in communication have revealed the curious fact that a telegraph wire can be charged like a Leyden jar. In land lines the static charge is slight, but in submarine cables thousands of miles in length it is very marked. The effect of the charge is to retard the time of delivery of a signal and to prolong it, so that although it is a momentary signal at starting, it becomes a prolonged signal at its destination. The mere slowing of the signal would not matter much, provided it was delivered at its destination as sent, but it is not. Each signal at the receiving station takes a longer time to leave the line than it did to enter it. Hence if the sender transmitted at the same rate that he does in land lines, the signals would run into one another and be indistinguishable. As a result the maximum speed of signaling through the 2,000 miles of the 1858 Atlantic cable was 2½ words per minute. Through the improved cable laid last year a speed of 17 words per minute has been attained."

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THE AUTHORS

GEOFFREY H. MOORE ("The Analysis of Economic Indicators") is vice-president for research of the National Bureau of Economic Research, Inc. His original interest, arising from his activity in raising chickens as a youth, was poultry husbandry, which he set out to study at Rutgers University. He was graduated in 1933 with a degree in agriculture and obtained his master's degree at Rutgers four years later. From 1936 to 1942 he taught agricultural economics at Rutgers, meanwhile becoming affiliated (in 1939) with the National Bureau of Economic Research. He has been with that organization ever since except for the period 1969–1973, when he was Commissioner of Labor Statistics in the U.S. Department of Labor. In 1947 he obtained his Ph.D. (in agricultural economics) at Harvard University.

CLARK R. CHAPMAN ("The Nature of Asteroids") is at the Planetary Science Institute in Tucson, Ariz., a group of independent researchers affiliated with Science Applications, Incorporated, of La Jolla, Calif. "Although I am a native Westerner," he writes, "born in Palo Alto, I grew up in Buffalo. I had an early interest in astronomy—planets in particular—and was an active amateur astronomer in high school. I have had a diverse academic background befitting the interdisciplinary nature of planetary studies; my undergraduate major was in the astronomy department at Harvard College (A.B. 1967); I then studied in the meteorology department at the Massachusetts Institute of Technology (M.S. 1968) and finally in the geology/geophysics department at M.I.T. (Ph.D. in planetary science 1972). I am in love with the deserts of the Southwest and spend less time than I would like hiking in the mountains near Tucson."

JOHN R. PIERCE ("The Fuel Consumption of Automobiles") is professor of engineering at the California Institute of Technology, to which he moved in 1971 after 35 years with the Bell Laboratories. At the time of his retirement from Bell Labs he had been for six years executive director for research in the communications sciences division. He was responsible for research in radio, guided waves, electronics, acoustics, vision, mathematics, statistics, econometrics and behavioral science. His work on the traveling-wave tube led to its successful application in communication satellites; the work of the Bell Laboratories on the Echo and Telstar satellites was based on his original suggestions. Pierce obtained his bachelor's, master's and doctor's degrees at Cal Tech in 1933, 1934 and 1936 respectively.

RODOLFO R. LLINÁS ("The Cortex of the Cerebellum") is professor and head of the division of neurobiology in the department of physiology and biophysics at the University of Iowa. He writes: "I was born in Bogotá, Colombia, and was educated there up to the level of medical school. I am a third-generation physician; my grandfather and father both have been in academic medicine (psychiatry and thoracic surgery respectively) at the Medical School of the Colombian National University. After medical training I came to the U.S. and worked in the department of neurosurgery at the Massachusetts General Hospital and then in neurophysiology at the University of Minnesota. As a research scholar at the Australian National University I obtained a Ph.D. in neurophysiology. I enjoy music, art and philosophy. Since coming to Iowa I have developed a liking for flying small planes. Besides being a sheer delight it has provided a rather dramatic way to acquaint oneself with the geography of the Middle West and the East Coast at a detailed level."

GARY A. STROBEL ("A Mechanism of Disease Resistance in Plants") is professor of plant pathology at Montana State University. He says his interest in the field "was brought on by a desire as a teen-ager to understand why the chestnut trees had died in my home state of Ohio." Strobel was graduated from Colorado State University in 1960 and obtained his Ph.D. (in plant pathology) at the University of California at Davis. "My family has become engaged in numerous church (Mormon) and outdoor activities," he writes. "Montana has offered us such activities as skiing, fishing, hunting, trail bike riding, river floating and hiking."

J. A. BISHOP and LAURENCE M. COOK ("Moths, Melanism and Clean Air") are respectively lecturer in genetics at the University of Liverpool and senior lecturer in zoology at the University of Manchester. Bishop writes: "I was fortunate to be born and educated in Sydney, Australia. There I was able at an early age to transport and observe a wealth of living creatures in containers as diverse as shoe boxes and laundry tubs. These activities received a certain amount of parental encouragement, and my interest was further developed by sympathetic teachers at the University of Sydney, where I graduated (B.Sc. in 1962 and Ph.D. in 1966). I moved 'temporarily' to the University of Liverpool in 1965 and have shuttled between the departments of genetics and zoology ever since." Cook obtained his bachelor's degree at University College London and his Ph.D. at the University of Oxford. He writes that he has "studied aspects of ecological genetics and evolution in several species of Lepidoptera and mollusks both at home and in the New and Old World Tropics."

RICHARD M. LEMMON and WALLACE R. ERWIN ("High-Energy Reactions of Carbon") are at the Lawrence Berkeley Laboratory of the University of California. Lemmon, who also serves as associate director of the University of California's Laboratory of Chemical Biodynamics, obtained his bachelor's degree at Stanford University, his master's degree at the California Institute of Technology and his Ph.D. (in chemistry) at the University of California at Berkeley. He lists three areas of interest apart from his work: "(1) A devoted wife (Marguerite) and three delightful college-age children; (2) mountaineering: I've been up all 14 of California's over-14,000-foot peaks, the Matterhorn and Mont Blanc in Europe and (last autumn) Mount Kilimanjaro; (3) flying: I have a private pilot's license and am a member of the 184 Flying Club, organized here at the Lawrence Berkeley Laboratory. (The 184 is the diameter in inches of Ernest Lawrence's big cyclotron.) When I can't climb mountains on foot, I do so by Cessna." Erwin was graduated from Berkeley in 1949 and worked there as an insect toxicologist until 1958, when he left to run a farm. He returned in 1963 to work with Lemmon. His outside interests include fishing; he writes that he and his family "still maintain a few precious riverfront acres along one of the blue-ribbon trout streams of Montana."

VAUGHN M. BRYANT, JR., and GLENNA WILLIAMS-DEAN ("The Coprolites of Man") are at Texas A&M University; Bryant is associate professor of both anthropology and botany and Williams-Dean is a doctoral student in botany. Bryant was graduated from the University of Texas at Austin in 1964 and obtained his Ph.D. (in botany) there in 1969. Williams-Dean obtained her bachelor's degree from the University of Texas at Austin in 1973.

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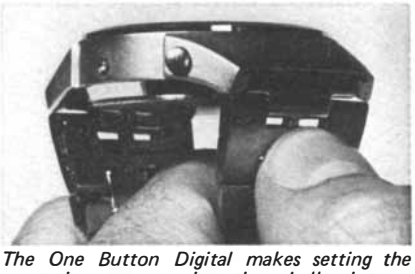

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The Analysis of Economic Indicators

Economic indicators are specific measures such as production, prices, incomes, employment and investment. Subtle relations among them must be perceived if they are to be used to predict economic developments

by Geoffrey H. Moore

Business cycles, large and small, appear to be a continuing feature of the economic landscape. A turn up or down in the economy is clearly an event of major social significance. Considerable interest therefore attaches to the means whereby an economic turn can be forecast and its extent can be estimated. That is the role of economic indicators, which rest on the numerous measurements of the pulse of the economy made by Government agencies, private organizations and individual economists. The analysis of economic indicators (a subject in which my colleagues and I at the National Bureau of Economic Research have been much interested) is a well-developed technique for ascertaining what the many pulse readings are saying about the state of the economy.

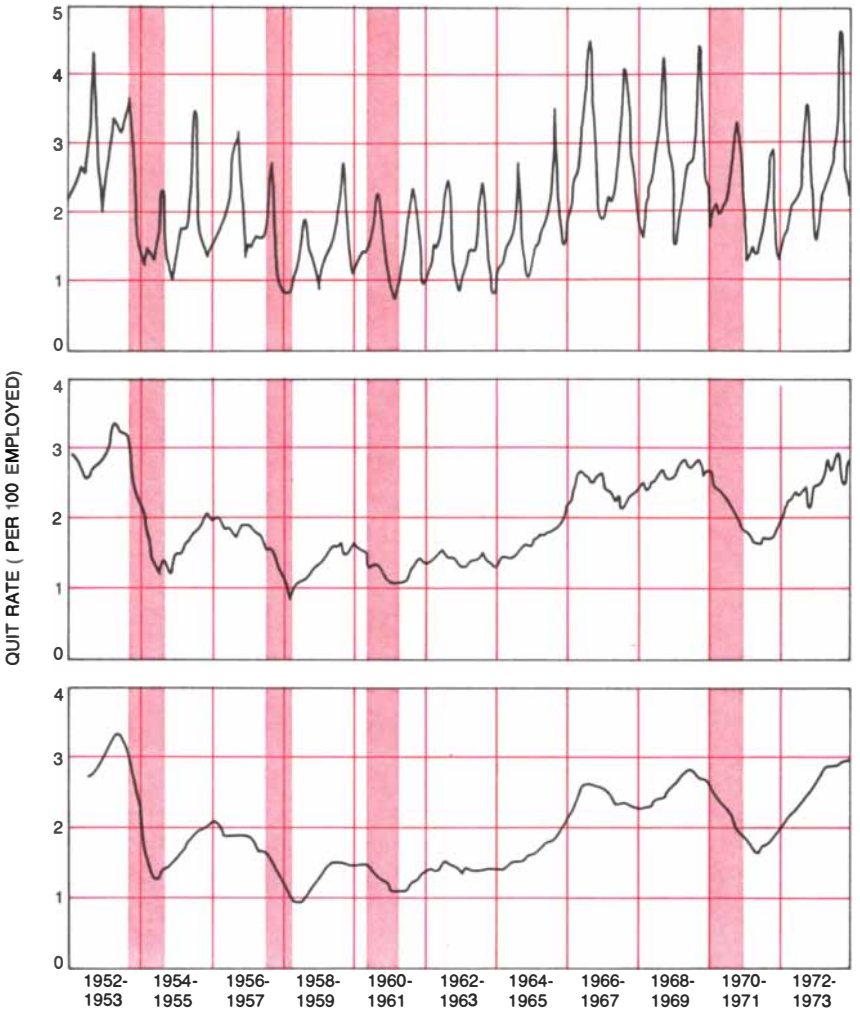
Economic indicators are often likened to a barometer because they register some significant aspect of the performance of the economy, are sensitive to changes in the economic climate and may portend further changes. A barometer, however, measures only one characteristic of the atmosphere. Moreover, the barometer itself does not cause a change in the weather. Hence it is frequently in a disparaging sense that the term barometer is applied to an economic indicator; the implication is that the indicator is only a barometer, having no real causal significance and covering only a small part of what one should know about economic change.

Such characterizations may apply to many individual economic indicators, but they do not apply to indicators as a class. Economic indicators have come to embrace virtually all the quantitative measures of economic change that are continuously available. One can find daily, weekly, monthly and quarterly indicators; they measure production, prices, incomes, employment, investment, inventories, sales and so on, and they record plans, commitments and anticipations as well as recent transactions. Some of the indicators, such as the unemployment rate or the consumer price index, are calculated by the Federal Government on the basis of elaborate sampling surveys conducted each month. Others, such as the indexes of stock-market prices and the surveys by purchasing agents of prices, orders and inventories, are constructed by private organizations on the basis of information they collect or obtain as a by-product.

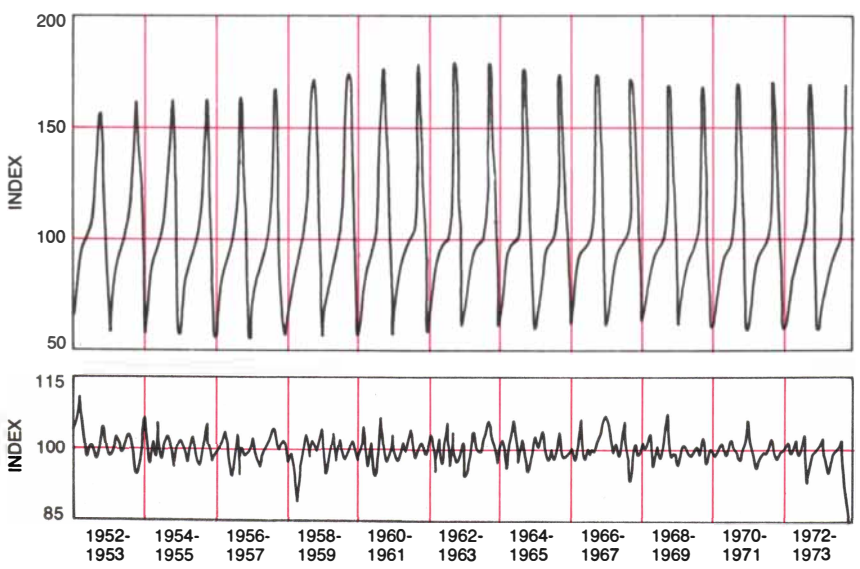
As a result the economist or businessman interested in forecasting change is faced, like the weather forecaster, with a mass of factual information that pours in constantly. He must assess in some systematic way what the information says about the present and the future. The technique of indicator analysis embraces various systematic ways of looking at this information with a view to discerning significant developments in the business cycle.

One of the earliest systems of the kind, which was devised shortly before World War I, came to be known as the Harvard *ABC* curves. The *A* curve was an index representing speculation, more specifically stock prices. The *B* curve represented business activity, measured by the dollar volume of checks drawn on bank deposits. The *C* curve represented the money market, measured by the rate of interest on short-term commercial loans. Historical studies, particularly those carried out by Warren Persons of Harvard University, showed that these three curves typically moved in sequence: stock prices first, bank debits next and interest rates last, with the lagging turns in interest rates preceding the opposite turns in stock prices. The economic logic of the sequence was that tight money and high interest rates led to a decline in business prospects and a drop in stock prices, which led to cutbacks in investment and a recession in business. The recession in turn led to easier money and lower interest rates, which eventually improved business prospects, lifted stock prices and generated a new expansion of economic activity.

The system came to grief in the Great Depression of 1929 because the interpreters of the curves took too optimistic a view and failed to foresee the debacle. Economists generally regard the episode as one of the great forecasting failures of all time. Curiously, however, the timing of the sequence of events on which the system was origi-



CONSTRUCTION OF INDICATOR involves the removal of factors that are unrelated to the business cycle. Here the indicator is the quit rate, meaning the number of people per 100 employed who voluntarily leave their jobs. At top is the curve reflecting the raw data, with shaded areas showing four periods of recession. Below it is the seasonally adjusted curve. Bottom curve shows the cyclical movement and the long-term trend of the quit rate.



ELEMENTS REMOVED from the quit-rate curve are a seasonal component (*top*) and an irregular component (*bottom*), which includes such factors as strikes and errors in sampling.

nally based has in large measure persisted. This is not to say, however, that the *ABC* curves would still suffice if they were revived; since 1929 much more comprehensive systems of indicators have been developed, and the empirical and theoretical base on which they stand has been far more thoroughly studied, documented and tested.

The sharp recession of 1937–1938, which occurred before the economy had fully recovered from the Great Depression, helped to spur that development. In the fall of 1937 Henry Morgenthau, Jr., the Secretary of the Treasury, asked the National Bureau of Economic Research (which is a private, nonprofit research agency) to devise a system of indicators that would signal when the recession was nearing an end. At that time the quantitative analysis of economic performance in the U.S. did not approach today's standards. The Government's national income and product accounts, which form the foundation of much modern economic analysis, were just being established. Other vital economic statistics, including unemployment rates, were being developed or refined by public agencies trying to provide information that would be useful in fighting the depression. Few statistical series were issued in seasonally adjusted form, as they are now. Comprehensive econometric models (systems of equations expressing quantitative relations among economic variables), which are widely employed now to forecast the economy and to evaluate economic policies, were virtually unknown then.

Under the leadership of Wesley C. Mitchell and Arthur F. Burns the National Bureau of Economic Research had since the 1920's assembled and analyzed a vast amount of monthly, quarterly and annual data on prices, employment, production and other factors as part of a major research effort aimed at gaining a better understanding of business cycles. This project enabled Mitchell and Burns to select a number of series that, on the basis of past performance and of relevance in the business cycle, promised to be fairly reliable indicators of business revival. The list was given to the Treasury Department late in 1937 in response to Morgenthau's request and was published in May, 1938. Thus originated the system of leading, coincident and lagging indicators widely employed today in analyzing the economic situation, determining what factors are favorable or unfavorable and forecasting short-term developments.

Since 1938 the availability, the study

ECONOMIC PROCESS	RELATION TO BUSINESS CYCLE			
	LEADING	ROUGHLY COINCIDENT	LAGGING	UNCLASSIFIED
Employment and unemployment	Average workweek and overtime Hiring and layoff rates New unemployment insurance claims	Job vacancies Total employment and unemployment	Long-duration unemployment	
Production, income, consumption and trade		Total production, income and sales		
Fixed capital investment	New investment commitments Formation of business enterprises	Backlog of investment commitments	Investment expenditures	
Inventories and inventory investment	Inventory investment and purchasing		Inventories	
Prices, costs and profits	Sensitive commodity prices Stock prices Profits and profit margins Cash flow	Wholesale price index for industrial commodities	Labor costs per unit of output	Consumer price index
Money and credit	Money and credit flows Credit delinquencies and business failures	Bank reserves Interest rates on money market	Outstanding debt Mortgage and bank-loan rates	
Foreign trade and payments				Imports, exports and export orders Balance of payments
Activities of Federal Government				Receipts and expenditures Defense orders, contracts and purchases

CLASSIFICATION OF INDICATORS is done in two ways. One is by major economic process, such as employment and unemployment. The other one is according to the relation the indicators have to turns in the business cycle. The leading, roughly coincident and lagging indicators shown in the table represent only a small portion of the many indicators that are normally classified in this way.

and the use of economic indicators have been greatly expanded under the leadership of the National Bureau of Economic Research, the U.S. Bureau of the Census and other public and private agencies. The list of indicators assembled in 1937 was revised in 1950, 1960 and 1966 to take account of the availability of new economic series, new research findings and changes in the structure of the economy. A new evaluation is currently in progress under the auspices of the U.S. Department of Commerce. With each revision the performance of the indicators both before and after the date of their selection has been carefully examined and exposed to public scrutiny.

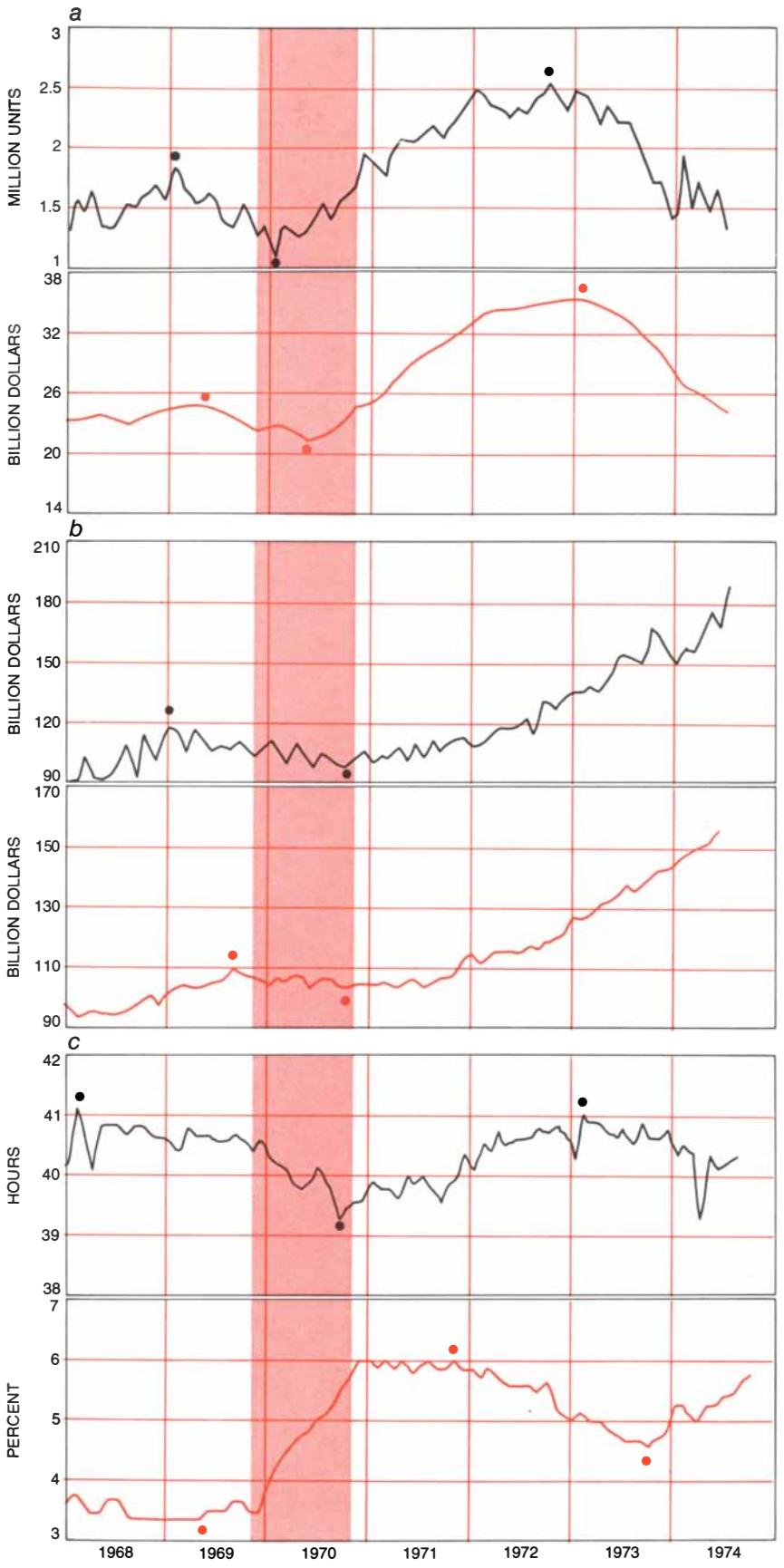
In 1957 Raymond J. Saulnier, who was then chairman of the President's Council of Economic Advisers, asked the Bureau of the Census to develop methods whereby the appraisal of current business fluctuations could take advantage of the large-scale electronic data processing that was becoming available at the time, with the results to be issued in a monthly report. Experimental work done over the next few years under the leadership of Julius Shiskin, who was the chief economic statistician of the Bureau of the Census, resulted (in 1961) in the publication by the Department of Commerce of *Business Cycle Developments.* (It is now called *Business Conditions Digest;* under both names economists have referred to it as *BCD,* and those initials appear on its cover in larger type than the full name does.) This monthly publication has greatly increased the accessibility of current indicator data and of various statistical devices that aid in their interpretation. As a result the analysis of the indicators has become a major tool of economic forecasting among the economists whose interest is in the current and future performance of the economy.

As I have noted, the analysis of economic indicators rests on an empirical footing and a theoretical one. Both the selection of particular indicators and the emphasis given to them have been guided by what is understood of the causes of business cycles. Obviously one would wish to examine recent changes in any economic process that is believed to play a significant role in any widely accepted explanation of cyclical fluctuations.

Many different explanations have been advanced for these fluctuations. Some of them lay primary stress on the swings in investment in inventory and fixed capital that both determine and are determined by movements in final demand. Others assign a central role to the supply of money and credit or to Government spending and tax policies or to relations among prices, costs and profits.

All these factors undoubtedly influence the course of business activity. Some of them may be more important at a given time than others. No consensus exists, however, on which is the most important or even on how they all interact. Hence it is prudent to work with a variety of indicators representing a broad range of influences. Ready access to a wide range of indicator data enables one to test competing or complementary hypotheses about current economic fluctuations.

With this principle in mind the National Bureau of Economic Research has classified economic activities into a few broad categories of closely related processes that are significant from the business-cycle point of view. Indicators have been selected from each group. The principal categories now included in *Business Conditions Digest* are em-



RELATIONS AMONG INDICATORS are traced through the business-cycle contraction of 1969–1970. The three pairs of curves represent leading indicators (*black*) and the activities they led (*color*), namely housing starts and expenditures on residential structures (*a*), orders for plant and equipment and corresponding expenditures (*b*) and average workweek in manufacturing industries against unemployment rate (*c*). Dots show peaks and troughs.

ployment and unemployment; production, income, consumption and trade; fixed capital investment; inventories and inventory investment; prices, costs and profits; money and credit; foreign trade and payments, and Federal Government activities.

The reader will note that these categories do not include all aspects of the economy. For example, statistics on agriculture, state and local government, population and wealth are omitted. Nevertheless, the categories do provide a framework of factors that enter into theories of the business cycle and are important in assessing the performance of the economy.

Within each category research on business cycles has uncovered statistical series that behave in a systematic way. These findings have provided a basis for selecting particular indicators and classifying them according to their characteristic cyclical behavior [*see illustration on preceding page*]. Two of the chief characteristics one looks for are the regularity with which the indicator conforms to business cycles and the consistency with which it leads or lags at turning points in the cycles. Other relevant considerations are the statistical adequacy of the data (since the statistical underpinning of an indicator has a bearing on how well the indicator represents the process it is supposed to reflect), the smoothness of the data (since highly erratic series are difficult to interpret at a given point in time) and the promptness with which the figures are published (since out-of-date figures have a limited bearing on the current situation).

Empirical measures of these characteristics have been drawn up for large numbers of indicators in the categories listed above. Such measures have been employed in the attempt to obtain data capable of conveying an adequate picture of the changes in the economy as it moves through stages of prosperity and recession. In addition the behavior of the indicators after they have been selected has been monitored closely. Many of the indicators have survived several successive evaluations. For example, the indexes of the average workweek, construction contracts and stock prices were on both the 1937 and 1966 lists of the National Bureau of Economic Research.

The same lists of indicators have also been tested by their performance in other countries, notably Canada, Japan and the United Kingdom. Every new recession or slowdown provides additional evidence against which the indicators can be assessed, as does every upturn. All this examination and reexamination

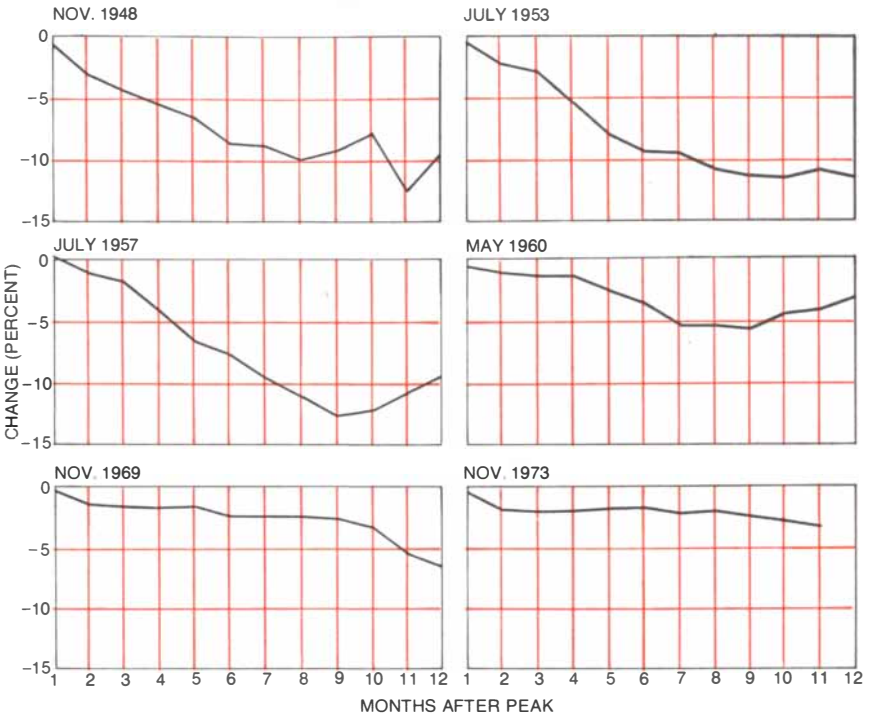
has accumulated a large amount of empirical evidence that demonstrates both the value of the indicators and their limitations.

A sampling of this evidence is contained in the accompanying illustrations. Let us consider the indicator called the quit rate, which measures the number of people in manufacturing industries (per 100 employed) who voluntarily leave their jobs [*see illustrations on page 18*]. The raw data are statistically decomposed in order to measure and eliminate regular seasonal variations and irregular movements. With factors that are unrelated to the business cycle thus removed, the indicator reveals the tendency for quits to diminish during a recession as new jobs become harder to find and to increase when more prosperous conditions return. The seasonally adjusted quit rate therefore reflects the view that workers have of the labor market and of economic prospects generally.

Most economic indicators today are available in seasonally adjusted form. Some of them are seldom reported in any other way. Examples of indicators that are invariably adjusted for seasonal factors include the gross national product, the unemployment rate and the index of industrial production.

The smoothing of irregular factors is less commonly practiced because the techniques are somewhat less routine. Certain statistical series, however, are subject to much wider irregular movements than others are because of differences in sampling error or in the effects of such factors as the weather and strikes. It is therefore useful in interpreting current changes to have a standard measure of the size of these irregular factors compared with the size of the movements reflecting long-term trends and the events of the business cycle. (In economic discussions these latter factors are often called trend-cycle movements.)

Two measures of this kind are provided for all the indicators carried in *Business Conditions Digest*. One shows how large the average monthly change in the irregular component is with respect to the average monthly change in the trend-cycle component. The other shows how many months must elapse on the average before the change in the trend-cycle component, which builds up over a period of time, exceeds the irregular component, which does not. For example, the measures show that monthly changes in housing starts are likely to be dominated by "noise," but that when these changes are measured over spans



COINCIDENT INDICATORS are traced through six recessions, starting with the date of the business peak preceding the recession. Each curve represents the percentage change in the index of five indicators, namely industrial production, nonfarm employment, unemployment rate, personal income in constant dollars and total sales in constant dollars. Through last October the current decline most nearly resembled the ones in 1969–1970 and 1960–1961.

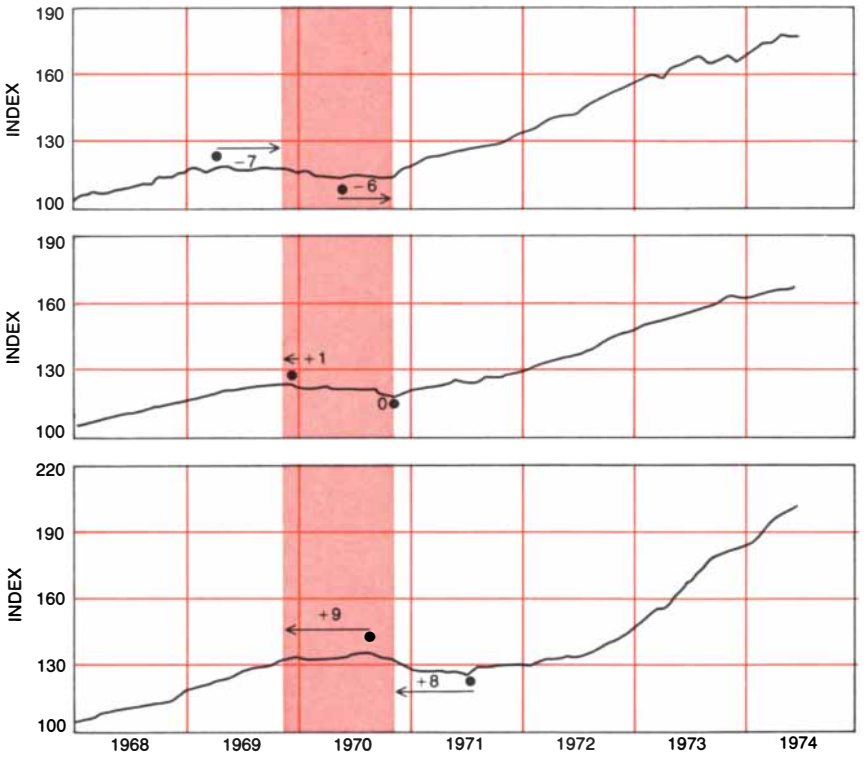
of four months, the trend-cycle "signal" becomes dominant. On the other hand, the index of industrial production is much less affected by noise, so that monthly movements are more significant.

The most important characteristic of an indicator from the point of view of forecasting is of course the evidence it provides concerning future changes in economic activity. Indicators differ in this respect for numerous reasons. Certain types, such as housing starts, contracts for construction and new orders for machinery and equipment, represent an early stage in the process of making decisions on investment. Since it takes time to build a house or a factory or a turbine, the actual production (or completion or shipping) usually lags behind the orders and contracts. The lag depends on, among other things, the volume of unfilled orders or contracts still to be completed; where goods are made for stock rather than to order there may be no lag because orders are filled as they are received.

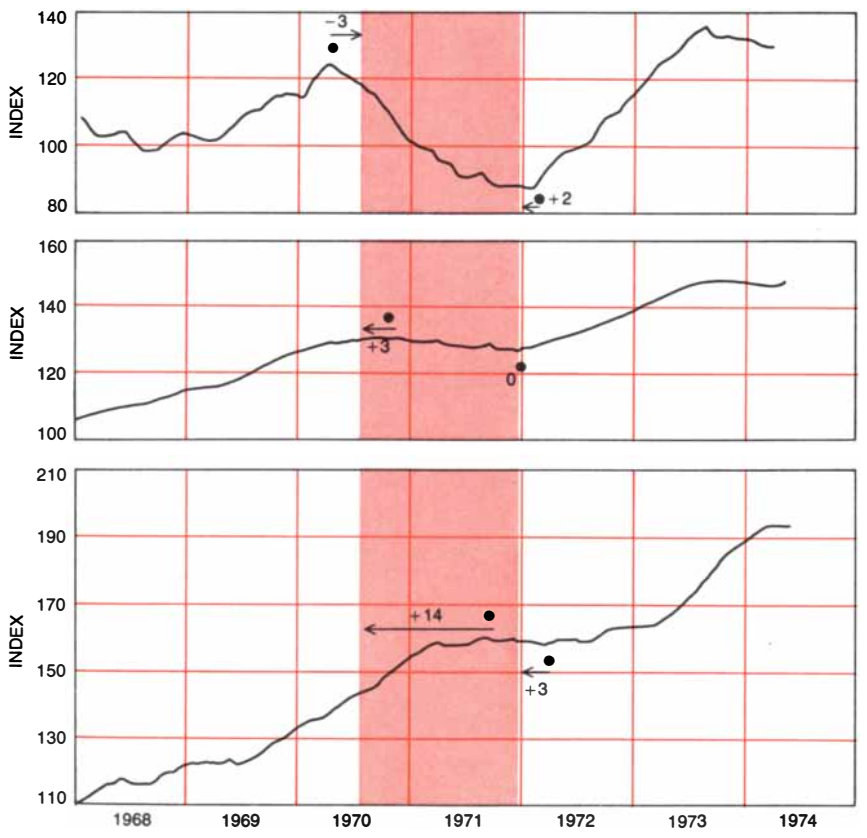
Another kind of lead-lag relation exists between changes in the workweek on the one hand and employment on the other. In many enterprises employers can increase or decrease hours of work more quickly, more cheaply and with less of a commitment than they can hire or fire workers. Hence in most manufacturing industries the average length of the workweek usually begins to increase or decrease before a corresponding change in the level of employment. The workweek is therefore a leading indicator with respect to the unemployment rate.

Many bilateral relations of this kind have been traced. The matter obviously becomes more complex, however, when the relations are multilateral. Indexes of stock-market prices, for example, have exhibited a long-standing tendency to lead changes in business activity (the Harvard *ABC* curves relied in part on this tendency), but the explanation seems to require the interaction of movements in profits and in interest rates, and other factors as well. A cyclical decline in profits often starts before a business expansion comes to an end; the proximate cause is usually a rapid rise in the costs of production. Interest rates also are likely to rise sharply. Both factors operate to reduce the attractiveness of common stocks and depress their prices, even though the volume of business activity is still rising. Near the end of a recession the opposite tendencies come into play and lift stock prices before business begins to improve.

One way to cut through such com-



U.S. INDICATORS behaved differently in the recession of 1969–1970 according to whether they were leading (*top*), coincident (*middle*) or lagging indicators (*bottom*). Each curve represents an index of several indicators in its class. Negative numbers with arrows mean the curve was that number of months ahead of the corresponding peak or trough in the business cycle. Positive numbers mean the curve was that number of months behind the cycle.



JAPANESE INDICATORS are portrayed for a recession that ran from July, 1970, to December, 1971. The method of presentation is the same as for the illustration at top of page.

plexities instead of pursuing each bilateral or multilateral relation separately is to measure leads and lags against a common standard. For this purpose a chronology of business cycles has proved useful. The National Bureau of Economic Research has defined business cycles in such a way that peaks and troughs can be dated with reasonable objectivity. (Indeed, much of the dating procedure can now be carried out by computer.) Since the vast majority of indicators that are of interest show cyclical movements conforming to these general business cycles, the peaks and troughs in each indicator can be matched with those of the business cycle to determine characteristic leads and lags.

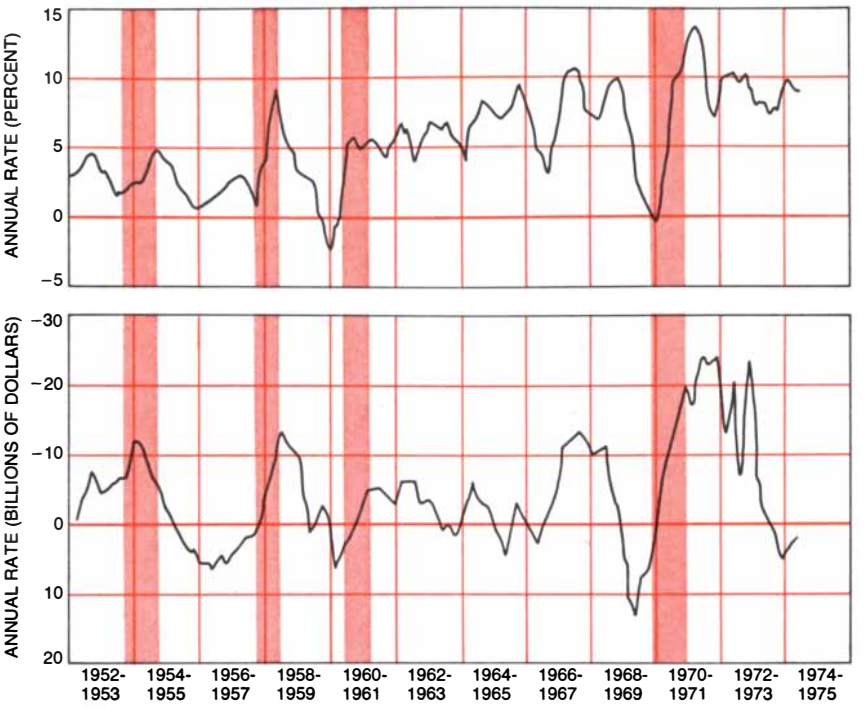
Following this plan, groups of indicator series that typically lead, coincide with or lag behind turns in the business cycle have been identified [*see top illustration at left*]. Summary indexes of these groups can be employed (as individual indicators can) to measure the relative severity of an economic downturn as it progresses from month to month. For example, indications of a slowdown in the U.S. economy began to accumulate during 1973. Early in 1974 it was possible to conclude that if a recession was under way, a reasonable choice for the date of the business peak from which it started was November, 1973. Percentage changes from then to successive months in 1973 and 1974 were calculated for a number of indicators month by month as new data became available and were compared with changes over corresponding intervals in earlier recessions, which had exhibited varying degrees of severity.

With such a monitoring scheme one could observe the relative severity of the current decline and draw certain inferences based on the fact that the rankings among different recessions have usually not changed a great deal after the first few months. The figures show that the decline of 1974 was relatively sharp early in the year as the effect of the oil crisis began to be felt. According to the latest data available (for October) as of this writing, however, the decline in most indicators appeared moderate compared with the declines in earlier recessions over corresponding intervals. The major exceptions were the sharp declines in housing starts and in prices of common stocks, both of which reflected the sharp rise in interest rates and rapid inflation.

It is of course essential in any appraisal of the economic outlook to take into account actual and prospective poli-

cy actions by the Government. Such actions include tax reductions or increases, changes in required bank reserves, changes in military expenditures and the establishment of a program of public employment. They often do not fit readily into the framework of indicators, although their effects, together with other influences, may be registered promptly in orders, contracts, housing starts, stock prices and so on. Still, certain indicators do provide a nearly continuous reading on Government activities.

Government moves are often countercyclical. In a recession, for example, the Government can exert a stimulative effect on the economy by making bank deposits or currency more readily available or by spending more than tax revenues are bringing in. The impact of such measures is a matter of debate. Indeed, it is possible to argue from the figures that policy shifts by the Government have sometimes contributed, with a lag, to the cyclical movements in the economy that they were designed to offset.



ROLE OF GOVERNMENT through four recessions is indicated by curves that portray rate of change in money supply (*top*) and Federal surplus or deficit (*bottom*). On bottom curve a rise indicates a shift toward smaller surplus or larger deficit, a fall the opposite. Behavior of curves in recessions indicates interaction of Government policy with business cycle.

The analysis of economic indicators is one way of assessing the behavior of the economy. Econometric models of the business-cycle process are another. Although the two techniques have developed along independent lines for many years, they have come together at a number of points. The mathematical equations that characterize econometric models can handle elegantly and systematically such matters as multilateral relations among indicators, the distinction between seasonal movement and other types of movement, the influence of changes in Government policy and the plausibility of alternative theoretical explanations of the cycle.

The econometric models focus their explanatory power on such roughly coincident indicators as the gross national product, unemployment and the rate of inflation. Ofter they include such cycle-leading indicators as housing starts, the average workweek, stock prices and changes in business inventories, together with such lagging indicators as mortgage interest rates and investment in plant and equipment. Although the models have so far had a mixed record in representing and forecasting developments in the business cycle, with the result that the competition among alternative models is keen and changes in the specifications of each model are frequent, no user of indicators can afford to ignore the insights that econometric models bring to economic analysis. By the same token, people working with models can benefit from the empirical findings of indicator analysis and from the additional information that indicators often provide from outside the boundaries of a particular econometric model.

Economic indicators of all types are followed more widely in the U.S. than in most other countries. The growth of trade, travel and international finance, however, has increased the demand for promptly available statistics and readily accessible analytical records. Last year the National Bureau of Economic Research began a program of assembling and analyzing indicators for a dozen industrial countries.

Fortunately the indicator approach is sufficiently flexible to be adapted readily to situations where, as in many countries since World War II, economic recessions have taken the form of retardations in the growth of aggregate activity rather than absolute declines, and where such retardations may have been deliberately induced by government policies in order to cool off inflation or restore a deteriorating trade balance. Moreover, the approach is flexible enough to accommodate differences among countries in the types of indicator data that are available or are most revealing. For example, in Europe statistics on job vacancies are relied on more than in the U.S. and data on the international migration of workers are more significant because they have larger effects on the size of the work force.

Furthermore, since many economic indicators are available in physical units (such as man-hours of employment or tonnage shipped) or can be expressed in constant prices, a system of indicators can be adapted to conditions where a high rate of inflation dominates the behavior of data that are expressed in current prices. Many countries have recently experienced such conditions. Physical indicators of demand, such as housing starts, hiring rates and orders for materials, can be expected to throw light not only on subsequent changes in output and employment but also on changes in prices and wages.

Our study is exploring these paths. Results already in hand for Canada, Japan, the United Kingdom and West Germany demonstrate the feasibility of the approach and its potential value in observing and appraising international fluctuations in economic growth rates and the accompanying trends in price levels, foreign trade, capital investment and employment. One can envision the evolution of a worldwide system of indicators, built on the plan originally developed for the U.S., to support the analysis of economic indicators on a global scale.

THE NATURE OF ASTEROIDS

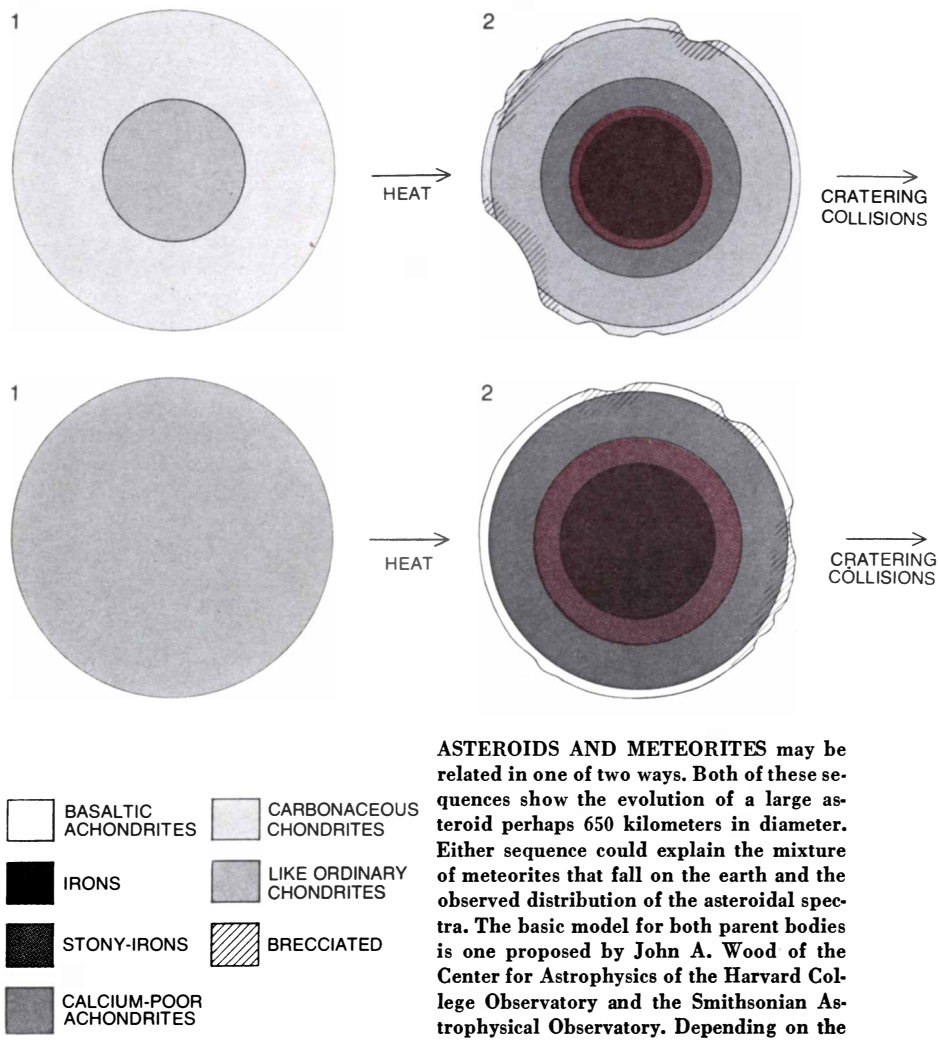
The spectra of sunlight reflected by the minor planets have yielded new clues to their mineralogical composition, their origin, their evolution and their relationship to meteorites

by Clark R. Chapman

Important clues to the origin of the solar system lie in "genesis rocks." These are rocks that have retained their character from nearly 4.6 billion years ago, when the planets were still accreting out of the cloud of dust and gas we call the solar nebula. Most meteorites are genesis rocks of a kind: their chemistry and mineralogy reveal that most of them were formed in environments characteristic of the early solar system. Indeed, inclusions in certain meteorites have been shown by Lawrence Grossman of the University of Chicago to be samples of the earliest solar-nebula condensates, and parts of the inclusions may even predate the solar system.

Genesis rocks may exist on at least some of the asteroids, the huge swarm of small worlds in orbit at distances between 2.2 and 3.2 astronomical units from the sun. (Some swing as close to the sun as the orbit of Mercury and some as far from the sun as the orbit of Saturn.) The study of the asteroids has been intimately associated with theorizing about meteorites, but until recently few nonmeteoriticists gave these minor planets much thought; little was known other than the numbers, names and orbital characteristics of somewhat fewer than 2,000 of them. Intensive new observational studies were undertaken some five years ago, and combined with theoretical and interpretive work they have yielded a fascinating picture of the physical nature of the asteroids. Moreover, the real relations between asteroids and meteorites are becoming established for the first time.

The discovery of the planet Uranus by William Herschel in 1781 and measurements of its distance from the sun seemed to lend credence to the formula of planetary spacings known as Bode's law. The formula also predicted the existence of a planet between the orbits of Mars and Jupiter, so that many astronomers undertook to find it. In 1801 the first and largest asteroid, Ceres, was discovered at about the right distance. Although its small diameter, now known to be 1,000 kilometers, was initially a disappointment, the rapid discovery of other asteroids (Pallas, Juno and Vesta) in similar orbits led to the hypothesis that the asteroids were fragments of a shattered planet. The hypothesis drew strength from the demonstration some years earlier by the German physicist Ernst Chladni that meteorites were of extraterrestrial origin. It became a popular assumption that meteorites also were debris of a shattered planet.



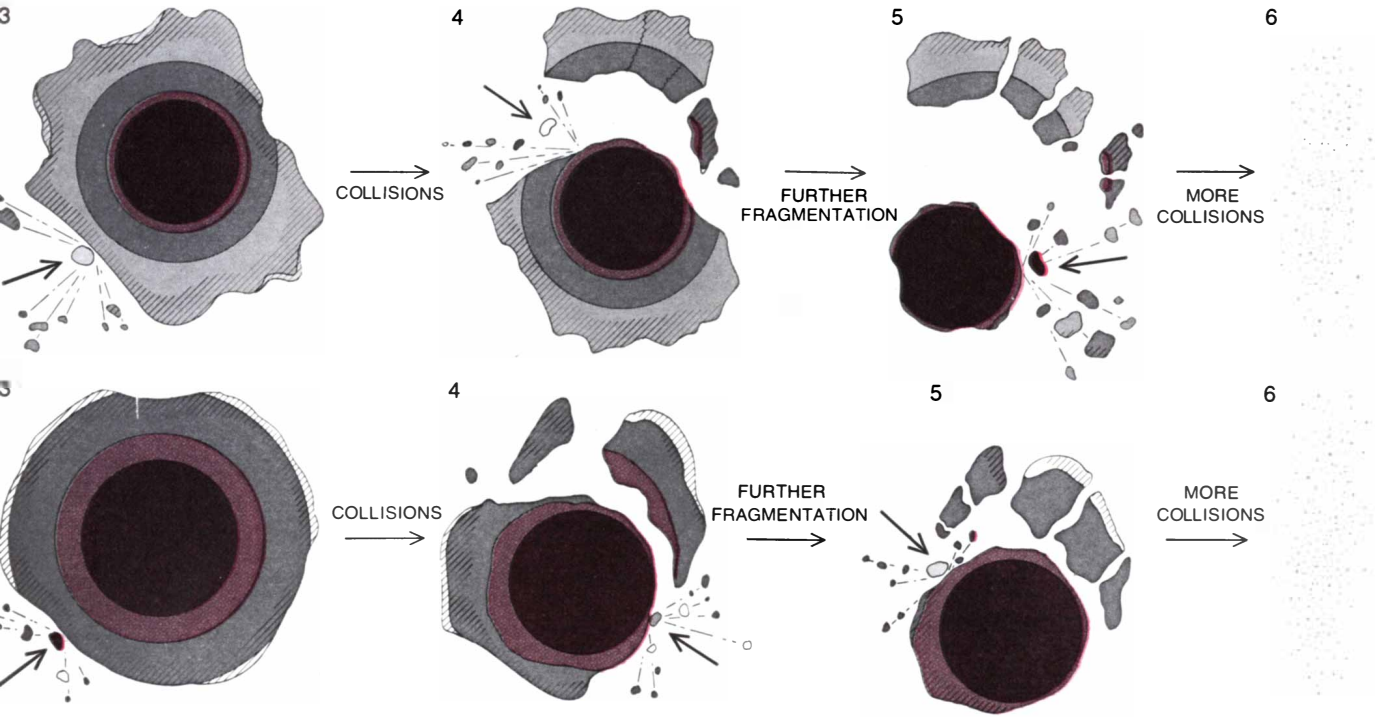
ASTEROIDS AND METEORITES may be related in one of two ways. Both of these sequences show the evolution of a large asteroid perhaps 650 kilometers in diameter. Either sequence could explain the mixture of meteorites that fall on the earth and the observed distribution of the asteroidal spectra. The basic model for both parent bodies is one proposed by John A. Wood of the Center for Astrophysics of the Harvard College Observatory and the Smithsonian Astrophysical Observatory. Depending on the

The shattered-planet hypothesis is widely known among laymen, and it does have some superficially attractive features. In scientific circles, however, the idea has now been abandoned for several reasons. First, the accumulated data gleaned from meteorites increasingly indicate that the parent bodies that fragmented to form the meteorites were not of the dimensions of a planet but were more nearly the size of the present-day asteroids. Second, there is no plausible source for the energy that would have been needed to violently disrupt a large planet and disperse its fragments against the pull of its own gravitational field.

Third, the theories of V. S. Safronov and others now predict (although one wonders with what hindsight) that the amount of material accreted in the asteroid belt at the time the solar system formed 4.6 billion years ago would be very small. The problem of explaining the accretion of material condensed from the cooling solar nebula lies in explaining how the particles came to agglomerate. Until the bodies grew to a diameter of hundreds of kilometers their gravity was weak, and only those particles with very low speeds with respect to one another stood a chance of sticking together. After the cloud had been thinned enough so that the bodies growing in the asteroid belt could move in gravitational orbits around the forming sun, the massive bulk of the nearby proto-Jupiter began to create havoc. Jupiter's gravitational effect on the small bodies, the diameters of which were possibly between 1,000 and 1,500 kilometers, probably increased their speeds with respect to one another toward the present-day five kilometers per second. If such bodies encountered one another at that speed, they would break up instead of somehow combining. This behavior would account for the fact that the asteroids never grew into a complete planet (or planets). Much of the material that originally condensed in the asteroid belt was eventually merged into the other planets of the solar system.

The asteroids we see today could hardly have made up a good-sized planet. Their total mass is only a few times the mass of Ceres alone, and that mass is 1.2×10^{24} grams, or .02 percent of the mass of the earth. The present asteroids, however, may be only a remnant of the original number. If asteroids were once much more numerous, collisions between them would have been common. The colliding asteroids may have been gradually reduced to an interplanetary dust that spiraled inward toward the sun, thereby removing mass from the asteroid belt.

Alternatively, the orbits of the asteroids could have changed so that the asteroids eventually collided with a planet. As was shown in the 1950's by S. Piotrowsky and by Ernst Öpik, the present asteroids are in stable, long-lived orbits and would collide with a planet such as Mars only once in several billion years. This consideration might seem to argue against any substantial depletions of mass from the asteroid belt in the past, but then any short-lived asteroids would have long since disappeared. Myron Lecar and Fred A. Franklin of the Center for Astrophysics of the Harvard Col-



process by which the center of each parent body heated up, the bodies would have differentiated to different degrees. In the top sequence the original object (*1*), which may have resembled the present-day asteroid Ceres, heats up and differentiates into an object (*2*) that may have been much like the asteroid Pallas. Collisions brecciate, or shatter, the outer layers (*3*) and give rise to an object that may have resembled the asteroid Dembowska. More collisions break the body into large chunks (*4*); the brecciated outer layers could have been the source of chondritic meteorites. The core (*5*) may have resembled the asteroid Nausikaa; after further fragmentation it could have been the source of iron meteorites and pallasites (stony-iron meteorites). Other pieces of the original mantle could have yielded calcium-poor achondrites and unbrecciated chondrites; one of the larger pieces could have resembled the asteroid Toro. In the bottom sequence similar events involving a parent body of different composition that was formed earlier or closer to the sun yields similar types of asteroids and meteorites. After the parent body had thoroughly heated up and then differentiated it may have resembled the asteroid Vesta; its crust could have been a source of basaltic achondrites. Further fragmentation of the smallest objects in both sequences would have created interplanetary dust (*6*) that would have eventually spiraled inward toward the sun and been consumed. The evolution of parent bodies that are smaller is shown in the sequence on the next page.

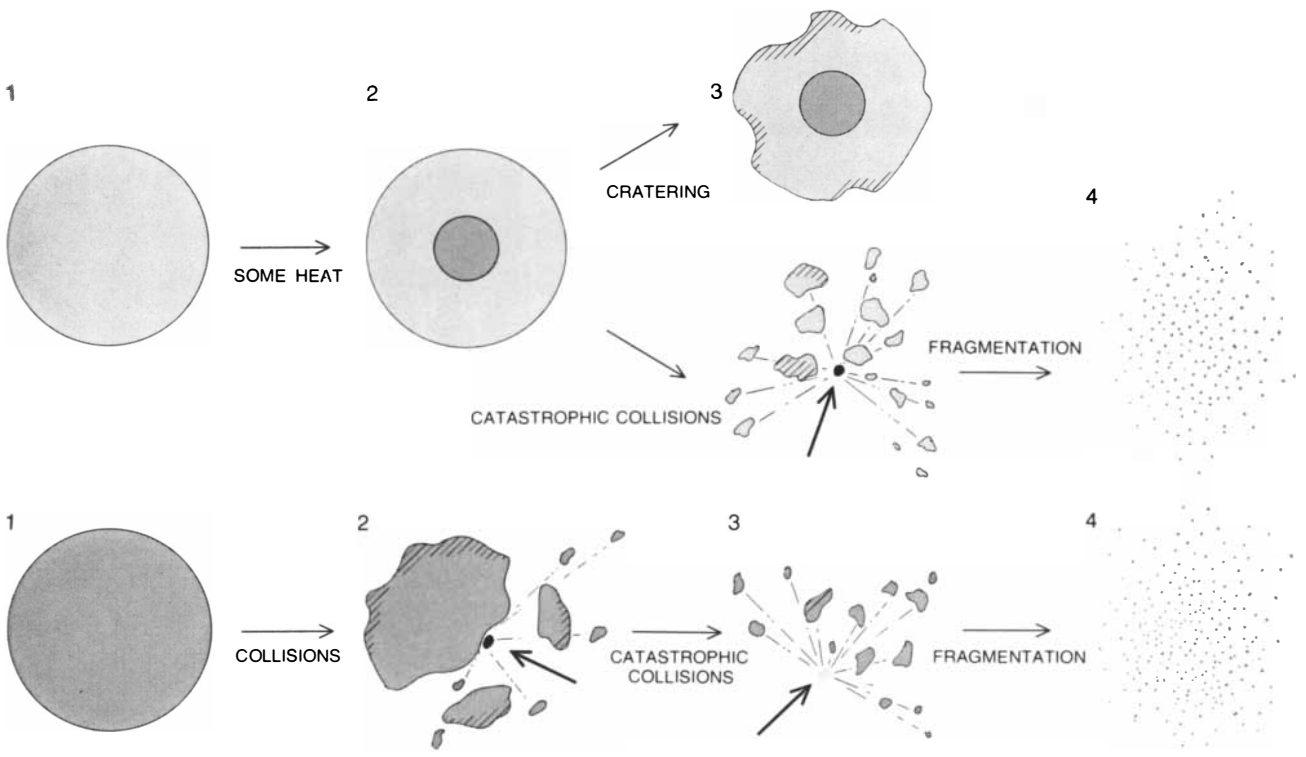
lege Observatory and the Smithsonian Astrophysical Observatory have calculated that any asteroids between the orbits of the asteroids in the Hilda group at four astronomical units from the sun and the orbit of Jupiter at 5.2 astronomical units would have been ejected from that region by perturbations due to the gravitation of Jupiter within the first few thousand years. Probably most of the asteroids that were originally located between the orbits of the Hilda group and the 2:1 orbital resonance with Jupiter at 3.27 astronomical units (where asteroids revolve around the sun twice in the time it takes Jupiter to revolve once) have also been ejected by Jupiter's influence but over a much greater period of time. Some asteroids must have been thrown out of the solar system altogether. Others fell onto the planets or collided with other asteroids.

In the 19th century the asteroids were treated as points of light to be discovered, named and charted. Although the description of their orbits gradually advanced, there was little study of their physical nature until the turn of the 20th century. Then E. E. Barnard and others attempted to use a micrometer to measure the diameter of the images of the four brightest asteroids in the field of telescopes. In spite of the difficulty of measuring images that were scarcely larger than star images smeared by the turbulence of the earth's atmosphere, Barnard's diameters remained unchallenged until a few years ago.

In 1929 N. T. Bobrovnikoff of the Lick Observatory thought that the points of light representing the asteroids might be colored, and he obtained photographic spectra that showed there were substantial differences in the colors of several of the minor planets. Both he and later investigators realized the importance of comparing the spectra of asteroids with the reflective properties of meteorites in the laboratory. Detailed chemical and petrological measurements can be made on meteorites; it is not known, however, where the meteorites come from and therefore to what part of the solar system the measurements pertain. If meteorite types could be related to specific asteroids through their spectral properties, it would be possible to accomplish what Edward Anders of the University of Chicago calls "a chemical mapping of the inner solar system."

Such goals guided the attempts in the decades after the 1930's by Russian, German and American astronomers to measure the colors of asteroids photographically. These initial attempts ultimately failed because many of the meteorite samples were literally rusty, so that the mineralogical significance of their colors was poorly diagnosed. Perhaps the worst error resulted from two little-heeded characteristics of asteroids: they are not spherical in shape and they spin rapidly. Differences in the brightness of an asteroid recorded on two photographic plates, one sensitive to red light and the other to blue, cannot be reliably interpreted if an irregularly shaped asteroid presented its end during the red exposure and its side during the blue one [*see illustration on opposite page*].

High-quality photoelectric photometry based on the standardized UBV color system, which measures the apparent brightness of an object in the ultraviolet, blue and visual (yellow) regions of the

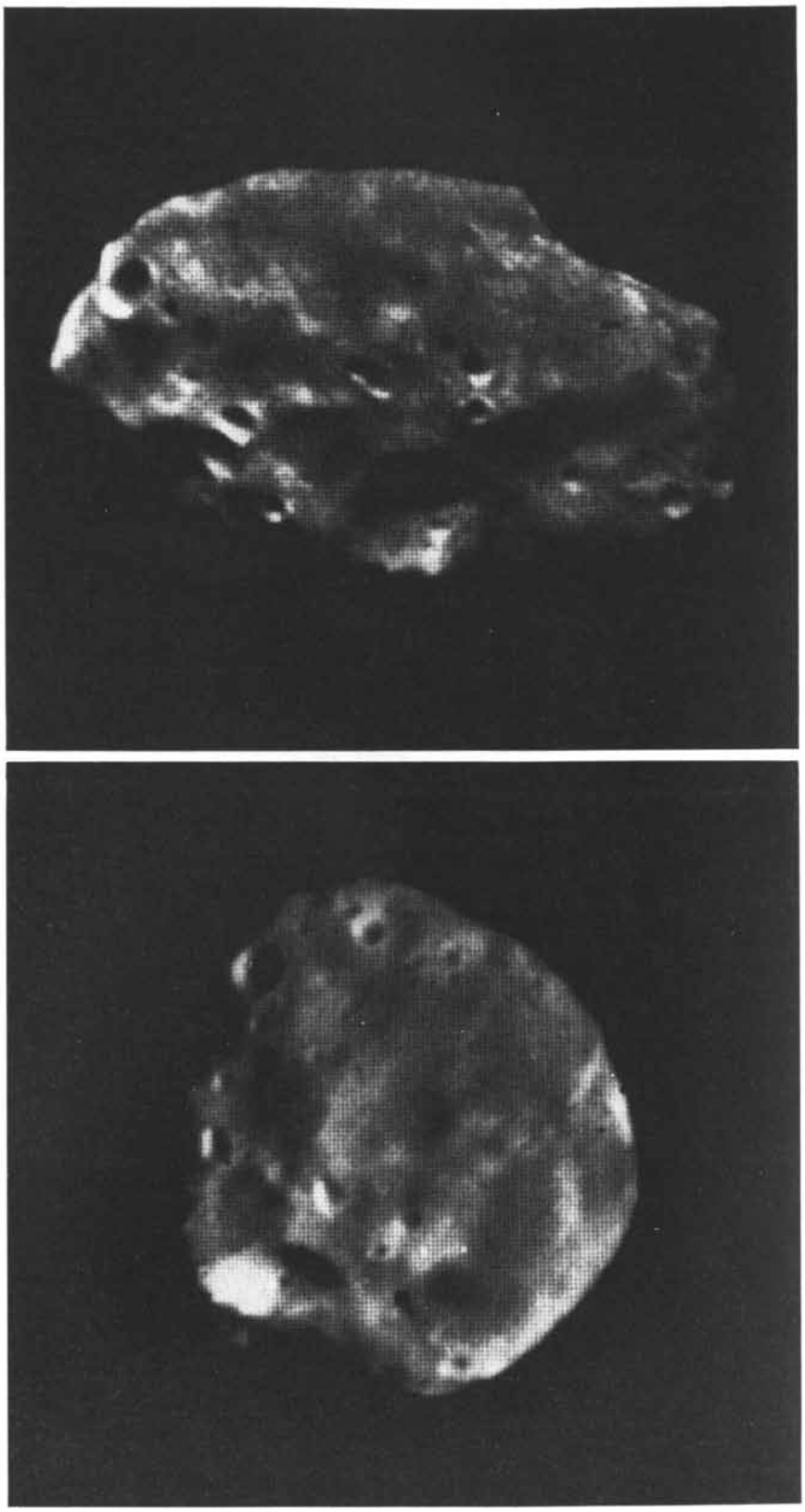


SMALLER PARENT BODIES at different distances from the sun would not have evolved as far as their larger counterparts. In the top example heating in the center of the object (*1*) might have metamorphosed it somewhat (*2*). At that point if the body had been simply cratered by collisions (*3*), its outer parts could have yielded carbonaceous chondrites; the object may have been similar to the asteroid Lumen. Alternatively catastrophic collisions could have disintegrated it and created interplanetary dust (*4*). Object is assumed to have been farther than 2.3 astronomical units from the sun. (One astronomical unit is mean distance from earth to sun.) Bottom example involves an object closer than 2.3 astronomical units; collisions could have yielded objects (*2*) that resembled asteroids Flora (largest chunk) and Ariadne (either of the smaller chunks).

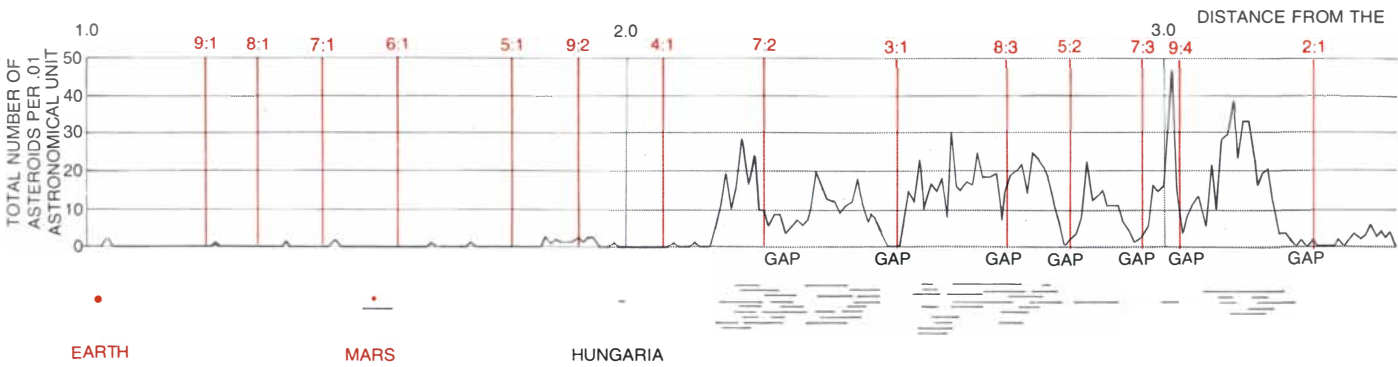
spectrum, was initiated in the 1950's by the late Gerard P. Kuiper and by Tom Gehrels at the University of Arizona. Such photometry measures the light curve—the record of brightness variations—of each asteroid as it tumbles in space. From these measurements rotation periods are now known for 72 asteroids. In addition some progress is being made in calculating the exact orientation in space of the asteroid's axes by comparing the light curves obtained at various orbital positions of the earth and the asteroid with respect to the sun.

In comparing the apparent brightness of asteroids in the ultraviolet, blue and visual regions of the spectrum, UBV photometry has shown that the colors of asteroids fall roughly into two groups: one in which the colors are reddish and one in which they are more neutral. In 1969 Thomas B. McCord and Torrence V. Johnson of the Massachusetts Institute of Technology obtained a spectrum of reflected sunlight of the asteroid Vesta in the visible and near-infrared regions of the spectrum; it showed a prominent absorption band in the infrared. Together with John Adams, who was then at the College of the Virgin Islands, they showed that the wavelength of the band corresponded to the energies of the transitions of electrons within the crystal structure of a particular pyroxene mineral called pigeonite. Furthermore, they compared the spectrum of Vesta with the reflectance spectra of meteorite specimens in the laboratory and concluded that the surface of the asteroid was composed of certain silicate rocks rich in pigeonite, rocks much like certain basaltic achondrites. (Stony meteorites are classified into two main groups: the chondrites, which contain the spherical aggregates of iron-magnesium silicates called chondrules, and the achondrites, which do not.)

McCord and I have now measured the spectra of 97 additional asteroids, and we have found that they show an amazing diversity. So far we have distinguished some three dozen different types of spectra, which implies that asteroids have many different mixtures of minerals on their surface. The spectra of a few asteroids have an absorption band as strong as the one in the spectrum of Vesta. The position of the band is a sensitive measure of the ratio of iron or of calcium to magnesium in the crystal structure of different silicate minerals. Although spectra of most of the minor



TWO PICTURES OF PHOBOS, one of the moons of Mars, were made by the spacecraft *Mariner 9*. Although there are no such views of asteroids, Phobos closely resembles one of those bodies. The pictures show the same side of Phobos but reveal its nonspherical shape (13.5 kilometers long and 9.5 kilometers wide), which is partly in shadow. The brightness of any asteroid shaped like Phobos would clearly vary considerably as it rotated. Unlike asteroids of same size, Phobos has a substantial regolith of fragments because debris ejected from it by impacts was trapped in orbit around Mars and reaccumulated on its surface.



DISTRIBUTION OF ASTEROIDS in the asteroid belt is presented in two different ways. The orbits of the major families of asteroids are shown with respect to the orbits of the earth, Mars and Jupiter at the bottom. The curve at top shows the total number of asteroids at various distances from the sun. "Gap" indicates the locations of the Kirkwood gaps: spaces where few asteroids travel because of

planets do not show such diagnostic absorption features, the spectra of many do match the laboratory spectra of carbonaceous chondrites: meteorites rich in water that are believed to be the least altered sample of the early condensates of the primordial solar nebula. Another group consisting mostly of rather large asteroids, with diameters of between 100 and 200 kilometers, has reddish spectra with weak absorption bands from several silicate minerals. Michael Gaffey of M.I.T. argues persuasively that the spectra show that the silicates are mixed with iron, just as they are in the small group of meteorites known as stony irons. Other unusual spectral types have not yet been associated with specific kinds of minerals.

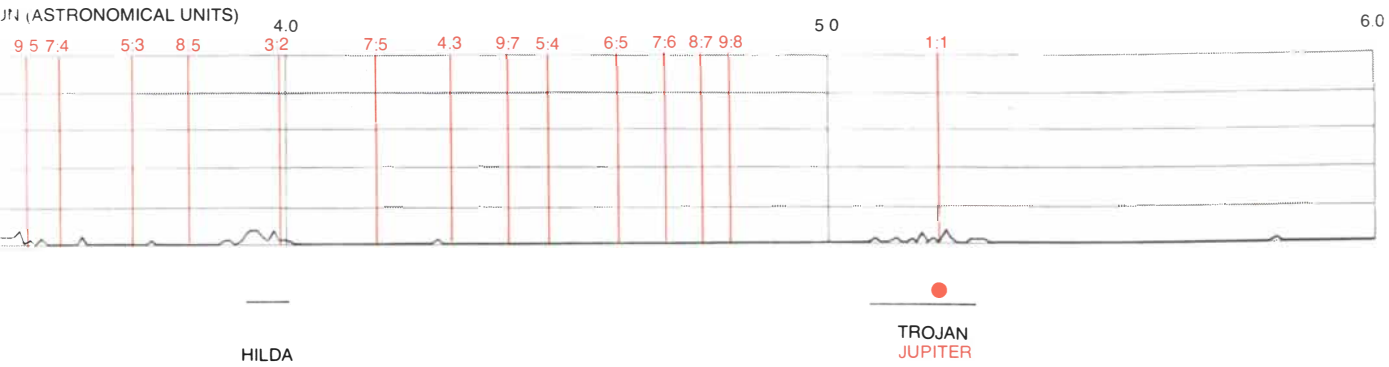
Curves of spectral reflectance portray the color characteristics of asteroids but not their absolute brightness. They are nonetheless reasonably diagnostic of the general mineralogical nature of the asteroid's surface. The power of comparing them with spectra of laboratory samples, however, is enhanced if the absolute albedo, or reflectivity, of the asteroid's surface is known. Two newly developed techniques are being used to measure the albedo of asteroids. Such measurements also yield accurate diameters, since the apparent brightnesses and distances of the asteroids are known. The surface of an asteroid polarizes the sunlight it reflects, that is, it causes the light waves to oscillate in one plane. The degree of polarization changes as a function of the angle from the sun to the asteroid to the observer, and it seems to be correlated with the albedo: the greater the change in the polarization with the sun-asteroid-observer angle, the darker the asteroid's surface. The relation has been calibrated with rock samples in the laboratory. With these calibrations Benjamin H. Zellner III of the University of Arizona has analyzed his polarimetric data for nearly 40 minor planets to obtain their albedo and diameter.

Zellner's results agree well with those from an entirely independent technique pioneered by David Allen at the University of Minnesota and by Dennis Matson at the California Institute of Technology. Thermal radiation near the wavelengths of 10 and 20 micrometers in the infrared is measured and compared with the brightness of an asteroid at visual wavelengths. The asteroid can be reasonably represented as a black body, or perfect radiator, in thermal equilibrium with the sunlight impinging on it. A body that is dark at visible wavelengths will be proportionately hotter and hence brighter in the infrared, and at the same time fainter at the visual wavelengths, than a light-colored body of the same size. With this technique the albedo and the diameter of the asteroid can be calculated; David Morrison and Dale P. Cruikshank of the University of Hawaii have done it for nearly 50 asteroids.

The reflectance spectra of 44 asteroids have been compared with the asteroids' measured albedo and also with spectra and albedos for various classes of meteorites [*see illustrations on pages 30 and 31*]. Although differences in albedo within a factor of two are not often important for deducing the composition of a body (because albedo also varies with such factors as the size of the particles reflecting the light), it is comforting that the spectra of asteroids identified as resembling the spectra of carbonaceous chondrites have the very low albedos typical of those meteorites. (Only between 3 and 8 percent of the light received is reflected back.)

The data from spectrophotometry, polarimetry and thermal-infrared photometry confirm that, except for a few unusual asteroids, there are two general classes of asteroid surface compositions. Asteroids in the first class are relatively bright and reddish; they have a surface composed predominantly of silicates and metals, and they lack appreciable amounts of opaque, light-absorbing minerals. Asteroids in the second class are very dark and neutrally colored; they are evidently rich in opaque carbonaceous material. As we investigate increasingly faint objects we find that a larger percentage belong to the second class. This finding confirms the implication of other studies (including the analysis of meteoritic material in the soils brought back from the moon) that asteroidal and interplanetary debris is largely of carbonaceous composition.

The sequences of condensation and accretion early in the history of the solar system might plausibly have varied with distance from the sun or distance above the central plane of the disk of the solar nebula. The variations due to differences of temperature and pressure within the nebula may be reflected today in variations of the spectral properties of asteroids with respect to the distance of their orbit from the sun. Asteroids whose maximum distance from the sun is more than 3.45 astronomical units are almost never reddish. Nearly all these bodies resemble carbonaceous chondrites, which are believed to have accreted in the coolest parts of the solar nebula. There are, it is true, many exceptions to the gross correlation of color and distance from the sun; perhaps gravitational forces "stirred the pot" after accretion. The distribution of composition with respect to distance may be more regular than it seems if, as appears likely, we are observing the fragments of geochemically differentiated parent bodies. Some asteroids might show their original



perturbations due to the gravitation of Jupiter. Numbers in color indicate the distances at which the orbital period of an asteroid traveling around the sun is in resonance with Jupiter's orbital period; for example, the resonance 7 : 2 indicates the distance at which the minor planets circle sun seven times in time Jupiter revolves twice. Names of several major families of asteroids are given.

surface and others might be fragments of the core or mantle of larger bodies that have different spectra.

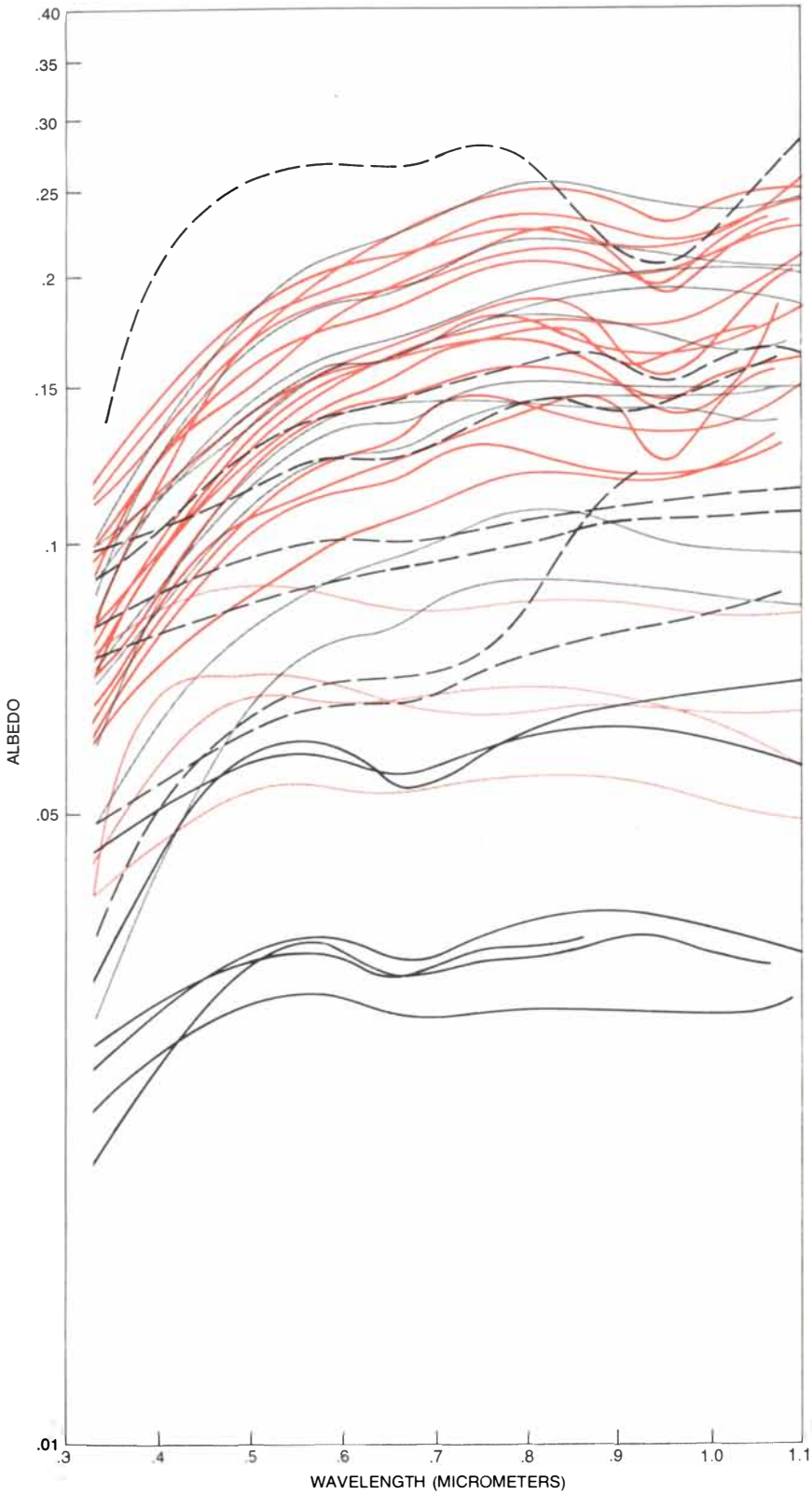
Although we now know something about the surface of more than 100 minor planets, we know about the interior of only three. Hans G. Hertz of the National Aeronautics and Space Administration and J. Schubart of the Astronomisches Rechen-Institut in Heidelberg have painstakingly measured the perturbations in the motions of certain small asteroids caused by Vesta, Pallas and Ceres and have thereby determined the masses of these three largest asteroids. From such measurements and knowledge of Vesta's diameter it appears that the asteroid has a density of about 3.5 grams per cubic centimeter, much the same as ordinary rocks and stony meteorites. Pallas seems to have a density of less than three grams per cubic centimeter, as carbonaceous meteorites of Type 2 do. Ceres has a density closer to two grams per cubic centimeter, as carbonaceous meteorites of the more primitive Type 1 do.

Thus far I have recounted what astronomical studies have told us about asteroids. If meteorites are actually asteroidal fragments that have fallen on the earth, however, we have much additional information about asteroids in the laboratory. The mineralogy, the content of trace elements and gas, the petrology and so on of literally hundreds of different meteorites have been measured. Intricate classification schemes have been devised and innumerable correlations are studied. Analyses are complicated by the fact that meteorites found on the earth are no longer in their original environment and cannot reveal the interrelations any field geologist needs in studying terrestrial rocks. In recent years the discipline of meteoritics has moved beyond the taxonomic stage, and sound geochemical and physical reasoning has been applied in interpreting the masses of data. Some meteoriticists boldly construct multistage scenarios of condensation, agglomeration, accretion, heating, metamorphism and differentiation to explain the accumulated facts.

Theoretical models of the parent bodies of meteorites have been put forward. The earlier model-builders may have been encouraged by the mere knowledge that asteroids exist and by the hope that the meteorites come from them, but they were not constrained by the then unknown characteristics of asteroids. In the 1960's model-builders began to face obstacles when studies of meteorite orbits led to dynamical calculations that seemed to suggest that meteorites came from comets, not asteroids. The first problem was that the models of the parent bodies of most meteorites differed from such models of the nuclei of comets as the "dirty snowball" model advanced by Fred L. Whipple. Another problem was that deductions about the environments in which the parent bodies had formed had to take into account not only the asteroid belt but also the region where comets originated, which was unknown because the orbits of comets have been grossly perturbed by Jupiter and other planets. The prospects for relating meteoritic results to the early temperature and pressure regimes of specific locations in the solar system seemed dim.

Since then further dynamical studies conducted by George W. Wetherill and Peter D. Zimmerman at the University of California at Los Angeles and by James G. Williams of the Jet Propulsion Laboratory of Cal Tech have revealed two different ways in which fragments of asteroids could have been delivered to the earth in the necessary times, orbits and quantities. In both cases the sampling is quite selective. The fragments must have come from a few asteroids located near the gaps in the asteroid belt known as Kirkwood gaps, or from orbits that were in resonance with the orbit of Jupiter. Fragments from asteroidal collisions that were knocked into the nearby orbital resonances could have been perturbed by the gravitation of Jupiter into more elliptical paths that crossed the orbit of the earth. Such highly selective sources for meteorites are compatible with the astronomical evidence that the composition of many asteroids resembles the composition of meteorites, and that the proportional distribution of various types of material in the population of asteroids differs from that in the population of known meteorites. We have not yet, however, been able to ascribe the origin of any one class of meteorites to any one minor planet.

Let us examine some of the requirements for the parent bodies of meteorites and models that fit these requirements. Conceptually the models are scaled-down versions of the original notion of a shattered planet. Although one might suppose that meteorites originated with objects the size of a boulder, the evidence suggests that about a dozen bodies the size of an asteroid are needed. For example, the distribution of nickel across crystals of the nickel-iron alloy taenite that is present in chondrites and in iron meteorites implies specific rates at which the body where they originated cooled. The rates vary from sample to sample, but typically they range from .2 degree to 10 degrees Celsius per million years. Such cooling rates require that the material be buried at depths of tens to hundreds of kilometers in a parent body below an insulating material such as silicates. Moreover, the characteristics of certain other meteorites seem to require



SPECTRA OF 43 ASTEROIDS and the measurements of their albedo (the percentage of incident sunlight they reflect) are compared with the mean spectral and albedo curves for the major classes of meteorites on opposite page. Asteroids are divided into five main groups according to their composition. Although there are many similarities between asteroids and some meteorite classes, there are also many meteorites that have no asteroidal counterparts.

that at one time they resided on the surface of asteroid-sized bodies. These are the brecciated meteorites: meteorites that are largely composed of shattered rocks, may include small fragments of different types of meteorites and may contain trapped gases of the "solar wind." Such meteorites resemble lunar breccias, and they seem to require that the material be part of a surface regolith: a fragmented layer created by the repeated impact of small particles on a comparatively large body.

As I have mentioned, the carbonaceous chondrites are the least altered sample of early condensates in the solar nebula. These meteorites have nearly the same abundances of various elements, except for the most volatile ones, as the sun itself. If an asteroid composed of such primitive material were to be melted, the minerals would separate according to their specific gravity and their chemical affinity for one another. Metals will sink because they are denser than basaltic rocks, and the basaltic rocks will be buoyed to the surface.

Brian H. Mason of the U.S. National Museum has constructed a model parent body on this basis. The basaltic achondritic meteorites, with their high content of the mineral pigeonite, would come from the crust. The mantle would yield meteorites of the class of hypersthene achondrites. The metals and the olivine in the core would form the iron meteorites and the pallasites: stony irons made up of olivine and nickel-iron alloy. All models and hypotheses for the origin of meteorites have shortcomings, but it is widely agreed that achondrites, iron meteorites and stony-iron meteorites originated with such chemically differentiated bodies of roughly chondritic composition. The density of Mason's model asteroid is about 3.66. This figure is in agreement with the measured density of Vesta, which, as we have seen, has pigeonitic basalts on its surface.

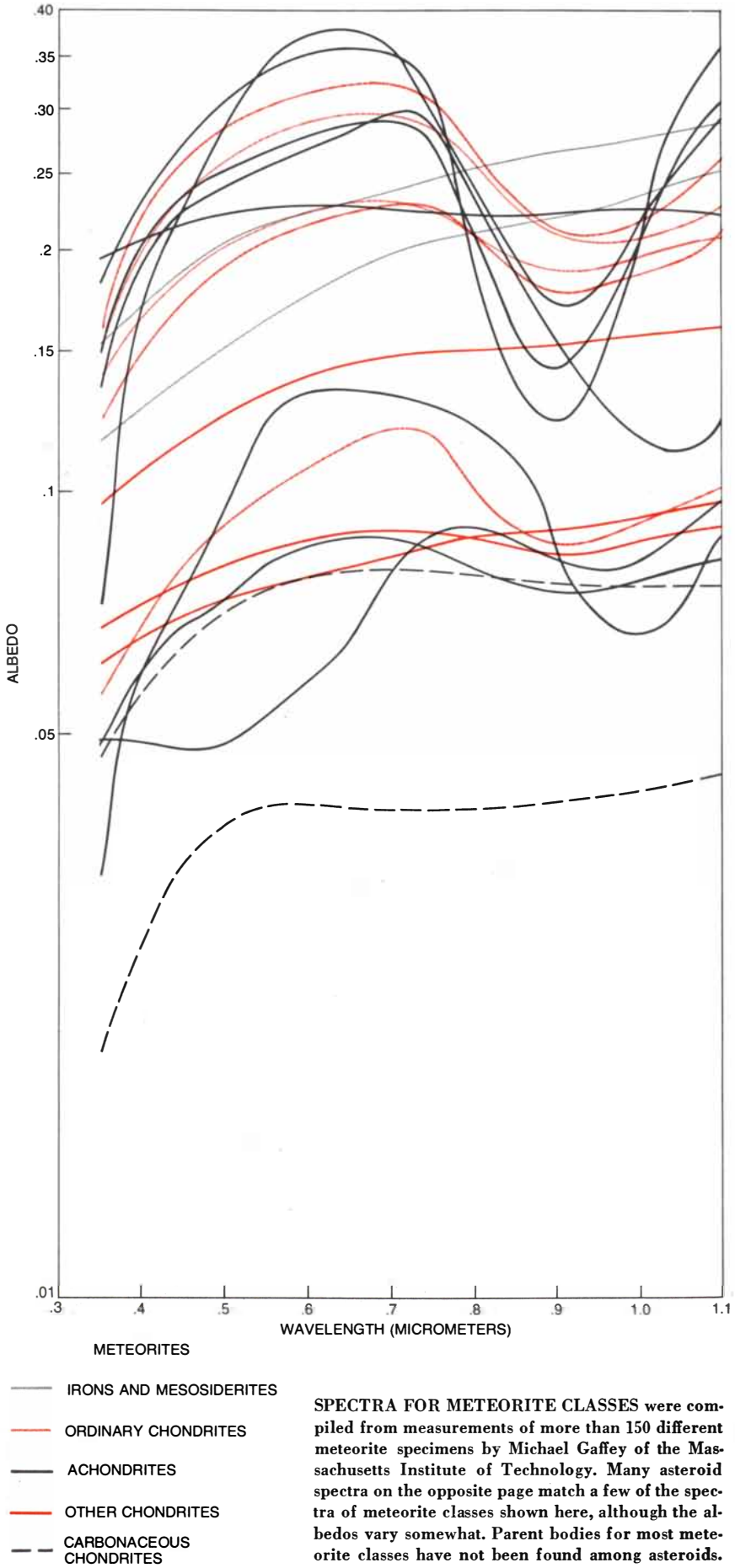
A different parent-body model is required for ordinary chondrites, which have not been melted but show different degrees of being metamorphosed by heat. Perhaps they originated within asteroids that were too small to have developed an internal temperature high enough to give rise to melting and differentiation, although McCord and I have already found one rather large asteroid, Dembowska, that has a surface composition similar to the iron-poor ordinary chondrites. Alternatively these meteorites could have been formed in the interior of a body that was heated from the outside. Or perhaps the ag-

glomerating chondritic material was heated prior to its incorporation in larger bodies.

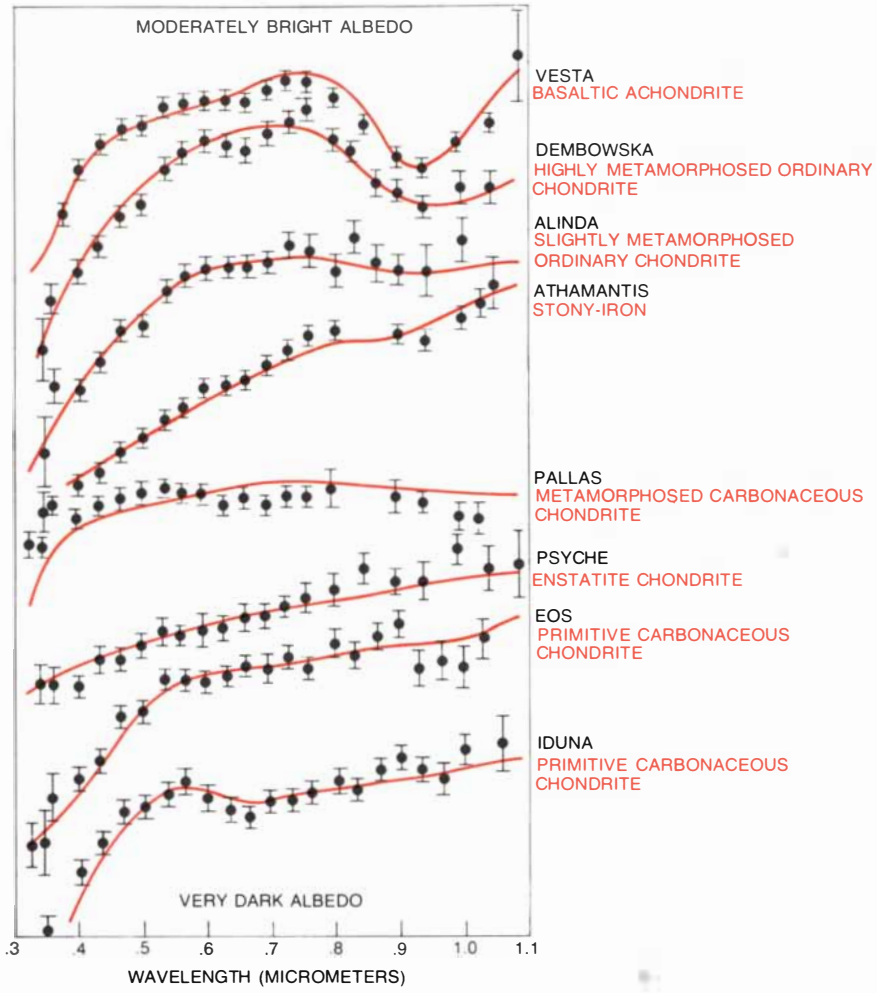
The source of the heating of the parent bodies is the critical question. Asteroids are too small to be appreciably heated by the gravitational energy of accreting matter or by the processes of radioactive decay that are responsible for the heating of the earth. The novel notion that some now extinct short-lived radioactive element caused an early episode of heating in rocky objects is no longer favored, since there is no evidence of appropriate end products of the suggested candidate elements. Radiation from the sun, even during an intensely luminous phase it went through before attaining its present-day stability, could have heated chondritic matter in small bodies but would have been entirely ineffective in warming larger objects such as Vesta to the temperatures necessary for melting.

Charles P. Sonett of the University of Arizona has proposed that the parent bodies may have been heated by electric currents induced by large electric and magnetic fields in interplanetary space that accompanied an earlier and more powerful solar wind. There is evidence that a strong wind and an accompanying fast spin may be a normal stage in the development of a star such as the sun. Although this kind of heating process could melt asteroids, specific predictions are not yet possible because its effectiveness would depend on the object's distance from the sun, its radius and its composition. For example, the process is strongly dependent on the electrical conductivity of the material, and conductivity is dependent on temperature. The electrical properties of meteoritic materials are only now being measured. It is not even certain whether objects of various sizes would be heated on the outside or on the inside.

Any model of heating in the solar system has to raise the temperature of Vesta to melting temperatures well in excess of 1,000 degrees Kelvin (degrees Celsius above absolute zero) while heating Ceres and other carbonaceous asteroids far less. We must also account for the evidence adduced by Dimitri Papanastassiou, Gerald J. Wasserburg and their colleagues at Cal Tech to the effect that at least two achondrites may have been formed from magma, or molten material, on a parent body a full billion years after the origin of the solar system. It is uncertain whether the magmatic activity continued on or within the large asteroids during the entire time the maria, or "seas," of the moon were being flooded



SPECTRA FOR METEORITE CLASSES were compiled from measurements of more than 150 different meteorite specimens by Michael Gaffey of the Massachusetts Institute of Technology. Many asteroid spectra on the opposite page match a few of the spectra of meteorite classes shown here, although the albedos vary somewhat. Parent bodies for most meteorite classes have not been found among asteroids.



SPECTRA OF METEORITES AND ASTEROIDS are superposed to show some of the relatively good matches between the two. The vertical error bars indicate the uncertainties in the astronomical data obtained by Thomas B. McCord of M.I.T. and the author. Although the albedos are not well known for some of the asteroids, the spectra have been arranged in the approximate order of their brightness. The spectral similarities between the meteorites and the asteroids suggest that their mineralogical compositions may also be similar. Metamorphosed chondrites have had their structure changed by heat; the enstatite chondrite is a meteorite in which the principal mineral is a magnesium-rich pyroxene lacking iron.

with magma or whether melting from some kind of impact formed these meteorites.

Impact processes have certainly played a major role in shaping many meteorites. Among the brecciated meteorites are the mesosiderite type of stony-iron meteorites: a physical mixture of roughly equal parts of nickel-iron alloy and achondrite-like silicates, perhaps produced by the collision of an iron body and an achondritic one. Were these brecciated meteorites formed on the surface of asteroids? Perhaps they were in the distant past, but in my opinion very few of them could have been formed recently.

As I have mentioned, asteroids today pass one another with a mean relative speed of about five kilometers per second. If two asteroids collided at that speed, the ejecta from the impact would almost entirely escape into space, although a small residue might remain on the asteroid's surface; the weak gravitational field of the body could not hold most of the ejected material. There are many more particles of interplanetary debris in the range of sizes from a millimeter to a meter than there are larger ones. They continually sandblast not only the exposed rock of asteroids but also whatever residue has been left on the surface from earlier impacts. Therefore on all the asteroids except the largest the regolith soil on the surface is thin and poorly developed. Today there is not much of an environment left for the creation of brecciated meteorites rich in gas atoms deposited by the solar wind.

Measurements of radioactive isotopes in meteorites show that these bodies have typically been exposed to cosmic rays for about 10 million years. Hence they were evidently ejected from their parent bodies about 10 million years ago. We can calculate from the distribution of the sizes among the interplanetary debris and the asteroids that the largest fraction of the meteorites were manufactured by the very few large impacts on asteroids during this period. These impacts excavated material to a depth of hundreds of meters and possibly even to a kilometer or more. Material in the thin surface regolith would constitute only a negligible fraction of the mass ejected from such a deep excavation, so that most brecciated meteorites could not have come from present-day regoliths on asteroids. The solar-wind gases could only have been incorporated in these meteorites very early, when the rocks were on the surface of accreting bodies. The upper layers of the asteroids were brecciated either during the later stages of accretion or during a subsequent cataclysmic period characterized by a high rate of bombardment (when the gases in some meteorites seem to have been released by the shock of impacts).

This period of cataclysmic bombardment seems to have been widespread throughout the solar system. The astronauts who journeyed to the moon brought back very few genesis rocks. The moon was heavily cratered during the first half-billion years of its existence; most lunar rocks date from the end of that period. Pictures of Mars and Mercury from the Mariner spacecraft show that those planets also suffered from heavy early cratering, although we have no rocks from them for dating purposes. Perhaps many of the original asteroids beyond the 2:1 resonance that may have been ejected by Jupiter into short-lived orbits encountered the planets and are responsible for the regions of craters superposed on craters that we see on the moon, Mars and Mercury. These short-lived asteroids in highly elliptical orbits passed repeatedly through the main belt of asteroids in circular orbits on their way to the inner solar system. Collisions between bodies in the two groups may have been responsible for the highly fragmented condition of the asteroids we observe today. Apparently the colli-

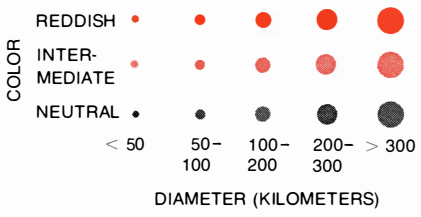
sions were numerous enough to shatter and fragment the crustal and mantle rocks of the differentiated asteroids, but many of the stronger stony-iron cores survived largely intact. Undifferentiated carbonaceous asteroids were easily fragmented, but evidently they were so numerous in the beginning that quite a few survived the probabilities of catastrophic collision.

The impact rate declined some four billion years ago. Since that time the larger asteroids have been fragmented only occasionally. Of course, all asteroids are slowly losing mass as a result of being cratered by smaller bodies. Some meteorites come from parts of the asteroids that were originally brecciated. Others come from the interiors of asteroids that were exposed to space late in the bombardment period. Brecciated layers are continually being sandblasted away by small-scale impacts; particularly thin layers may be entirely removed, revealing reasonably pure unbrecciated material. In regions such as these we may expect to find genesis rocks in their least altered form.

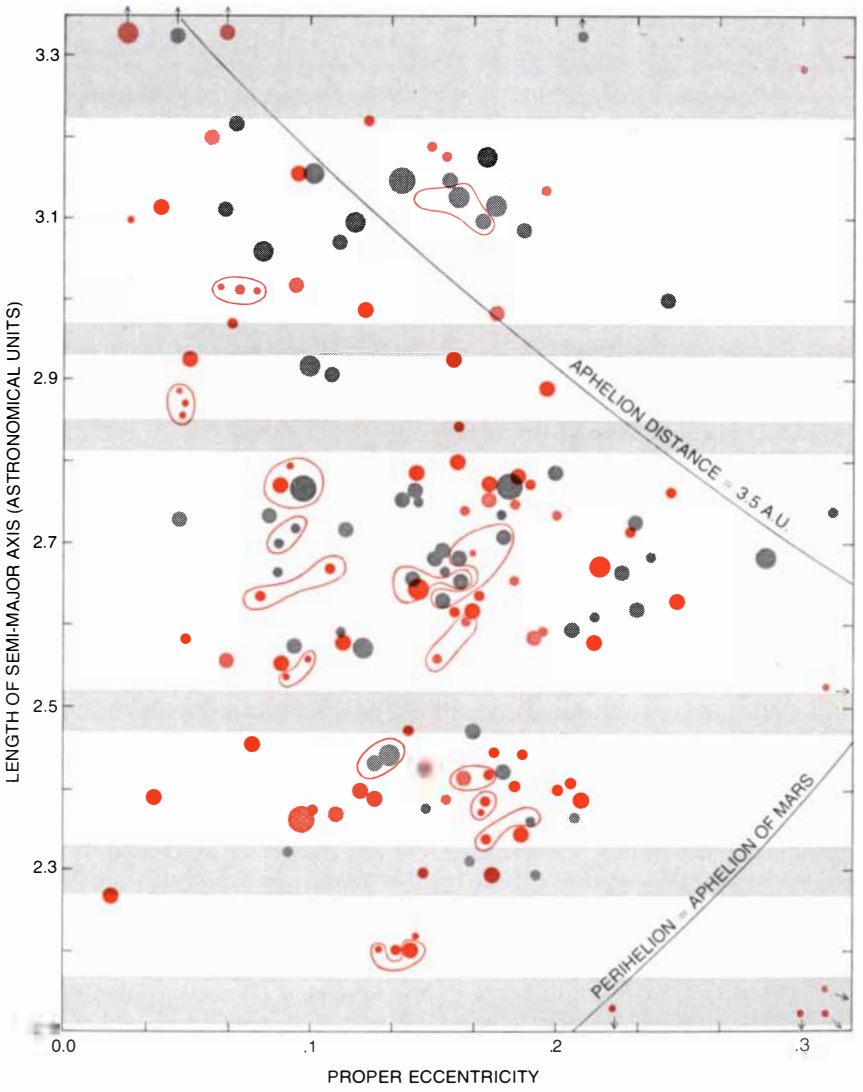
Thus for two main reasons asteroids are prime sites for finding early solar-system rocks. First, most asteroids have probably escaped the periods of differentiation, vulcanism and (in some cases) weathering and plate tectonics that in different degrees have altered the rocks on all the smaller planets and on the moon. Second, since asteroids are small and have such a weak gravitation, the unaltered genesis rocks would not be buried under the large regoliths that accumulate on the surface of larger bodies.

This, then, is the tentative picture of asteroids emerging from the synthesis of astronomical data and studies of meteorites. Chondritic matter accreted in the asteroid belt; carbonaceous material predominated beyond 2.3 astronomical units, at least during the later periods of accretion. Some of the larger objects, of which Vesta is the prime remaining example, were melted or metamorphosed by heat. They were fragmented or were stripped of their exterior, revealing an interior core composed of metals and silicates; they account for most of the reddish asteroids with absorption bands in their spectra. A disproportionate number of these asteroids have a diameter of between 100 and 200 kilometers—just the right size to be iron cores of differentiated parent bodies the size of Vesta. Undifferentiated asteroids were even more readily fragmented by collisions forming a distribution of carbonaceous fragments of all sizes. All these fragments from collisions constitute the Hirayama families of asteroids: groups of minor planets having the same distance from the sun, the same shape of orbit and a similar inclination to the plane of the ecliptic. In agreement with the picture I have given here, the members of some families show disparate spectral types and other families display a homogeneous composition.

Few individual asteroids have been found, however, that show a plausible cross section of layers from one side to the other, ranging from primitive unaltered carbonaceous chondritic matter to iron core material. The search is under way for such asteroids because they would be the ones that would exhibit the genesis rocks and all their modifications *in situ* for geological study by some future space mission to an asteroid.



COLOR AND SIZE of 147 asteroids are plotted here with respect to their distance from the sun and the shape of their orbit. Semimajor axis is half the length of the long axis of an elliptical orbit; proper eccentricity is a measure of the degree of ellipticity. Diameter of each asteroid is given by five sizes of symbol; approximate colors are indicated by the color of the symbol. Symbols circled in groups are believed to be members of the same family and may be the fragments of one parent body. Few objects with an aphelion (greatest distance from the sun) greater than 3.45 astronomical units are red. Asteroids bordering on the Kirkwood gaps (*horizontal bands in gray*) and those with a perihelion (closest distance to the sun) near the orbit of Mars seem to be predominantly reddish. The nine asteroids with arrows fall off the scale of the illustration.



The Fuel Consumption of Automobiles

The biggest target for energy conservation is the poor fuel economy of American cars. Here is how their efficiency can be increased at least 40 percent by 1980

by John R. Pierce

A fourth of all the energy used in the U.S. is devoted to transportation, and of that fraction close to 60 percent is supplied in the form of gasoline to roughly 100 million automobiles and small personal trucks. Americans use more energy to fuel their cars than they do for any other single purpose. At the current price of some 55 cents per gallon, the average family is obliged to spend more than $600 a year just on gasoline. The fuel used by American cars and personal trucks would approximately fill all the energy needs of Japan, a nation of 108 million and the world's largest consumer of energy after the U.S. and the U.S.S.R. In the urgent effort to reduce U.S. consumption of an increasingly costly fuel whose chief reserves lie overseas, the American automobile and current habits of its utilization are a prime target.

One does not have to be a partisan of the automobile to recognize that virtually every aspect of American life—industrial, commercial, cultural and recreational—is now organized around the existence of motor vehicles. Whether or not they provide the most rational means of transportation in an advanced technological society is, of course, a matter of debate. In order to illuminate that debate a colleague and I organized a series of six two-day seminars on the subject "Energy Consumption in Private Transportation." The series, supported by the U.S. Department of Transportation, was held at the California Institute of Technology between December, 1973, and April, 1974, a period that coincided with the Arab oil embargo, with President Nixon's call for "Project Independence 1980" ("To ensure that by the end of this decade Americans will not have to rely on any source of energy beyond our own") and with the quadrupling of oil prices after the embargo was lifted.

The seminar participants addressed themselves to the following questions (among others): In any rational energy program what role will the private automobile play? Can it be replaced by more economical forms of transportation? To what extent can communication replace transportation? Will our pattern of life change in such a manner that we simply do not travel as much?

Although many fascinating and even plausible alternatives to the gasoline-powered automobile were discussed, it became evident to the participants that no dramatic change in transportation methods or habits can be expected or effectuated in the short run, say before 1990. In this article, therefore, I shall deal only with existing or readily foreseeable technologies for improving the fuel economy of automobiles as we know them.

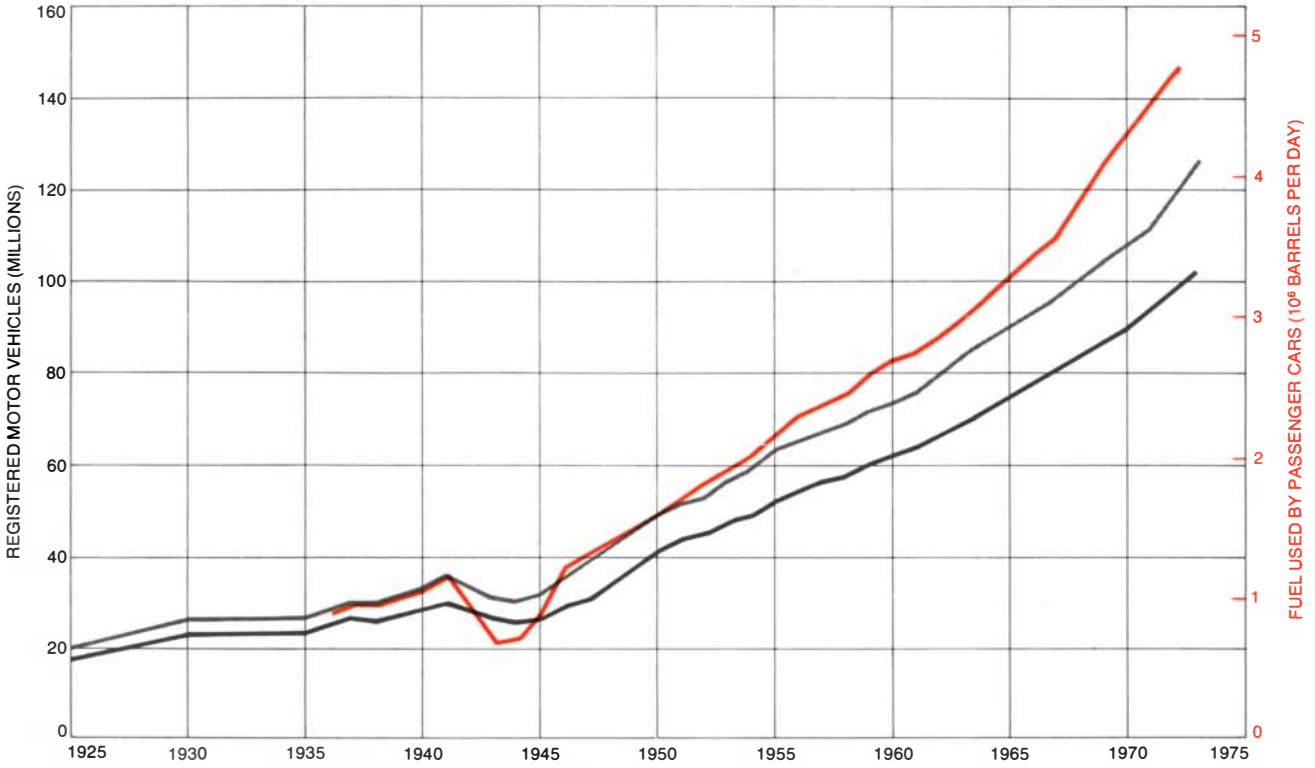
In President Ford's address before a joint session of Congress last fall he announced his determination to obtain "either by agreement or by law a firm program aimed at achieving a 40 percent increase in [automobile] gasoline mileage within a four-year development deadline." Subsequently, in late October, the Department of Transportation (DOT) and the Environmental Protection Agency (EPA) submitted a report to Congress ("Potential for Motor Vehicle Fuel Economy Improvement") that provided a careful review of feasible engineering changes that should make it possible for 1980-model cars to go 40 percent farther on a gallon of gasoline than the average 1974 model did.

According to the DOT-EPA report, the average 1974 model, adjusted for the sales of different brands and models, achieved 14 miles per gallon on a "composite" fuel-economy cycle based on EPA dynamometer tests that simulate city driving conditions and highway driving conditions in a 55 : 45 ratio (a ratio chosen as being typical of American car use). The new 1975 models, on a projected sales-weighted basis, achieve 15.9 m.p.g., an improvement of 13.5 percent [*see top illustration on page 36*].

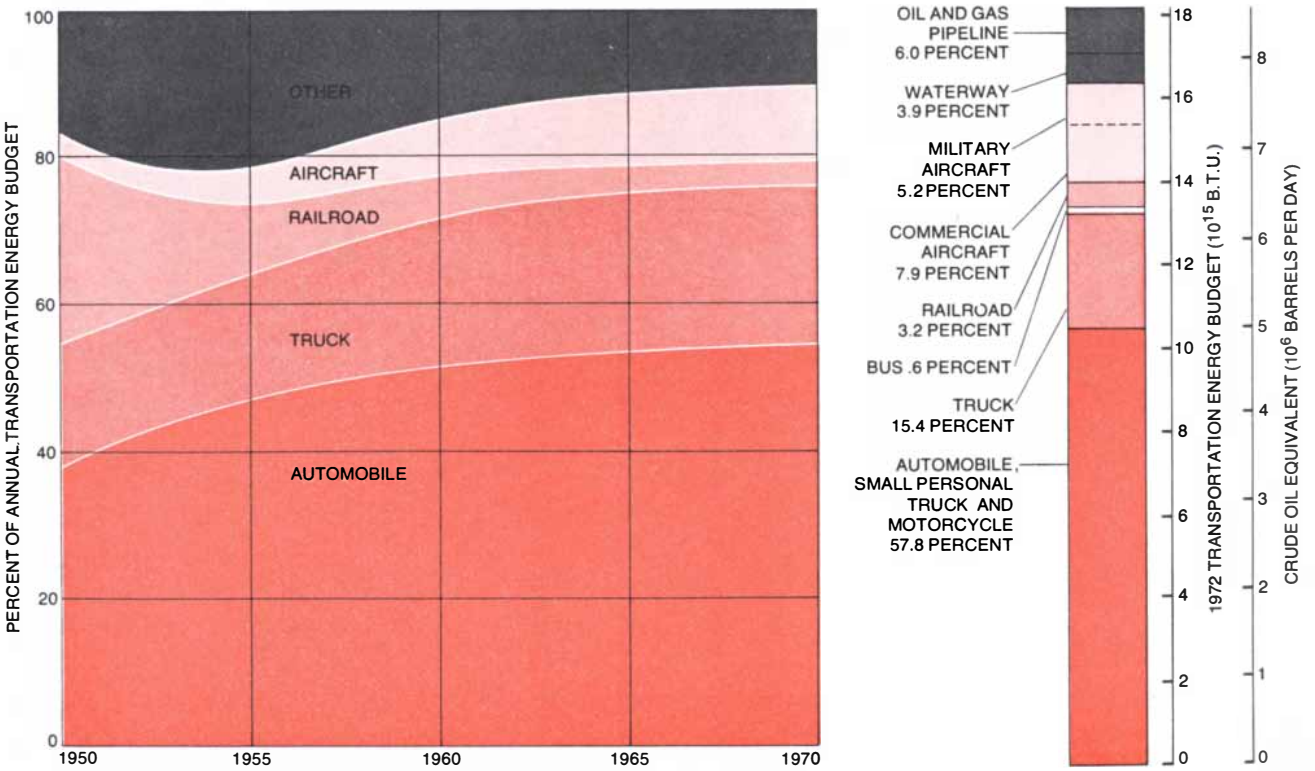
The improvement is chiefly attributable to engineering changes that regained much of the efficiency previously lost in adjusting engines to meet Federal exhaust-emission standards. Many of the 1975 models have catalytic converters to clean up exhaust emissions, making it possible for the engine to be retuned for higher efficiency. Partly because of emission controls and partly because of vehicle weight and other factors, the fuel economy of American cars dropped about 12 percent between 1967 and 1974, climaxing a long, steady decline that began as early as 1951 [*see top illustration on page 37*].

If the performance of 1974 models is taken as the base line, as the DOT-EPA report recommends, the industry has already moved a third of the way to the 40 percent improvement asked by President Ford. A 40 percent improvement would mean that the average car built in the 1980-model year would have to achieve a minimum fuel economy of 19.6 m.p.g. (Bills that are now being drafted for presentation to Congress will undoubtedly pick a round number for minimum 1980 performance, probably 20 or 21 m.p.g.)

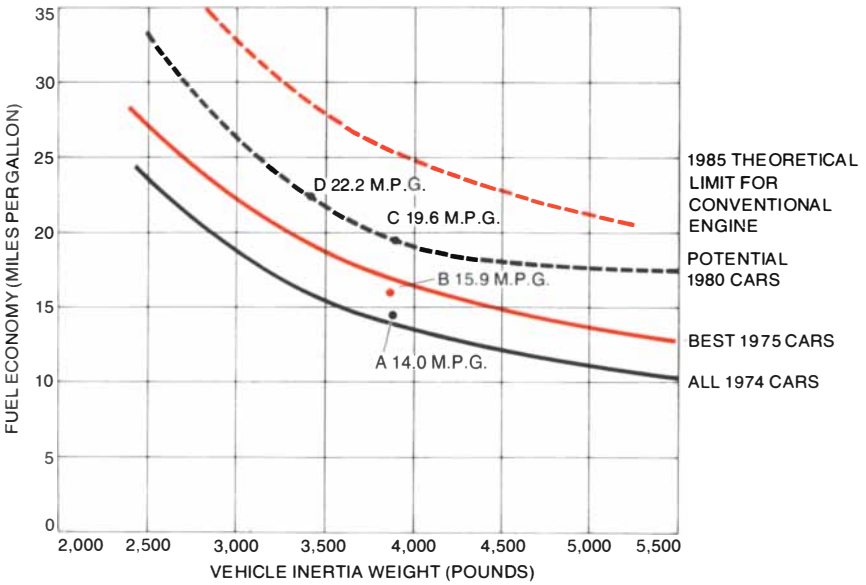
According to the DOT-EPA report, the 40 percent improvement by 1980 should be attainable with the present Otto-cycle (four-stroke) gasoline engine, in combination with improved transmissions, reduced weight and aerodynamic drag and improved accessories. If the composition of sales can also be altered to include a much higher proportion of compact and subcompact models than



NUMBER OF MOTOR VEHICLES IN THE U.S. (*gray curve*) has been doubling approximately every 20 years, corresponding to an increase of 3.5 percent per year. Private cars (*black curve*) make up about 82 percent of the total motor-vehicle population; the balance consists chiefly of trucks. Gasoline consumption by private cars (*curve in color*) has been increasing more rapidly than the car population, owing primarily to a steady downward drift in average fuel economy (*see top illustration on page 37*). Because of duplicate registrations when cars change hands or owners move the registration figures may overstate the car population by about 10 percent.



TRANSPORTATION ENERGY BUDGET depicts the decline of railroads and the ascendancy of trucks, automobiles and airplanes over the 20-year period 1950–1970 (*left*). "Other" includes mass-transit systems, buses, waterways and oil pipelines. The detailed breakdown for 1972 (*right*) is based chiefly on a study by the Rand Corporation. In 1972 the nation's total energy consumption was 72.1×10^{15} British thermal units, of which transportation took 25.2 percent. Oil supplied 45.5 percent of all energy used in 1972.



FUEL-ECONOMY RESULTS, computed by the Environmental Protection Agency (EPA) from dynamometer tests, show a substantial increase in the performance of 1975-model cars over 1974 models. The sales-weighted average for the 1974 "fleet" was 14 miles per gallon (*A*); for the 1975 fleet, assuming the same model mix, it is 15.9 m.p.g. (*B*), or an average improvement of 13.5 percent. The change in performance between the two model years, however, varied considerably among different car lines (*see illustration below*). The curves shown here are from a report recently presented to Congress by the EPA and the U.S. Department of Transportation (DOT). The fuel-economy figures represent a new "composite" cycle, consisting of a 55 : 45 combination of two test cycles conducted by the EPA: a suburban-urban cycle with several stops and starts at an average speed of 20 miles per hour and an uninterrupted highway cycle at an average speed of 49 m.p.h. (The EPA publishes the two figures separately for 1975 cars; these are the figures often seen in car advertisements.) The DOT-EPA report to Congress suggests that it should be possible for 1980 cars to achieve an average of 19.6 m.p.g. (*C*), an improvement of 40 percent over 1974 models. With a shift to smaller, lighter cars, average of 1980 automobile fleet might even reach 22.2 m.p.g. (*D*).

MANUFACTURER	FUEL ECONOMY (MILES PER GALLON)		CHANGE (PERCENT)
	1974	1975	
GENERAL MOTORS	10.60	13.30	+25.5
FORD	12.16	11.92	−2.0
CHRYSLER	11.56	12.45	+7.7
AMERICAN MOTORS	14.64	17.05	+16.5
VOLKSWAGEN	22.11	21.95	−.7
TOYOTA	16.89	16.37	−3.1
NISSAN	20.63	22.04	+6.8
VOLVO	16.55	15.61	−5.7
AUDI	19.14	20.17	+5.3
PEUGEOT	17.33	19.09	+10.2
SAAB	17.28	21.41	+23.9
DAIMLER-BENZ	10.93	11.80	+8.0
BMW	17.44	15.47	−11.3
FLEET	11.95	13.33	+11.5

FUEL-ECONOMY RESULTS BY MANUFACTURER for 1974 and 1975 automobiles, assuming the 1974 sales-weighting for various models for both years, appear in a paper by Thomas C. Austin and Karl H. Hellman of the EPA. The m.p.g. values are for the suburban-urban cycle only and reflect the changes in the two model years that can be attributed solely to engineering "system" changes (for example changes due to engine emission-control-system calibrations and changes in transmission and axle ratios). The table thus omits the effect of new engine sizes and new engine-vehicle combinations that contributed to a total improvement of 13.8 percent in the performance of the 1975 fleet over the 1974 fleet in the suburban-urban test cycle. (The gain is 13.5 percent when the highway cycle is included.)

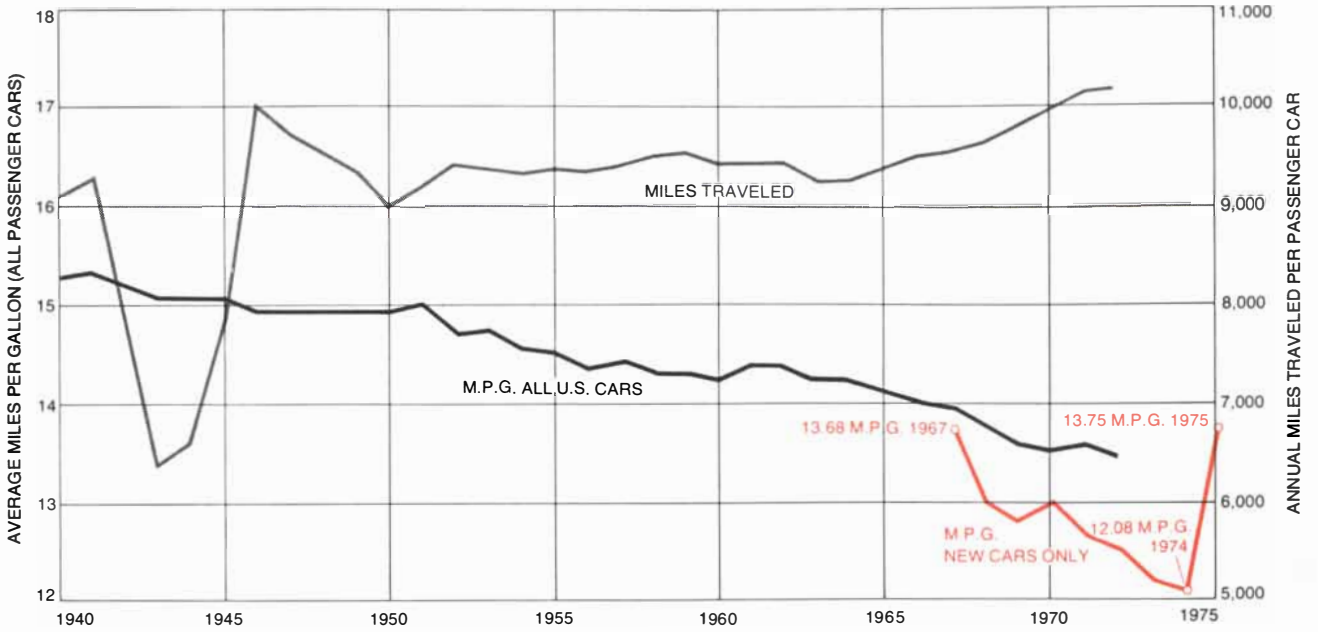
it does at present, it may even be possible for the 1980 "fleet" of new cars to exceed 22 m.p.g., an improvement of nearly 60 percent over 1974.

To achieve still greater advances in fuel economy for 1985 and beyond, it will probably be necessary to introduce new types of engines. The DOT-EPA report suggests the use of diesel engines in medium-size and large cars and, for smaller cars, gasoline engines designed to operate on a "stratified charge," engines in which the air-fuel mixture is made intentionally nonhomogeneous to provide an average lean mixture, with a consequent improvement in efficiency.

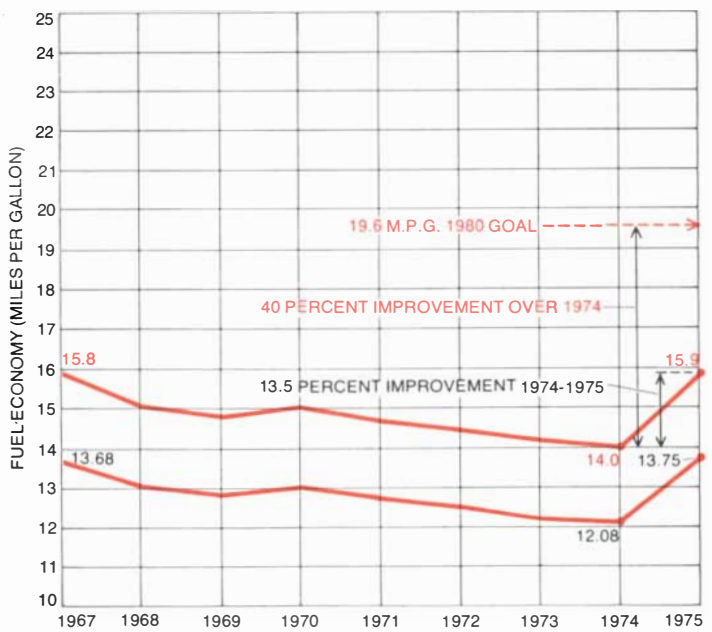
The present Otto-cycle automobile engine typically achieves a thermal efficiency of between 22 and 27 percent. Under the normal range of driving conditions, however, the net efficiency of power delivered to the wheels is only about 10 percent. Gasoline-fueled aircraft engines attain efficiencies of about 30 percent. The efficiencies of diesel engines range from 35 percent to as high as 38 percent. (In EPA tests the 1975 Mercedes-Benz 300D, which has a five-cylinder, 77-horsepower diesel engine, gets 24 m.p.g. in the simulated city-driving cycle and 31 m.p.g. in the highway-driving cycle, yielding a composite fuel economy of 27.2 m.p.g. These values are 50 percent higher than those of the comparable gasoline-engine model of the Mercedes: the four-cylinder, 93-horsepower Model 230. It should be noted, however, that diesel fuel contains about 10 percent more energy than ordinary gasoline.)

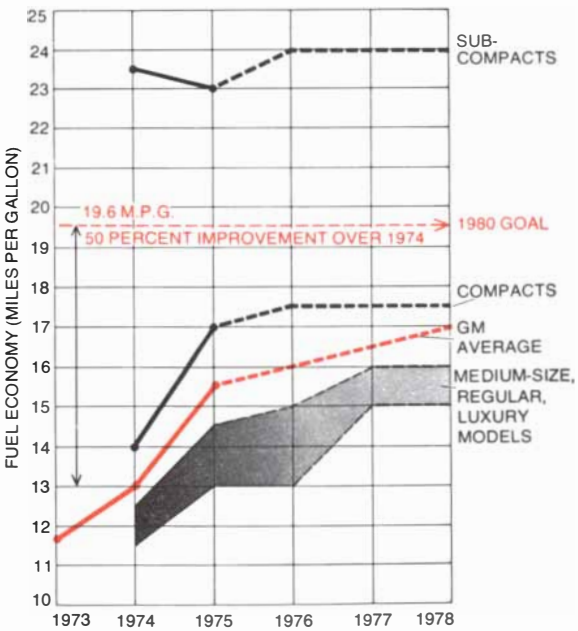
Those who are as old as I am can remember a time when mass transit dominated urban life in the U.S. In St. Paul toward the end of World War I my parents did not own an automobile. The roads between towns were unmarked and often badly rutted, making travel unattractive for those who did drive. Everything was within easy walking distance of the streetcar or interurban line, even the cottage at White Bear Lake where we stayed during the summer. Small stores and shops were within easy walking distance of our home, and in St. Paul itself the stores and offices in the central business district were accessible by streetcar.

Between 1920 and 1930 the number of passenger cars registered in the U.S. nearly tripled, from eight million to 23 million. In spite of the Great Depression the public desire for private transportation continued to grow (even though most streetcar lines were still running), until by 1940 there were more than 27



DETERIORATION IN FUEL ECONOMY of American automobiles has been virtually uninterrupted since 1940 (*black curve*). The figures are compiled by the Federal Highway Administration on the basis of gasoline sales and state-by-state surveys of annual miles traveled per vehicle (*gray curve; scale at right*). The sharp drop in miles traveled between 1941 and 1946 represents the effects of strict World War II gasoline rationing. If the average car on the road still obtained 15 m.p.g., as it did in 1951, the U.S. consumption of gasoline would be 450,000 barrels per day (or nearly 10 percent) less than it actually is. Between 1967 and 1974 the fuel economy of new cars fell sharply owing to a number of factors: increased body weight, the growing popularity of air conditioning and particularly engine resettings to meet new Federal standards on exhaust emissions. The curve in color, based on the paper by Austin and Hellman, shows that for the suburban-urban test cycle a 13.8 percent improvement between 1974 and 1975 models has returned the fuel economy of new cars to approximately the level that prevailed in 1967. Austin and Hellman point out that the suburban-urban test cycle yields fuel-economy figures that agree closely with the national figures based on gasoline sales and total miles traveled.





1980 FUEL-ECONOMY GOAL may be embodied in a law requiring a 40 percent improvement over the performance of 1974 models, which averaged 12.08 m.p.g. as measured by the EPA suburban-urban test cycle (*lower curve at left*) or 14 m.p.g. as measured by the composite cycle of city and highway driving (*upper curve*). By the second measurement the 1980 goal would be 19.6 m.p.g., which will probably be rounded upward to 20 or even 21 m.p.g. It will obviously be easier for makers of light, small cars to meet that goal than for a manufacturer such as General Motors. The solid curve in color at right shows the fuel economy for the GM fleet in 1973, 1974 and 1975 as measured by GM's own "city-urban" cycle conducted on the road. The GM method gives results that compare fairly well with the EPA composite cycle. The 1974 GM fleet averaged about 12.2 m.p.g. by the EPA method and 13 m.p.g. by the GM method. (For the 1975 fleet the two methods yielded 15.7 and 15.5 m.p.g. respectively.) Thus by 1980 GM must improve the performance of its new car fleet by 6.6 m.p.g. (50 percent) or 7.4 m.p.g. (60 percent), depending on the test method selected. GM has already announced that its 1978 fleet will achieve 17 m.p.g. (*broken curve*) if no more changes are made in safety or emission standards.

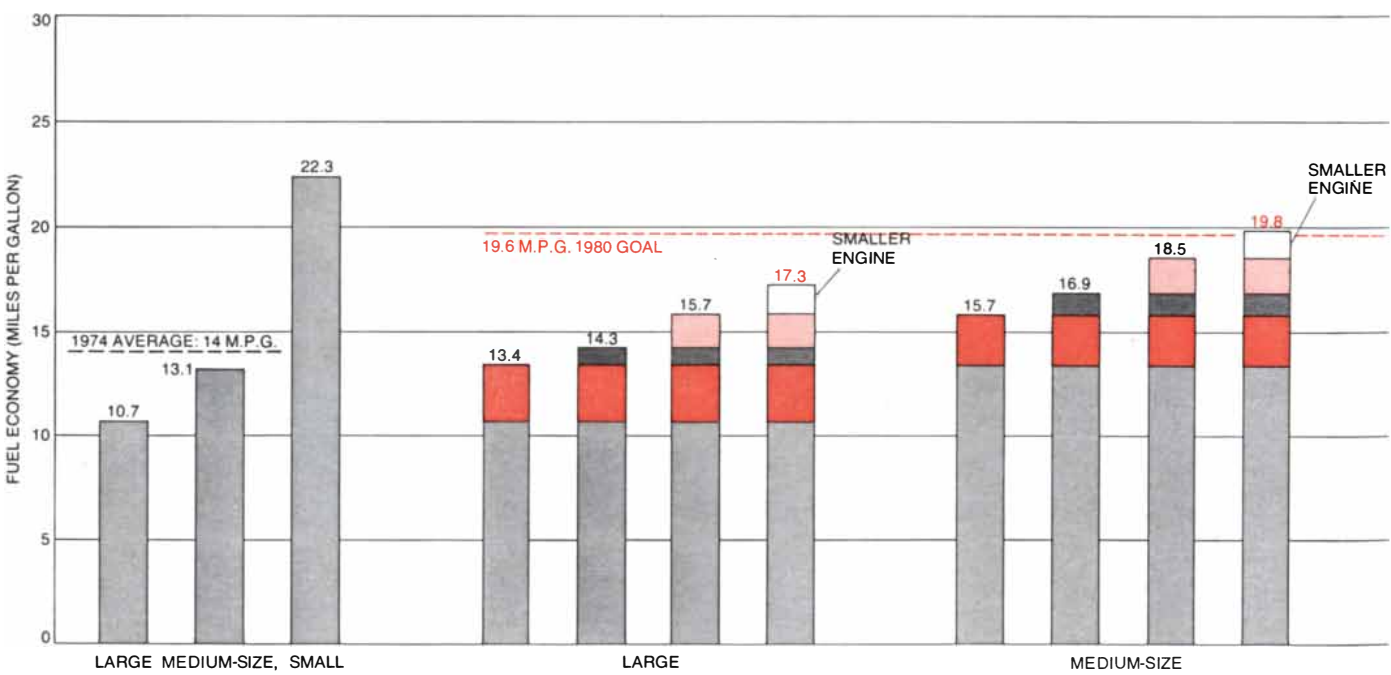
million automobiles registered in the U.S., or one car for every 1.3 families. When the production of automobiles resumed after World War II, automobile registrations climbed swiftly to 40 million in 1950, to 61.7 million in 1960 (approaching 1.2 per family), to 89 million in 1970 (1.4 per family) and to an estimated 105 million in 1974 (1.5 per family). Today more than eight families in 10 own automobiles, and one family in three has two or more vehicles, if small personal trucks are included.

Nationwide studies show that automobiles are used primarily for short trips: about half of all trips are five miles or less and three-fourths are less than 10 miles. These short trips account for nearly a third of all vehicle miles traveled and for a substantially larger fraction of the total gasoline consumption. Moreover, about 40 percent of all automobile travel is work-related, chiefly commuting trips (with an average occupancy of 1.2 per car) at hours of high traffic density and resulting low efficiency of operation. Except for the special case of Manhattan Island, where 79 percent of all workers reach their jobs by public transit, the automobile provides the principal means for getting to work. According to the 1970 census, 60 million Americans commute by private automobile (51 million travel alone and nine million in car pools); 4.2 million use a bus or streetcar; 1.8 million use a subway or an elevated-railway line; 500,000 use railroads; 300,000 use taxis and 5.7 million live close enough to their jobs to walk to them. Clearly an enormous national effort, extending over several decades and costing many billions of dollars, would be required to provide public-transit facilities attractive, convenient and extensive enough to persuade a large number of Americans to leave their cars at home. In the absence of such a commitment any substantial reduction of gasoline in automobile usage can come only through changing the efficiency of the use of private automobiles or changing the efficiency of the automobiles themselves. National statistics show that if automobiles could achieve 25 to 30 miles per gallon, they would be about as efficient in moving people, at least thermodynamically, as present-day bus transit systems are.

The efficiency of the use of automobiles of a given construction and state of repair is chiefly affected by freeways and traffic-control systems. Our suburban pattern of living preceded the construction of freeways and it exists where freeways are few or absent. Once freeways have been built, however, they frequently lead to the creation of new locations of work and residence. Thus it is not clear whether in the long run freeways increase distances to and from work or decrease them.

Apart from (usually) reducing the travel time between two points, freeways have other important consequences. They have lower accident rates than country roads or city streets. The number of fatal accidents per million vehicle miles are: city streets, 2.47; country roads, 1.64; urban streets, 1.63, and urban freeways, .44. In addition the stop-and-go character of city-street traffic causes high gasoline consumption. For an equivalent trip it is usually more economical of gasoline to travel by freeway. It is doubtful, however, that construction of freeways can be justified as a way of reducing the energy demand. Such construction should be decided on other grounds.

Like freeways, traffic control can affect energy consumption as well as safety and convenience. Repeated starting and stopping wastes fuel. Although traffic lights are old, computer-controlled signal systems designed to facilitate the flow of traffic are fairly new. Computerized traffic control can reduce the number of starts and stops. Clogged free-



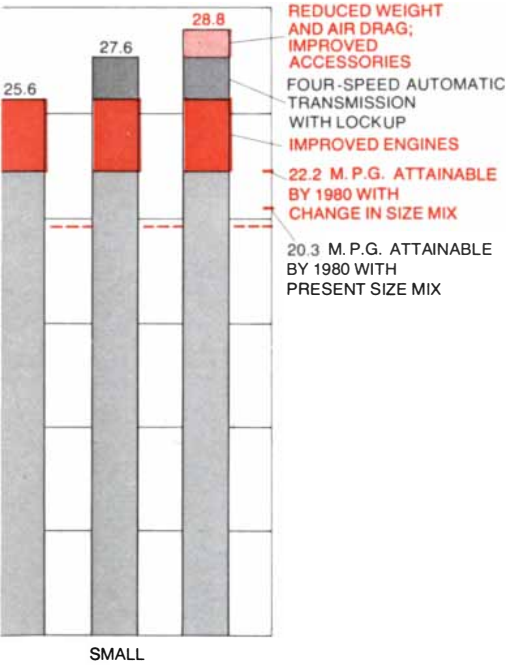
REASONABLE TECHNICAL IMPROVEMENTS that should enable car makers to reach the fuel-economy goal of 19.6 m.p.g. by the 1980-model year are described in the DOT-EPA report to Congress. The first set of three bars shows the average fuel economy of 1974 models (city-highway cycle) in three size categories. The large size is represented by present standard-size and luxury cars, which carry six people in comfort. The medium size corresponds to present compact and intermediate size, which carry four or five people. The small size corresponds to subcompacts and small imported cars designed for four passengers. The market share of each size category in 1974 was respectively 27, 45 and 28 percent. The largest single increase in fuel economy (from 15 to 25 percent) will come from engine modifications, some of which have already been incorporated in the 1975 models of some manufacturers. Further gains, amounting to about 9 percent in each size class, can be expected from more efficient four-speed automatic transmissions with

ways are wasteful of energy. Ramp control can reduce the congestion and increase the traffic flow on freeways. Indeed, it is estimated that fuel consumption can be reduced by about 10 percent in the controlled area.

The cost of computerized traffic control is considerable. Its principal benefits are reductions in travel time, increased traffic flow without the construction of additional roads and reduction in accidents. Fuel savings are an attractive added benefit. The fact remains that computer control of traffic must be justified by its overall benefits and not solely as a means of saving fuel.

Apart from a reduction in automobile usage (and a strict enforcement of the 55-mile-per-hour speed limit), more efficient automobiles seem the only sure way to achieve substantial savings in petroleum consumption in any future we can now foresee and make plans for. Fortunately there are many opportunities for making the private car more efficient.

As the Federal figures show, there are already large differences in gas mileage among current automobiles, ranging in economy tests of 1975 models from 27 m.p.g. in simulated city driving for the subcompact Datsun B-210 in the 2,250-pound inertia-weight class to 12 m.p.g. for typical American cars in the 4,500-pound inertia-weight class down to 10 m.p.g. or less for the largest models in the 5,500-pound inertia-weight class. ("Inertia weight" is curb weight plus an allowance of 300 pounds for occupants.) In simulated highway driving the performance in the three weight categories rises to between 33 and 39 m.p.g., 15 and 18 m.p.g. and 14 and 16 m.p.g.



a lockup in high to prevent slippage. The third category of improvements (of 5 to 12 percent) will result from reductions in curb weight, aerodynamic drag, rolling resistance and power required by accessories. For large and medium-size cars a still further gain of 10 to 15 percent in fuel economy can be achieved by reducing the sizes of engines.

If one compares the average fuel economy of the lightest cars with that of the heaviest, one finds that each additional 100 pounds of car weight requires an extra 15 to 17 gallons of gasoline per year of average driving (10,000 miles). This does not mean, however, that simply by removing 100 pounds of weight from a heavy car one can achieve a comparable fuel saving. What it does mean is that the owner of one of the smaller, more economical cars will need to buy 500 to 550 fewer gallons of gasoline in the course of a year than the driver of a big car. Looked at another way, if all the automobiles now on the road averaged 23.5 m.p.g. instead of the estimated 13.5, U.S. gasoline consumption would drop more than 40 percent, or some two million barrels of gasoline per day below the current demand of about five million barrels. With crude oil at $11 per barrel, this would translate into an annual saving of more than $8 billion.

The most obvious way, therefore, to save energy is to cut the weight of the average car sold. At low speeds, where aerodynamic drag is not a major factor, rolling resistance and the energy needed to overcome it are proportional to weight. On the EPA composite cycle of city and highway driving, rolling resistance and aerodynamic drag each absorb 24.7 percent of the useful power delivered by the engine of the typical American car [*see top illustration on page 42*]. Existing cars, American as well as foreign, show that lighter cars can be as quiet, easy-riding, roomy and comfortable as heavier cars, but to attain these qualities in a lighter car requires good engineering.

Although lighter cars tend to have less rolling resistance per unit of weight than heavier cars, the rolling resistance depends on the nature of the tire and its pressure. The energy loss in rubber tires is caused by the flexing of rubber; because of hysteresis the tire does not give back all the energy that went into deforming it. At the same pressure radial tires offer significantly less rolling resistance than conventional bias-ply tires. In mixed city and highway driving existing cars equipped with steel-belted radials will go about 2.5 percent farther on a gallon of gasoline than a car with bias-ply tires. In a car with less air resistance than current cars, the percentage gain in going to radial tires would be even larger. With either kind of tire the rolling resistance can be cut about a fourth by raising the tire pressure from 20 pounds per square inch to 40 pounds. Beyond that a worn tire toward the end of its life has only a little more than half the rolling resistance of the same tire when it was new. Perhaps we have incorporated too much rubber in tires in seeking long tire life rather than good gasoline mileage.

Shock absorbers absorb energy only in going over bumps. Tires absorb energy in rolling on a smooth surface. Lighter wheels combined with suspension systems carrying less unsprung weight would make it possible to mount harder, lower-loss tires. Thus it appears that substantial energy savings could be attained through better suspensions and smaller, harder tires, particularly if a rubber could be developed with lower hysteresis at ambient temperatures than present rubbers have.

Next to building (and persuading Americans to buy) smaller and lighter cars, important gains in fuel economy can be made in cars of every size category by improving the performance of present engines, by reducing transmission losses, by reducing weight (without sacrificing safety or passenger comfort) and, not least important, by reducing aerodynamic drag. With 1974 car performance as a base line, the DOT-EPA report to Congress estimates that engine improvements should yield economy gains of between 15 and 25 percent, depending on car size. The adoption of four-speed transmissions that would eliminate slippage losses at cruising speed by "locking up" at high gear ratios should yield gains of about 9 percent in each size class. Reductions in curb weight, air resistance, rolling resistance and the power required by accessories would provide another fuel-economy gain of at least 12 percent for large and medium-size cars and 5 percent for small vehicles. In addition the fuel economy of medium-size and large cars could be raised another 10 to 15 percent by reducing engine size so that their power-to-weight ratio is brought into line with the ratio of current small cars [*see illustration on these two pages*].

It is somewhat surprising that the single factor of aerodynamic drag has received so little attention from American automobile makers. As we have seen,

overcoming air resistance absorbs about 25 percent of the engine's output in present-day cars in city-highway driving. Between the late 1920's, when most cars were still shaped like boxes, and the late 1940's the drag coefficient of American cars was reduced about 25 percent, from .70 to .52. (A drag coefficient of 1 corresponds roughly to the air resistance of a rectangular block.) Twenty-five years later the drag coefficient of the typical American car has declined only another 10 percent, to .47. The Citroën, perhaps the most highly streamlined car in large-scale production, has a drag coefficient of about .33.

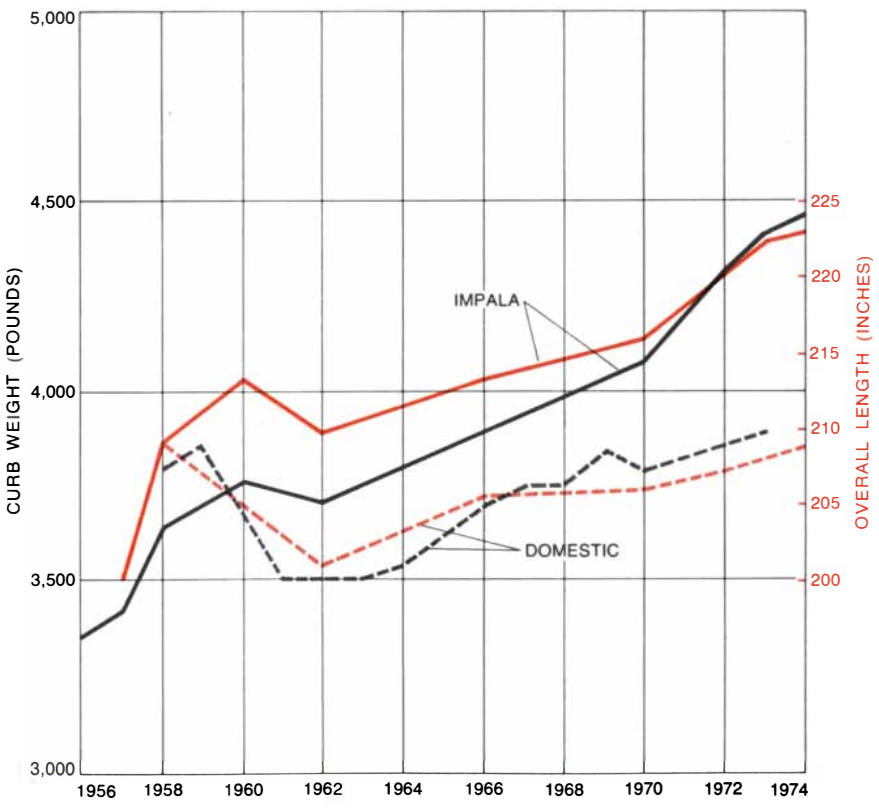
Since air drag increases as the square of vehicle speed, it has substantial importance at speeds above 45 m.p.h. In the speed range between 45 and 65 m.p.h. each additional 10 m.p.h. above 45 m.p.h. subtracts between 1.5 and two miles per gallon from fuel economy [*see illustration on page 43*]. We can look at a reduction in air drag either as saving energy or as enabling us to go faster with the same expenditure of energy.

It should be possible to reduce the air resistance of present-day large cars by 40 to 50 percent and of compacts by about a third. Such reductions can be achieved by designing cars to have a sloping front, smooth contours, a fairly flat back and a "dam" extending below the front bumper. For cars of roughly the current weight, size and construction but with an engine appropriately reduced in size to hold performance constant, a one-third reduction in aerodynamic drag should yield an improvement of about 10 percent in fuel economy under typical city-highway driving conditions. The percent improvement could be larger in a car with reduced rolling resistance.

There are various power drains in addition to the energy required to propel the car. Air conditioning, now installed in about 75 percent of all new cars, takes about six horsepower in a car traveling at 55 m.p.h. when the air temperature is 100 degrees F. Other accessories such as the engine fan, water pump, air pump and power steering will collectively absorb another five to 15 horsepower, depending on engine speed. Such accessories have to be designed to operate satisfactorily when the automobile is operating at low speeds, and commonly no provision is made to avoid unnecessary power consumption when it is operating at high speeds. A few cars now have electrically driven fans that operate only when the coolant temperature is high. Avoidance of unnecessary power loss at high speeds would cost something in design and complexity but would save energy.

One matter brought up during our Cal Tech seminars is the surprising inefficiency of cars for short trips without warm-up. Starting from an ambient temperature of 70 degrees F., a car gets an average of only 50 percent of its warmed-up gas mileage in a one-mile trip and only about 60 percent in a two-mile trip. In very cold weather the efficiency is much worse [*see bottom illustration on page 42*]. For full gasoline mileage the tires, the grease in the differential-gear box and the oil in the transmission system as well as in the engine must all be warmed up.

Thus substantial savings in fuel consumption could be achieved by reducing vehicle weight and air resistance, by using better and harder tires together with better suspensions, by cutting the waste of energy by accessories at high speeds, by designing better transmissions and, if possible, by achieving efficient operation with a shorter warm-up period. Beyond these possibilities we must consider engine efficiency.



SIZE OF STANDARD AMERICAN CAR has grown sharply in curb weight and overall length since 1956. The best-selling car in the U.S., the Chevrolet Impala, has increased more than half a ton in weight (1,100 pounds) and nearly two feet in overall length. Changes in the standard Ford, the Galaxie 500, are comparable. Because of the introduction of intermediate, compact and subcompact model lines, however, the sales-weighted average of all domestic cars has shown only small changes in curb weight and overall length (*broken curves*).

In the past engines have been chosen on the basis of cost and performance rather than efficiency. The diesel engine, as we have seen, is at least 40 percent more efficient than comparable gasoline engines and gives proportionately better fuel economy. Diesel engines, however, are heavy, costly and tend to be somewhat noisy. Moreover, the acceleration of diesel cars is below that of gasoline cars in the same price range. Thus for all their advantages diesel cars have not been notably popular.

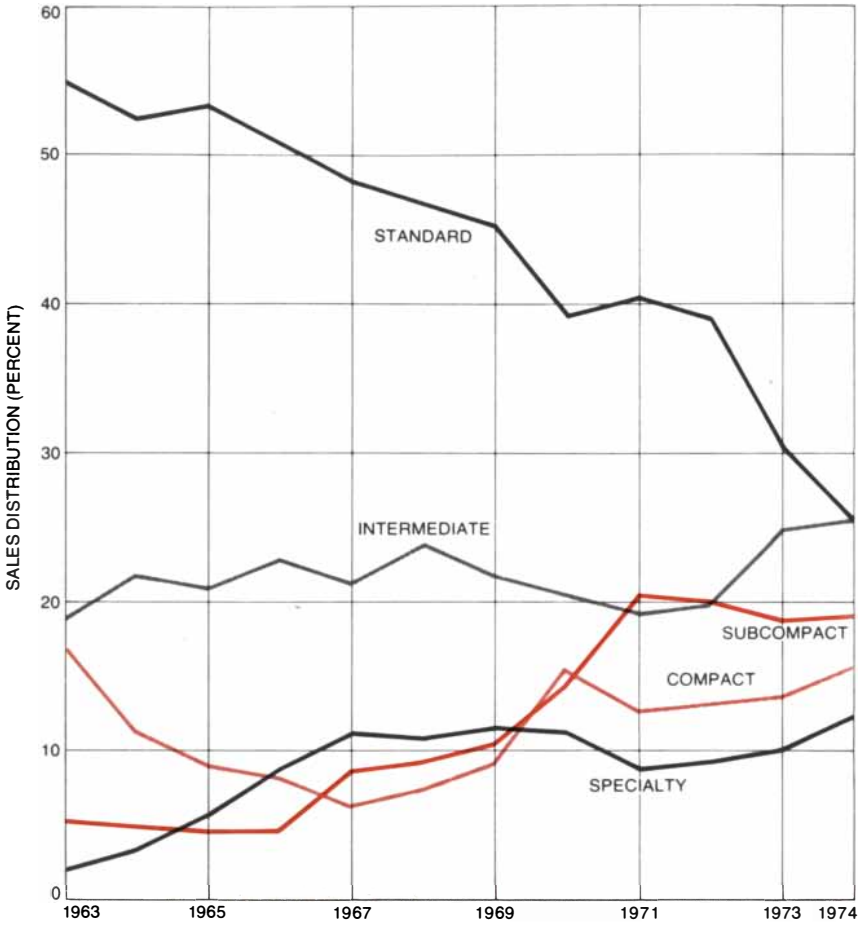
The diesel engine is efficient partly because of its high compression ratio (21 : 1 in the Mercedes-Benz diesel) and partly because it operates with a lean fuel mixture (that is, with an excess of air). Power is controlled not by throttling, as it is in most gasoline engines, but by varying the amount of fuel injected into the combustion chambers. When a diesel engine is idling, it consumes only about 15 percent as much fuel as an idling gasoline engine. Operation with a lean mixture has the added advantage of reducing the emissions of hydrocarbons and carbon monoxide. Indeed, if the mixture is lean enough, the oxides of nitrogen are reduced as well. Ideally one could meet emission stan-

dards without costly emission-control devices and with high engine efficiency.

The advantages of lean burning have been sought in a modified form of the present gasoline engine that is receiving much attention. This is the stratified-charge engine in which the air-fuel mixture is made intentionally nonhomogeneous. Near the spark plug it is initially rich enough for ignition, but on the average the mixture is lean, with a resulting improvement in efficiency and reduction in emissions. The charge can be stratified in a single combustion chamber by injection of the fuel, as in a diesel. In the Honda engine it is stratified by using an auxiliary combustion chamber in which the mixture is rich. Ignition by means of a special spark plug allows operation at a lower compression ratio than in a diesel engine and gives good starting in cold weather.

One form of stratified-charge engine, developed by Texaco, employs what is called the Texaco controlled-combustion system. A converted 1950 Plymouth using the Texaco system showed a 37 percent improvement in miles per gallon, as compared with the original engine, at speeds between 40 and 60 m.p.h. More recently a converted four-cylinder engine for a military jeep has shown improvements in fuel economy ranging between 40 and 70 percent in road tests. Texaco is now trying to see how much of this gain can be retained while meeting the 1977 emission standards. The Texaco engines operate equally well on gasoline, diesel fuel or jet fuel. Potential disadvantages of the Texaco system include the need for specially shaped pistons and a fuel injector and the tendency of the engine to produce particulate emissions under some conditions. Another form of stratified-charge engine, the PROCO engine (for programmed combustion process), has been under development by the Ford Motor Company. It is stated that the PROCO engine would improve fuel economy about 25 percent in medium-size and large cars and 15 percent in small cars.

Although very lean nonstratified mixtures of gasoline and air cannot be ignited, mixtures of hydrogen and air can be ignited even at an air-hydrogen ratio of 40 : 1, which is about twice as lean as the leanest air-gasoline ratio. Such ratios suggest the addition of hydrogen to the fuel mixture as a way of achieving lean burning both to raise efficiency and reduce emissions. This stratagem has been demonstrated in a Chevrolet V-8 engine in work at the Jet Propulsion Laboratory of Cal Tech. In dynamometer tests, using a fuel consisting of gasoline and bottled hydrogen, the equivalent miles per gallon increased from 9.4 for the unmodified engine to 12 for the modified engine, or more than 27 percent. A generator to produce hydrogen from gasoline has been built and operated, but not in an automobile.

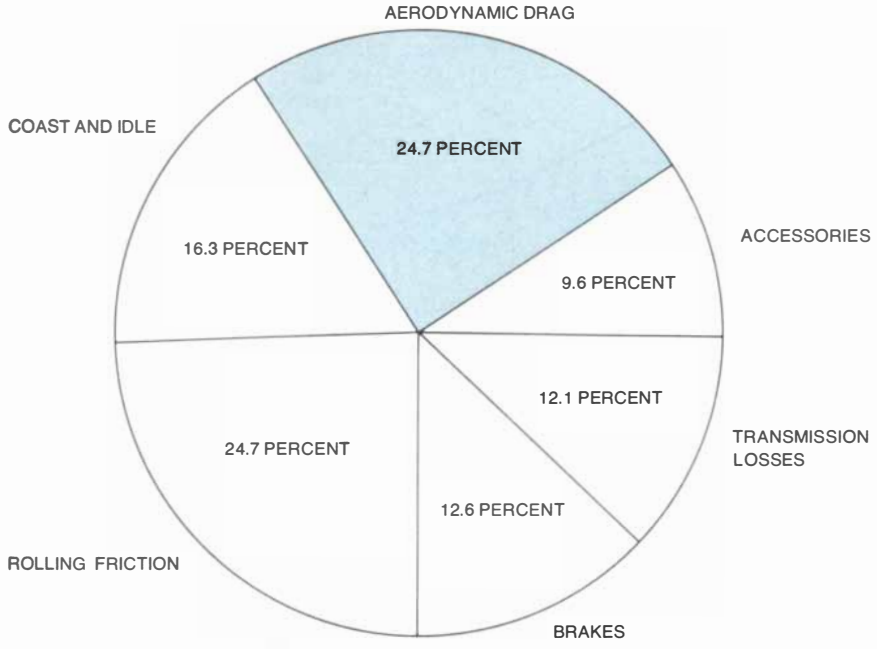


DISTRIBUTION OF CAR SALES by market category has been changing sharply. Sales of subcompact and standard-size models are now about equal. After a drop, sales of compact cars have started to climb again. The curves are based on compilations by *Automotive News*.

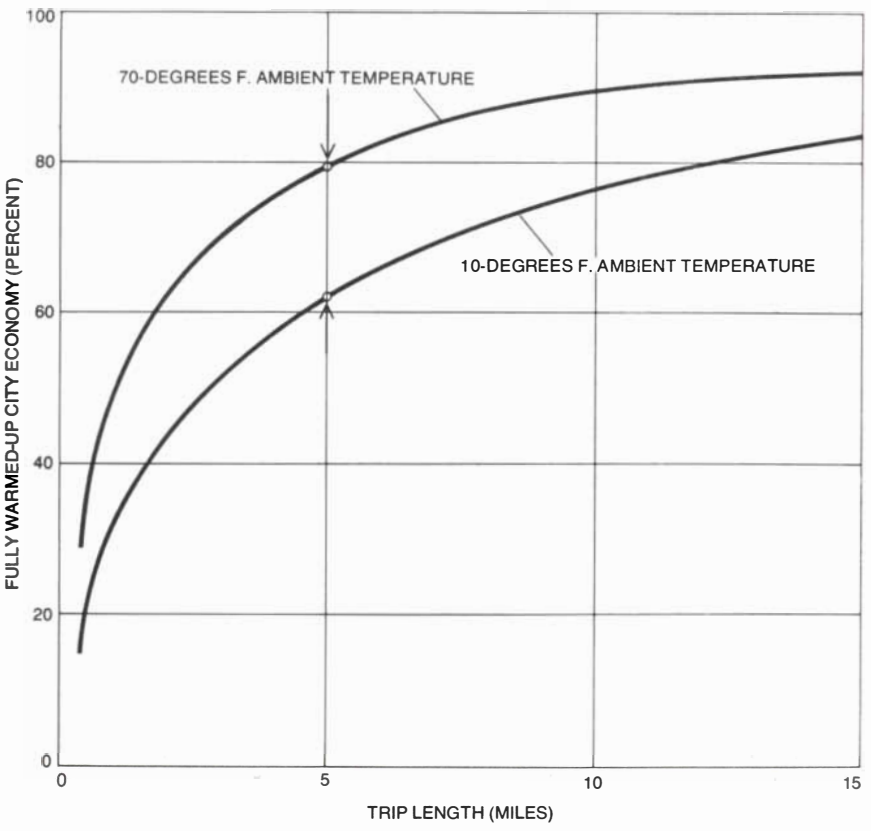
All three approaches—diesel, stratified charge, hydrogen admixture—achieve higher efficiency through use of a leaner air-fuel mixture. As we have seen, they also reduce emissions of hydrocarbons and carbon monoxide in the exhaust, perhaps to the point of meeting present emission standards. Proposed standards on emission of oxides of nitrogen, however, are difficult to meet. The production of oxides of nitrogen can be reduced only if the mixture is made lean enough to lower the temperature of combustion substantially. It may be that the proposed standards on emission of oxides of nitrogen are unrealistically stringent.

To sum up, reductions in fuel consumption ranging from 20 to 40 percent have been claimed for lean-mixture engines under the most efficient operating conditions. Much of the improvement in the past has been lost, however, in adjustments for meeting emission standards. One can hope that further development will lead to a lean-mixture engine with both high efficiency and low exhaust emissions.

Federal emission standards have indirectly had the effect of blocking efficiency improvements that could be achieved with conventional automobile engines simply by raising their compression ratio. Before 1970, when the first Federal standards went into effect, the engines in many American cars had compression ratios as high as 10 : 1 and in a few cases even 10.5 : 1. For efficient antiknock performance an engine with a 10 : 1 compression ratio needs a gasoline with a research octane number of about 100. Oil companies have traditionally added lead alkyl compounds (such as tetraethyl lead) to raise by some five to seven points the octane number of gasoline as it is produced at the refinery; thus a gasoline of 93 to 95 re-



DIVISION OF ENERGY REQUIREMENTS is shown for a 3,500-pound automobile when operated on the EPA composite city-highway test cycle. The energy lost in braking corresponds roughly to the amount of energy previously used to accelerate the car's inertial mass. In steady high-speed cruising most of the engine power is required to overcome aerodynamic drag. In low-speed cruising most of the power is needed to overcome the rolling resistance. In general reducing the power-to-weight ratio will increase the fuel economy.



COLD STARTS are a more important cause of poor fuel economy than most drivers realize. These General Motors curves show, for example, that a car that gets, say, 10 m.p.g. when it is fully warmed up in city driving would average only 8 m.p.g. for a five-mile trip when the initial car temperature was 70 degrees Fahrenheit and would average about 6.3 m.p.g. for the same trip on a cold winter morning. About half of all car trips are five miles or less.

search octane can be raised to 100 octane by adding "lead."

With the adoption several years ago of emission standards that would probably require the use of catalytic converters on 1975-model cars it was recognized that gasoline containing lead would poison the catalyst. As a result car makers began to lower compression ratios to between 8:1 and 8.5:1 in order to make it possible for 1975 models to run on unleaded fuel of 91 research octane.

Exxon engineers have calculated that for a typical engine of 350 cubic inches' displacement in a 4,000-pound automobile traveling at 40 m.p.h., raising the compression ratio from 8:1 to 10:1 would yield a 10 percent improvement in fuel economy; at a ratio of 12:1 the improvement would be about 18 percent. The Exxon study shows, however, that since the cost of producing unleaded gasoline rises steeply with octane number (about three cents per gallon to go from 95 octane to 100 at the time the study was made in 1971), the lowest transportation cost to the consumer is achieved with a research octane number of 97, which corresponds to an engine compression ratio of about 9.75:1. (The Exxon study assumes that three grades of gasoline, with an average octane number of 97, would be made available at the pumps.)

Although cars with power plants other than the internal-combustion engine have often been suggested, most of the power plants proposed (steam, gas-turbine, Stirling-cycle) would still need fuel from petroleum. In principle an electric car could get its energy from central power stations running on coal or on nuclear fuels. Electric vans powered by conventional lead-acid batteries have been operated in the U.S. and in other countries for many years. As a private car, however, an electric vehicle with lead-acid batteries seems only marginally promising. A Datsun converted by a Los Angeles engineer, Wally Rippel, gives some idea of the attainable performance.

The car has a range of 70 miles and a top speed of 61 m.p.h. The original transmission is retained, and acceleration is reasonable at the lower gear ratios. By using regenerative braking to recharge the batteries when the vehicle is slowing down or going downhill, electric consumption is reduced 15 percent for a mixture of city-street and freeway driving and as much as 25 percent when the route is a hilly one. The car will travel 3.5 miles per kilowatt-hour of charging

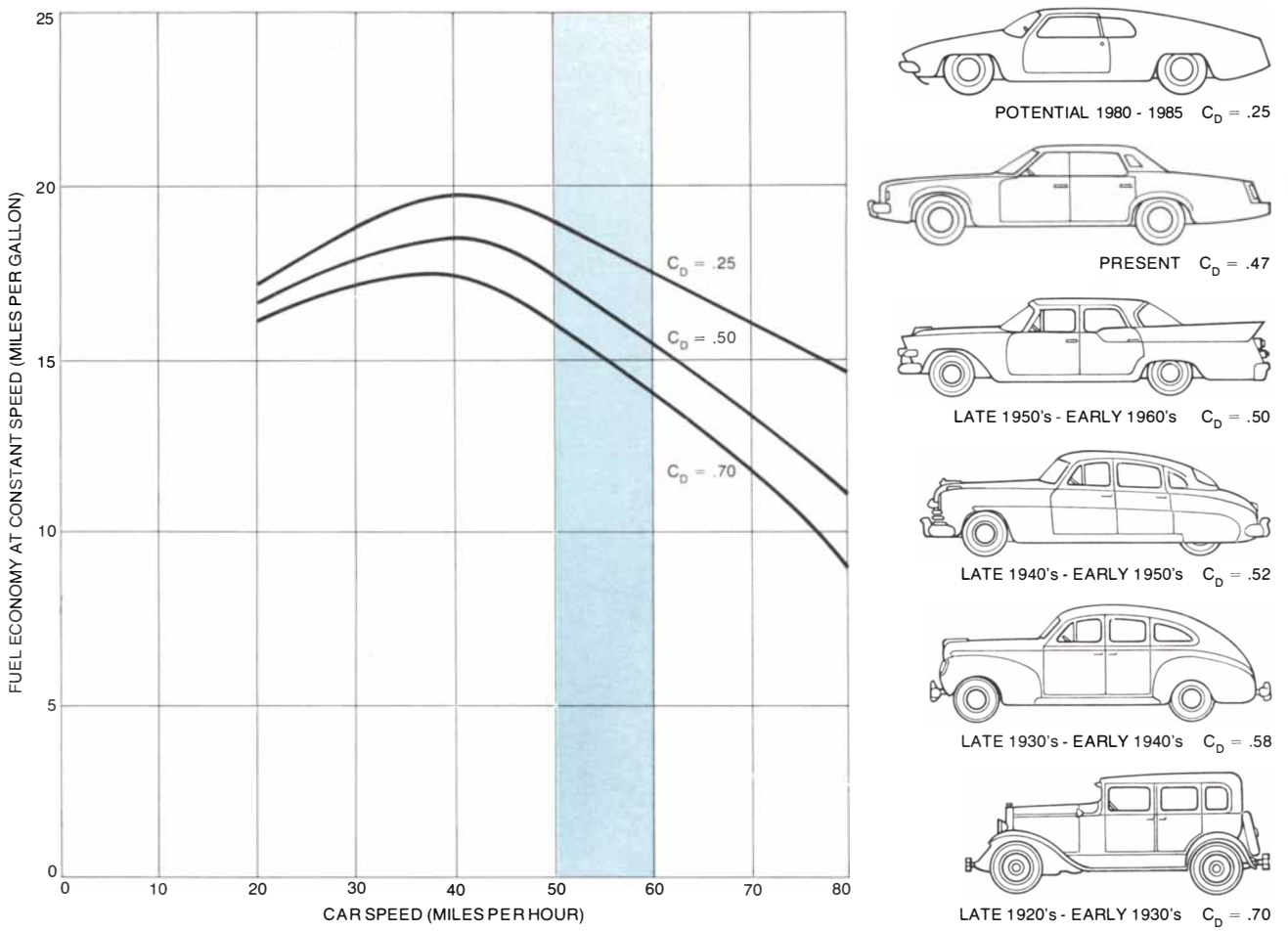
power. When this performance is converted to equivalent miles per gallon, it is seen to be quite remarkable: about 52 m.p.g., assuming an efficiency of conversion of fuel to electricity of 40 percent at the power plant. (The energy in a gallon of gasoline is about 125,000 British thermal units, or 37 times the energy in a kilowatt hour; 37 times 3.5 times .40 is 52.) Even though energy in the form of electricity is considerably more expensive than energy in the form of gasoline, the Rippel car still gets about 38.5 miles for the price of a gallon of gasoline, assuming five cents per kilowatt-hour and 55 cents a gallon for gasoline. (It is true, of course, that gasoline carries Federal and state taxes ranging from nine cents to 14 cents per gallon, which should be taken into account in such a calculation, either by subtracting the tax from the price of gasoline or by adding an equivalent tax to the price of electricity.) Fundamentally the efficiency of an electric automobile will depend on the efficiency of electric generating plants (about 40 percent for the best present fossil-fuel plants) minus losses involved in power distribution and the charging of batteries. The batteries in the Rippel car weigh about 1,400 pounds and have a retail value of about $1,200.

An improvement of 2:1 in power-to-weight ratio of batteries would make electric cars more attractive. The nickel-zinc battery or some other kind of battery may provide such an improvement. A more revolutionary regime that might do even better is to store energy in a composite flywheel made of lightweight materials, as has been proposed by Richard F. Post and Stephen F. Post [see "Flywheels," by Richard F. Post and Stephen F. Post; SCIENTIFIC AMERICAN, December, 1973].

There is a formidable obstacle to the production of a satisfactory electric car. Any gasoline-driven vehicle can be given acceptable performance by putting in a big enough engine. Fuel economy can then be improved gradually by reducing rolling resistance through low weight, hard tires and low unsprung weight, low-friction bearings and good streamlining. If an electric car is to perform satisfactorily, the engineering must be first-class right from the start; a low-loss control system, perhaps with regenerative braking and a high-efficiency motor, must be used.

Such sophisticated engineering design is contrary to the tradition of American automobile manufacturing. Commercial success is not assured even if the engineering is good. Who will take the chance? If we do have electric cars, they may come first as government-purchased vehicles, as high-cost novelties (such as sports cars) or as low-performance vehicles for special uses.

If we continue to use internal-com-



AERODYNAMIC DRAG begins to increase fuel consumption at car speeds of between 40 and 45 miles per hour. The drag coefficients for typical automobile designs of the past 50 years are given at right. As much drag reduction was achieved in the decade between the late 1920's and the late 1930's as in the next three and a half decades. The top car in the group shows a hypothetical design by William H. Bettes of the California Institute of Technology. The car would be a "fastback" with a sloping front, tapered fenders, hard edges and a "dam" below the front bumper. The three curves are computed for a car with the wheelbase and frontal area of present-day cars. The smaller Bettes car, with less frontal area, should considerably exceed the performance represented by the top curve.

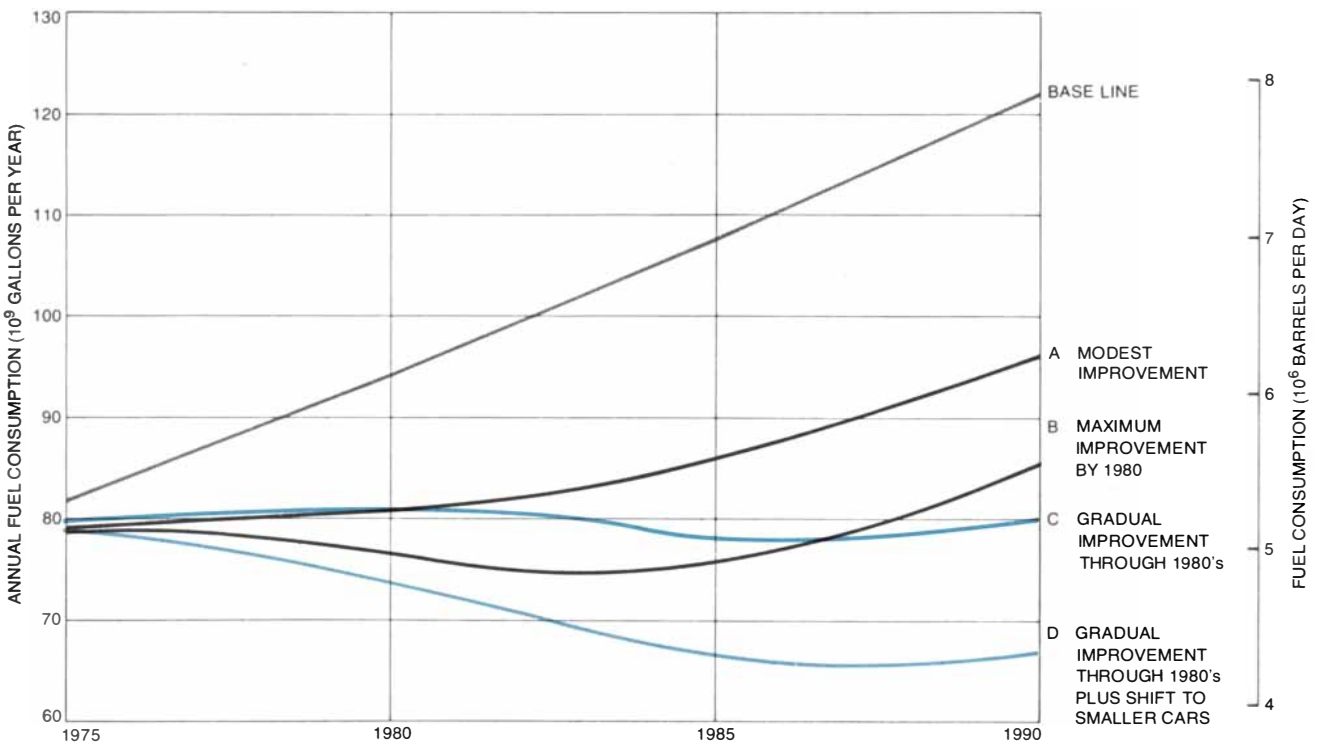
bustion engines rather than electric power, we are faced with an inherent but remediable inefficiency. Cars are overpowered for driving on the level in order to provide satisfactory acceleration. Thus the engine operates far below its most efficient power level most of the time. The remedy for this inefficiency is to provide some way of storing energy for use during acceleration. If this were done, a very modest engine could provide lively performance, at least on a level road. Early steam cars attained such performance with steam stored in a boiler.

In the 1930's Robert C. Burt installed a pneumatic transmission in a Plymouth. The gasoline engine pumped air into a tank; the compressed air drove the wheels by means of a converted steam engine. Energy stored in the air tank provided acceleration; the gasoline engine provided steady power. Such a drive system allows regenerative braking (through use of the air engine to compress air in deceleration) and the utilization of waste (exhaust) heat in heating the compressed air.

Recently tests have been made on vans where a small gasoline engine serves to charge batteries. The batteries provide extra power for acceleration; the gasoline engine provides sufficient power to propel the van on the level. A group at the Technical University at Aachen in Germany has constructed a power system in which energy for acceleration is stored in a flywheel; a small gasoline engine drives the flywheel and propels the van during constant-speed driving. The system has been installed in a Volkswagen Microbus. Acceleration better than that of a standard Microbus and a 60 percent fuel saving have been reported.

Vehicles combining a low-power internal-combustion engine and some means for storing energy are generally called hybrid vehicles. Perhaps they are the wave of the future. Perhaps they are too complex for private cars. Perhaps effective means for storing energy, either improved batteries or flywheels, will take us all the way to vehicles driven by electric power. It is sometimes overlooked, however, that all-electric private transportation would impose an enormous new load on the electric-utility industry. Today the nation's 100-odd-million private cars and small trucks consume nearly 60 percent as many energy units as all the nation's electric-power plants. To increase the capacity of the electric-power system between now and, say, the year 2000, to provide power for a national fleet of vehicles swollen to perhaps 160 million—in addition to expanding generating capacity 5 or 6 percent per year for all other purposes—would be an immensely costly undertaking.

Our view of the future is full of perhapses. What we do know with certainty is that in the near future private cars will continue to consume a great deal of gasoline and that there are many ways in which they could be made more efficient. Plausible projections by the Department of Transportation indicate that automobile fuel consumption could be stopped from growing before 1980 and thereafter even reduced [*see illustration below*]. Whether or not cars become more efficient will depend not only on technical ingenuity and enterprise but also on the economic pressure of the price of gasoline, and on any other pressure that may come into being.



POTENTIAL FUEL SAVINGS between now and 1990, corresponding to four different levels of private-car improvement, were presented to Congress in the DOT-EPA report. The base-line curve represents a steady growth in vehicle miles of 2.6 percent per year. Curve *A* is based on announced industry goals (some engine changes, use of radial tires, slight weight and air-drag reduction) with no significant improvements beyond 1978. Curve *B* is based on maximum improvements through 1980 with little change thereafter. Changes would include rapid weight and air-drag reduction, improved transmissions and optimization of conventional engines. Curve *C* visualizes somewhat slower changes before 1980 but substantial improvements thereafter, including the phasing in of diesel engines for larger cars between 1981 and 1989 and adoption of stratified-charge engines for smaller cars. Curve *D* includes all the changes projected in curve *C* combined with a sales mix after 1980 consisting of 10 percent large cars, 25 percent intermediates, 25 percent compacts and 40 percent subcompacts. Curve *D* would yield a total saving of 3.6 million barrels of fuel per day by 1990.

We want to be useful ...and even interesting

A gas

We have discovered a gas in which to immerse certain films and plates if you want to cut exposure time from, say, 5 hours to 10 minutes. Sorry it took so long to discover this gas.

The gas is highly explosive, though. It must be handled with utmost respect. Do not mess with it in the home. We wouldn't want to say even that it works on the film people buy for personal cameras. On the astronomical-type photomaterials where we have tried it, it works.

Before immersion in the gas at one atmosphere or so of pressure, O_2 and water vapor must be removed by vacuum or by flushing with dry, inert gas. Stay too long in the gas and fog goes too high. Optimum immersion time for the most speed gain with the least fog and loss of contrast depends on the particular batch of emulsion. For the current favorites in astronomical work, KODAK "Spectroscopic" Plates and Film, Type IIIa-J, immersion times run around 1½ to 3 hours.

The treatment almost completely eliminates the photographic devaluation of photons when they hit at low rates that call for hours of exposure (low-intensity reciprocity failure).

Little of the added sensitivity is lost by removal to room air for a few hours before exposure.

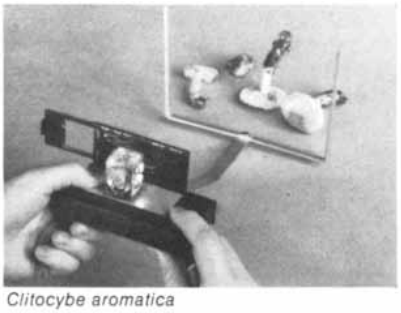
Hypersensitization by this gas is more even over the emulsion surface, and it gives more effect in much less treatment time than with previous methods. It can probably be made to work even on KODAK High Resolution Plates, but for them a few *days* of immersion in the gas might be needed just to bring a one-hour exposure down to 20 minutes. With longer treatment one might do better. Immersion time should be determined anew when the emulsion number changes.

We do not manufacture this hypersensitizing gas. Indeed, we are willing to reveal its chemical formula.

Here it is: H_2.

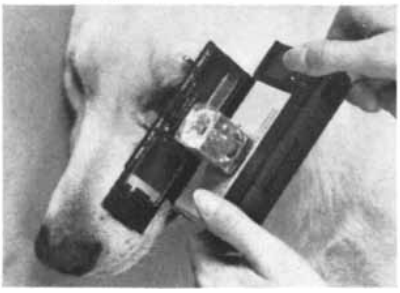
Adequate, adequate

Aralia sp.



Clitocybe aromatica

Roman lamp, *circa* 100 B.C.



Veterinary subject

The KODAK Pocket INSTATECH Close-Up Camera is for those who need photographic records of objects sized 25 cm or less (even a lot less, as can be seen from these illustrations) but hesitate to expend much talent or money on photography.

Certain accessories make the camera effective. Though we make only the camera, we can arrange to have information sent to you on the whole outfit. Write Kodak, Dept. 55W, Rochester, N.Y. 14650.

Stimulation in the simulation

Most cameras, including the one advertised at left, are used for color pictures today. Many decades ago we knew it would be so. In preparation, studies of a fundamental nature were done at the Kodak Research Laboratories on the measurement of differences in color sensation. Early on, it became clear that differences could be measured more precisely in the psychophysical laboratory than the fidelity with which photographic processes can simulate color sensations aroused in an original seeing experience.

Photographic duplication of color is a deep, multi-level subject.* Kodak ads go only so far as to suggest that you will find stimulation in the simulation.

"You" are assumed to be just folks, not a toxicologist who wants to press a button on an INSTATECH Camera to document the difference in color between *Amanita phalloides* and *A. citrina.* If such a button exists, don't look for it on any make of camera.

Cameras can and do serve as mnemonic devices, though, whether to recall distinctions between two similar toadstools or a marvelous afternoon with a beautiful child on the green grass under a blue sky.

Take notice that we have demonstrated a public preference in color prints for grass and Caucasian skin slightly yellower than average reality. As for blue sky, preference and reality in various climes pretty well coincide.

*A paper entitled "Objectives in Colour Reproduction," obtainable from Kodak, Dept. 55W, Rochester, N.Y. 14650, digs into it.

Kodak

One of the best fire fighters in your town is a pair of pajamas.

Every town, big or small, needs experienced fire fighters.

The ones you see here — in full battle gear — belong to Engine Company No. 1 of Freeport, New York.

The fire fighter that looks out of place is the pair of pajamas on the child.

You see, by law all sleepwear up to size 6X must be made flame-retardant.

And these pajamas are made of 100% Dynel modacrylic, a flame-retardant fiber created by Union Carbide.

When exposed to fire, properly constructed fabric of Dynel does a very sensible thing. It shrinks from it.

And if a flame should reach it, it extinguishes itself as soon as the flame is removed.

Dynel has a lot more going for it. It's soft, non-allergenic, durable, colorfast, mothproof.

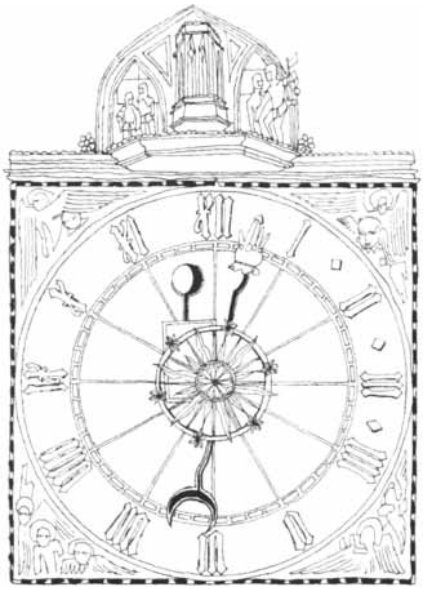
So you're likely to find this versatile fiber in all sorts of things. Wigs, draperies, carpets, tents, paint rollers.

But we doubt that there will ever be a better use for Dynel than helping protect young children against a very old enemy. Fire.

UNION CARBIDE

Today, something we do will touch your life.

SCIENCE AND THE CITIZEN



The New Arms Race

The arms race between the U.S. and the U.S.S.R. is undergoing a fundamental change. It is becoming qualitative rather than quantitative. The shift has been under way for some years. It was tacitly recognized in the terms of the tentative agreement on offensive nuclear weapons reached at Vladivostok in November, and it will apparently be institutionalized in a treaty to be negotiated by the two superpowers this year. The agreement worked out by President Ford and General Secretary Brezhnev placed a ceiling of about 2,400 on the aggregate number of strategic delivery vehicles (long-range missiles and bombers) and provided that 1,320 missiles may be equipped with multiple independently targetable reentry vehicles, or warheads (MIRV's). The MIRVed missiles will reportedly have to be divided about equally between land-based and submarine-based ones; the precise combination remains to be set.

The tentative agreement represents an incremental advance for arms control in that it runs until 1985 (the current agreement expires in 1977) and in that for the first time it includes strategic bombers and limits at least the number of missiles that can be MIRVed. What has dismayed some specialists in arms control is that the number of MIRV missiles is very high, that no limit is placed on the number of warheads each may carry and that no attempt is made to control many qualitative improvements that are now being designed or contemplated.

The agreement sets numerical limits that effectively encompass the present arsenals of both sides. The U.S.S.R. has more missiles, and heavier ones, than the U.S.; the agreement does not curb that advantage. The U.S. chooses to rely more on strategic bombers, and the agreement does not interfere. The U.S. has deployed 776 MIRVed missiles and is now free to have 1,320, more than the Department of Defense had planned. The Russians are just beginning to deploy MIRVed missiles and are now free to emplace the same number. Presumably they will do so. And both sides are apparently free to develop new and improved models of every weapon and to substitute them at will for currently emplaced missiles, provided only that they do not exceed the overall numbers.

The agreement was hailed by a U.S. spokesman as a diplomatic "triumph" for this country. Perhaps it was, according to Kosta Tsipis of the Stockholm International Peace Research Institute and the Massachusetts Institute of Technology—in the sense that it virtually forces the U.S.S.R. to undertake an enormous MIRVing effort that will strain its financial, technological and manpower resources. In the long run, however, the newly authorized quality race can only cost both sides dearly and destabilize world politics. The U.S. already has a large advantage in accuracy of delivery, the major factor in determining the ability of a warhead to destroy a land-based missile in its silo. Further refinements in accuracy are planned. As the Russians deploy MIRV's, the U.S. could counter with MARV's: maneuverable reentry vehicles. Eventually such improvements might provide one side—presumably the U.S. first—with a true counterforce capability: the ability to destroy most of the opponent's land-based missiles before they could be fired, and thus partially frustrate massive retaliation, which has been the basis of the balance of terror.

The cornerstone of any arms-control agreement is verification, which is now satisfactorily accomplished by satellite surveillance. The trouble with a qualitative race is that levels of quality, unlike numbers of missiles, cannot be similarly verified. Tsipis suggests that one way to limit qualitative advances would be by limiting testing, which is necessary for developing new vehicles and evaluating their performance and also for checking on the readiness of existing vehicles. A stringent limit on the number of test launchings per year, which would be easy to verify, would provide a strong constraint on the development of new weapons.

Charmed Lifetime?

To the theoretical physicist the most puzzling aspect of the recent discovery of a new kind of subnuclear particle in experiments conducted independently at two high-energy-physics laboratories is the observed particle's extraordinarily long lifetime of 10^{-20} second. It is this unexpectedly "slow" decay, more than any other property, that sets the comparatively massive new particle apart from hundreds of other unstable subnuclear species, sometimes called resonances, that have been created with the aid of particle accelerators. Most of the latter particles have lifetimes on the order of 10^{-23} second.

The new particle, called the *J* particle by one group of experimenters and the psi particle by the other, manifested its existence in two quite different experiments. At the Brookhaven National Laboratory a group headed by Samuel C. C. Ting of the Massachusetts Institute of Technology had been searching for evidence of new particles in the debris formed by bombarding stationary protons (in a beryllium target) with a beam of protons accelerated by Brookhaven's 30-GeV (30-billion-electron-volt) alternating-gradient synchrotron. For this purpose the experimenters employed a special two-armed mass spectrometer capable of detecting electrons and positrons in coincident pairs resulting from the same collision event. The large number of such pairs observed with a rest energy of about 3.1 GeV indicated that a new particle with a mass equivalent to that energy (roughly three times the mass of the proton) had been created in the course of the proton-proton collisions and had subsequently decayed to form an electron-positron pair. It is the Brookhaven group that calls the new particle *J*.

Meanwhile at the Stanford Linear Accelerator Center (SLAC) another group, under the general direction of Burton Richter, was engaged in studying what happens when electrons collide with pos-

itrons in counterrotating beams extracted from the SLAC two-mile linear accelerator. The SLAC experimenters found that when the combined energy of the colliding beams was exactly 3.105 GeV, there was a sudden enormous increase in the number of particles produced. At nearby beam energies the excess production of particles abruptly disappeared. This evidence indicated the creation at that energy of a heavy new particle, which subsequently decayed to form other particles. The SLAC group chose to call the new particle psi(3105). In an experiment 12 days later the same group observed a second new particle at 3.695 GeV; they call it psi(3695).

The surprising combination of a large mass and a long lifetime observed in these experiments has suggested to some that the new particle might be the as yet unobserved neutral intermediate vector boson, the hypothetical agent of the recently observed neutral-current interactions (see "The Detection of Neutral Weak Currents," by David B. Cline, Alfred K. Mann and Carlo Rubbia; SCIENTIFIC AMERICAN, December, 1974). The existence of such a particle is central to a theory, put forward independently by Steven Weinberg and Abdus Salam, that seeks to establish a deep link between the weak force and the electromagnetic force. One trouble with this interpretation is that, although the mass of the new particle is quite large, it is about three times smaller than a lower limit established by previous experimental evidence, and some 25 times smaller than what is predicted by the new unified theory of weak and electromagnetic interactions.

Another possibility being discussed is that the new particle represents a "bound state" consisting of a "charmed" quark and its corresponding antiquark. The notion of a quark possessing a new quantum property called charm was put forward a decade ago by James Bjorken and Sheldon L. Glashow to supplement the original three quarks postulated by Murray Gell-Mann and George Zweig. Although only three quarks were required to describe the particles then known, the fourth quark was invented in order to produce a symmetry between heavy particles and light particles. Later Glashow and others pointed out that the fourth quark was needed to account for the observed absence of certain kinds of neutral currents. The need for charmed quarks has become even more compelling with the growing acceptance of the Weinberg-Salam theory.

Some theoretical physicists believe that if the new particle is viewed as an "atom" of "charmonium," that is, an entity consisting of a charmed quark bound to a charmed antiquark, then its anomalously long lifetime would be accounted for. Theory predicts that it would take on the order of 10^{-20} second for the two quarks to annihilate each other in a flash of radiation, out of which other heavy particles could be created. On this view psi(3695) would be simply an excited state of charmonium. Fortunately this interpretation is subject to experimental test. If the charmed quark of Glashow and his colleagues exists, then a new class of particles with a net value of charm must be observed in certain collisions of energetic particles.

Resisting the appeal of such speculations, at least for the time being, are theorists such as Victor F. Weisskopf, who cautioned recently that "it is still too early to tell what it [the new particle] is." Weisskopf added: "I subscribe at this time to the statement that it is as yet something completely mysterious coming to us from the world of the subnucleus and nobody knows what it is."

The Experience of Gheel

With the phasing out of state mental hospitals in many parts of the U.S. the responsibility for the care of the mentally ill is being shifted to community mental-health centers. The newly released patients are largely free to come and go as they please. Often the community is not prepared to receive and help these patients; many citizens express fears about having mentally ill people walking the streets. Charles D. Aring of the University of Cincinnati Medical Center suggests that such communities may have much to learn from the experience of the Belgian town of Gheel, which has had a community system of caring for the mentally ill for a remarkably long time: some 600 years.

Aring writes in *The Journal of the American Medical Association* that Gheel, about 25 miles east of Antwerp, has been a haven for the insane since the 13th century. Today people with mild or chronic mental illness are lodged in the homes of selected townspeople. The patient has his own room and eats his meals with the family. He may help the family with the work in the house or in the fields, secure employment elsewhere in the town or do nothing. Wages earned by the patient belong entirely to him. The families providing board and room for patients receive a modest monthly fee from a government agency.

Gheel's tradition of housing the mentally ill is linked to the legend of St. Dymphna. In A.D. 600, the story goes, Dymphna, an Irish princess, fled to Belgium when her father insisted that she marry him. The king followed her, and when Dymphna continued to resist, he beheaded her. The king's behavior was regarded as insanity, and in time the belief grew that Dymphna, in having been able to resist the demon that had possessed the king, had been granted the privilege of being the patron saint of the insane. Miraculous cures at her tomb were reported, and in 1247 Dymphna was canonized. A cathedral was built in her honor, and when the influx of the mentally ill continued, patients began to be housed under church guidance with the townsfolk. The sponsorship of the church continued until 1852, when the care of the patients was taken over by the Belgian government and placed under medical direction.

Patients come to Gheel voluntarily or on the recommendation of a physician. On admission a patient is observed for several days by the medical staff and is then assigned to a family. Although there is a certain amount of patient selection, most of the people who come to Gheel are admitted to the community. Patients who become unmanageable are treated in a local infirmary and are returned to their boarding homes after recovery. Those who fail to recover are eventually transferred to other care facilities. Acts of violence involving patients are extremely rare.

Aring believes the system of care in Gheel offers a "happier and more normal life" for the mentally ill person. He notes in addition that the mental patient can provide a special contribution to the community: he or she makes other members of the community more tolerant and more humane. Aring concludes: "Were it possible to disseminate the spirit of Gheel, there would be little problem in gracefully phasing out the population of mental hospitals."

Crack! Rumble! Boom!

What makes thunder roll? After all, although a lightning discharge can consist of many strokes, the total duration of the flash is only a few tenths of a second. Why does the resulting sound persist for half a minute or even longer? The answer, which like many good answers is obvious in retrospect, lies in the difference between the speed of light and the speed of sound. A typical lightning discharge consists of three strokes

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It has a *high resolution display*, easier to read than any CRT terminal we've ever seen. Each character is well resolved on a 7- by 9-dot matrix; each is well formed, thanks to the 2640's dot-shifting capability (it makes a curve look like a curve); and each is centered on a 9 by 15 cell that allows distinct separation between characters and lines. It can handle four plug-in 128-character sets *concurrently*, including a line drawing set and a math set with sub- and superscripts and Greek letters.

$$\Xi(t) = \xi(t) \int_0^1 \int_0^1 y^{\gamma} \sin 2\pi\theta \, d\theta \, dy$$

Inverse video, underlining, blinking, and half-bright displays are possible in all sets, and sets may be mixed in adjacent characters.

It has *comprehensive editing* capability. The 2640 can operate character-by-character in completely interactive mode; or touch a switch, and it can transmit a block at a time. In block mode, you can prepare and edit text off-line before transmission to the computer, thus significantly reducing computer time. And you save a lot of your own time through such standard editing features as character and line insert or delete; cursor addressability and positioning control; scrolling; programmable protected fields; and eight special function keys for user-defined routines.

It has *pop-in modularity and expandability*. Push the TEST key, for example, and the 2640 checks its own RAMs, firmware, and display, then signals NO GO if service is required. Pop-in modularity makes it easy to replace logic boards when needed, without tools. The terminal's computer-like structure has 14 powered slots to accommodate a wide choice of pop-in options, memory additions, peripheral interfaces...and the capacity to handle new developments as they come along. The 2640A price is $3,000*.

The cardiorespirograph: a new way to keep the newborn healthy.

Ask almost any American to name the nation's greatest health problem and he's likely to say cancer or heart disease. Another answer is more surprising: Estimates are that each year in the U.S. alone some 50,000 newborn suffer permanent brain damage and another 50,000 die immediately after birth. Although most are high-risk neonates—either premature or low-weight infants—a large number are apparently healthy and normal...until disaster strikes.

Most neonatologists contend that many of these tragedies can be prevented by specially-trained perinatal medical teams using intensive care techniques. The point has already been conclusively demonstrated in the growing number of hospitals that operate well-staffed intensive care nurseries.

For distressed neonates, the greatest need is to monitor their respiration and heart rate continuously because a dramatic change in either requires an immediate response by the medical team. It's also important that the physician know the *correlation* between heart rate and respiration: an accurate diagnosis of the child's specific condition may well depend on it.

Now, HP introduces the cardiorespirograph, a new instrument for monitoring the newborn. Based on patient monitoring techniques evolved at HP during the last decade, the cardiorespirograph fills three important needs in caring for distressed infants.

First, it continuously *monitors* heart rate and respiration, displays each digitally, and sounds an alarm when either falls outside the limits set by the medical team. Using adhesive electrodes that are easily and quickly applied to the neonate, the instrument measures beat-to-beat heart rate and thus makes available valuable variability information that is not seen in averaged heart rate values. Respiratory status is further monitored by a respiration waveform. This, measured through impedance changes, portrays the newborn's pulmonary status in more detail than a mere rate index.

Second, it continuously records these two vital parameters, thus giving the physician an objective *documentation* of the effectiveness of therapy and of the infant's progress throughout a period of crisis. Finally, it provides a detailed record of the correlation between heart rate and respiration, a valuable *diagnostic* aid. The cardiorespirogram is sufficiently sensitive to help detect and differentiate between various life-threatening abnormalities such as asphyxiation, inflammatory cerebral diseases, cardiopulmonary disorders and respiratory distress syndrome.

The Model 78250A Cardiorespirograph is priced at $4765* and is completely compatible with HP's extensive line of modular patient monitors. In the hands of a skilled perinatal medical team, the cardiorespirograph not only helps prevent disaster in the nursery but also helps reduce the frequency of permanent damage to distressed neonates.

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through a channel extending some 10 kilometers. The light from all parts of the channel reaches the observer almost instantaneously. The sound from the various parts, however, usually reaches the observer at different times because it originates at different distances. If the lightning channel is generally at right angles to the line of sight, the sound will reach the observer at almost the same time, and he will hear an abrupt, loud crack. If the channel is generally parallel to the line of sight, the sound from the farthest part will reach the observer many seconds later than the sound from the nearest part, and he will hear a long rumble.

The variations in the intensity of the sound of rolling thunder have a number of causes: the shape of the lightning channel, the number of branches in it, the number of strokes in the discharge, the wind, the refraction of sound by temperature gradients in the atmosphere and so on. The relative importance of such effects is discussed by Arthur A. Few, Jr., of Rice University in *EOS* (*Transactions of the American Geophysical Union*). Few has recorded the "signatures" of thunder with arrays of microphones and then has reconstructed lightning channels from his recordings.

Few points out that the amateur observer can enjoy analyzing thunder to determine the nature of the lightning discharge that gave rise to it. The time lags between the flash and the first sound, then the loudest crack and finally the rumble enable one to estimate the distance to the nearest branch of the discharge, the distance to the main channel and the distance to the farthest branch. (The distance in kilometers is roughly the time lag in seconds divided by three.) Low-pitched thunder is emitted by energetic lightning discharges, and the pitch of the thunder gets lower as the sound arrives from higher altitudes. Window-rattling booms of thunder that are felt as much as they are heard are generated by extremely energetic discharges, particularly those at high altitudes. Few cautions that the enthusiasm of the observer should be tempered by good judgment. "We do not recommend... standing under a tree in an open field.... Extreme caution should be exercised to prevent an active personal participation in the lightning event."

Filthy Swine on Hadrian's Wall

What was it really like to live, say, in a Roman frontier outpost of the second century? Archaeology has done much to answer such questions in broad outline, but homely details are often missing because so much of the residue of human life is perishable. At the site of a second-century Roman fort in Britain, however, a remarkable amount of such material is preserved in a layer of waterlogged soil. The deposit provides unique glimpses, not to say smells, of the garrison's daily existence.

The site is Vindolanda, a Roman strongpoint in Cumberland that stood about a mile behind the western wing of Hadrian's Wall. Excavations at the site have been in progress since 1971, under the direction of Robin Birley. Two seasons ago, while installing a drainage pipe to carry off water that was flooding the center of the dig, the excavators cut a trench through a three-foot layer of clay that had previously been thought to be a natural formation. Sealed under the clay they found the remains of structures belonging to an earlier Roman fort. The floor of one of the buildings consisted of a five-foot accumulation of waterlogged organic debris, composed mainly of layer on layer of straw, ferns, twigs and moss. The plant materials had apparently been strewn as carpeting on the building's original earth floor, and the occupants had laid down a new carpet from time to time without bothering to remove the old one. During the centuries since the clay seal was first dumped on top of the accumulated rubbish to provide a foundation for a later building the plant debris was slowly compacted into a peatlike mass that the excavators were obliged to cut up and remove, block by block, and then take apart by hand.

Mingled with the plant material they found fragments of cooking pots and glassware, a bronze harness ornament, projectiles for a catapult, bone gaming counters, women's hair combs and slippers, a gold earring, the shells of oysters and mussels, the bones of pigs, sheep, hares and songbirds, the skulls of a number of oxen (some displaying multiple punctures, as if they had been used for target practice), several bits of cloth and more than 2,000 pieces of leather. Among the 2,000 pieces were wornout boots and shoes, pieces of leather garments and tenting, scraps of cut leather and a variety of undamaged leather goods. Also present were a shoe last and several leatherworking tools.

Additional finds within the layers of plant debris were the fragments of 13 wax-coated writing tablets, 14 iron stylus pens for writing on wax and the fragments of perhaps another 70 shinglelike wood tablets, many bearing traces of writing in carbon ink. One of the inked tablets, virtually intact, carried a record of supplies dispensed on June 22, 23 and 24; the year is unknown but probably fell between A.D. 100 and 105. Items of issue included barley, pork fat, garlic, vinegar, brine, hay, wine and "Celtic beer." The wine ration was particularly liberal.

The failure of the fort's occupants to clear away one straw-and-fern carpet before laying down the next shows a disregard for basic camp hygiene that is untypical of the rigorous Roman military tradition; so does the presence within a building of such food scraps as bone and shell. The picture of laxness is reinforced by the fact that scattered throughout the deposit are the pupae of the stable fly; it is estimated that a million pupae are present. All of this has inspired press commentary in Britain suggesting that the garrison's personnel (and by extension all the Romans who invaded Britain) were "filthy swine." Birley, writing in *Current Archaeology*, provides a somewhat different interpretation.

The stable-fly pupae indicate an environment rich in urine. Furthermore, the excavators have found the remains of feces amid the plant debris. As students of the history of technology are well aware, both of these excreta were used in the tanning of leather; they were still being used as recently as the beginning of this century. The large quantity of finished leather goods in the deposit, in combination with the apparent presence of tanning materials, strongly suggests that at least part of the structure was a working tannery. The mutilated ox skulls imply further that the hides may have been a by-product of the garrison's beef ration.

The evidence for tanning activity does not prove, however, that the Romans at the site were not filthy swine. As Birley notes, "the idea of leatherworking being carried on within the fort and meals being eaten and records made in the same building still takes some getting used to."

Faraday and the Psychics

When someone professes to read minds or to bend spoons by psychic force, scientists as a group are sometimes chastised for ignoring a revolutionary new finding and not putting it to the test of experiment. What may be forgotten is that this particular kind of claim has a long history, including many investigations by competent workers. One particularly lucid series of experiments was conducted by Michael Faraday in 1853. It was brought to public attention by Marvin Margoshes of Tarrytown, N.Y.,

in a recent letter to *The New York Times*.

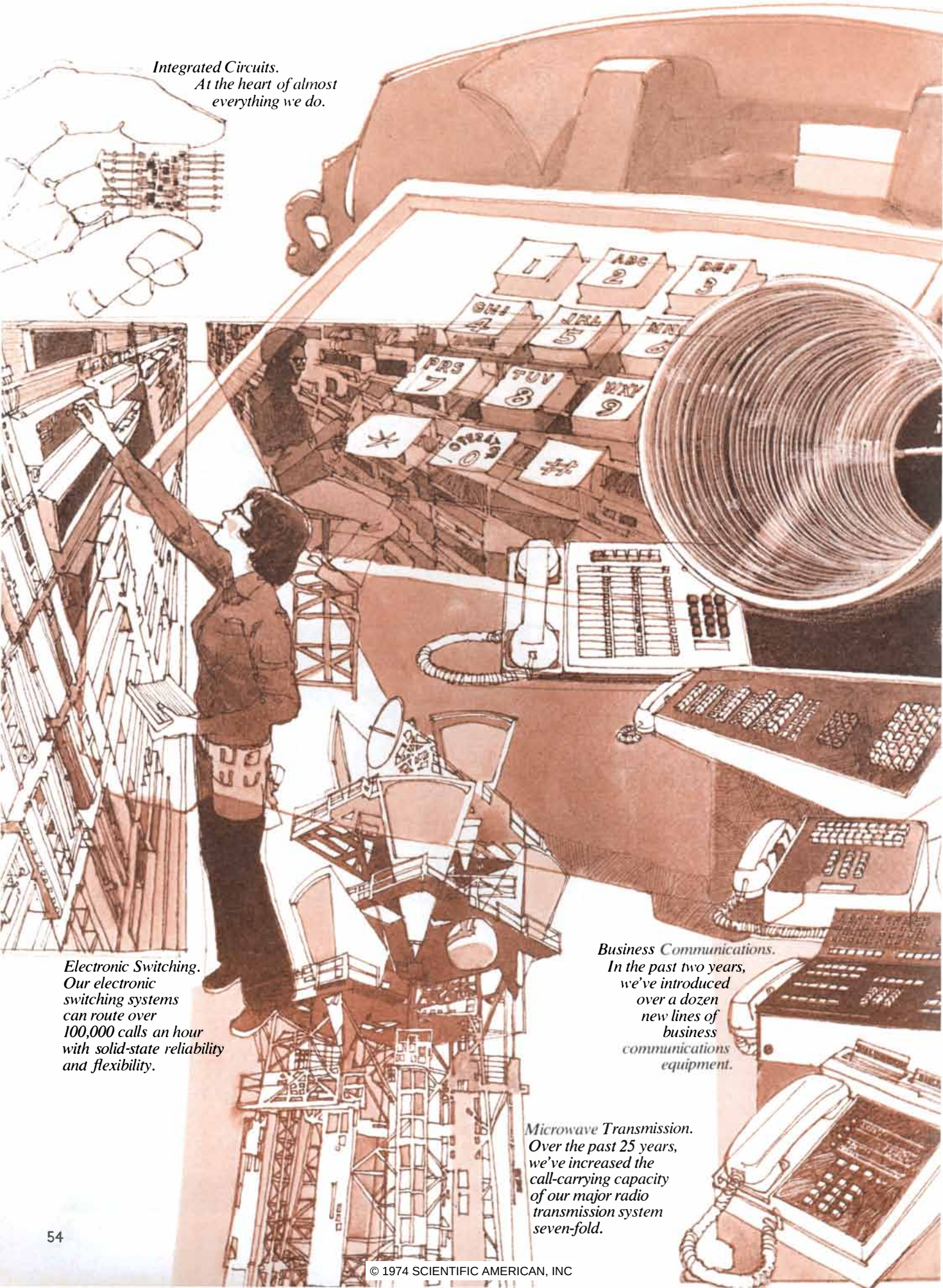
In Faraday's era the preoccupation of psychics was not spoon-bending but table-turning. A "sensitive" pressed his fingertips to the table and concentrated on the task; soon the table was seen to move. The movement was attributed to unrecognized effects of electricity or magnetism, or to "diabolical or supernatural agency." Faraday set out to discover a more mundane motive force. The results of his investigation are reported in *Annual of Scientific Discovery: or, Year-Book of Facts in Science and Art, for 1854.*

In a series of preliminary trials Faraday interposed various materials between the fingers of the table-turner and the table; none of the materials interfered with the movement of the table. He then prepared a small pack of cards, held together by a waxy cement "strong enough to offer considerable resistance to mechanical motion, and also to retain the cards in any new position which they might acquire—and yet weak enough to give way slowly to a continued force."

The relative position of the cards at the start of the experiment was marked on their underside in pencil. They were then placed on the table, and the "sensitive" placed his fingers on them. Faraday describes the results: "When at last the table, cards, and hands all moved to the left together... I took up the pack. On examination, it was easy to see by the displacement of the parts of the line, that the hand had moved further than the table, and that the latter had lagged behind—that the hand, in fact, had pushed the upper card to the left, and that the under cards and the table had followed and been dragged by it. In other similar cases when the table had not moved, still the upper card was found to have moved, showing that the hand had carried it in the expected direction."

Faraday later constructed a more elaborate apparatus in which a pointer indicated whether the table or the hand moved first. With the pointer concealed from the experimental subjects, he found that the table invariably lagged behind. When the pointer was in view, none of the subjects was able to induce the table to move.

In stating his conclusion Faraday was restrained: "The parties with whom I have worked were very honorable," he said. "It is with me a clear point that [they] do not intend, and do not believe that they move [the table] by ordinary mechanical power." He was also unequivocal: the table moved because it was pushed.



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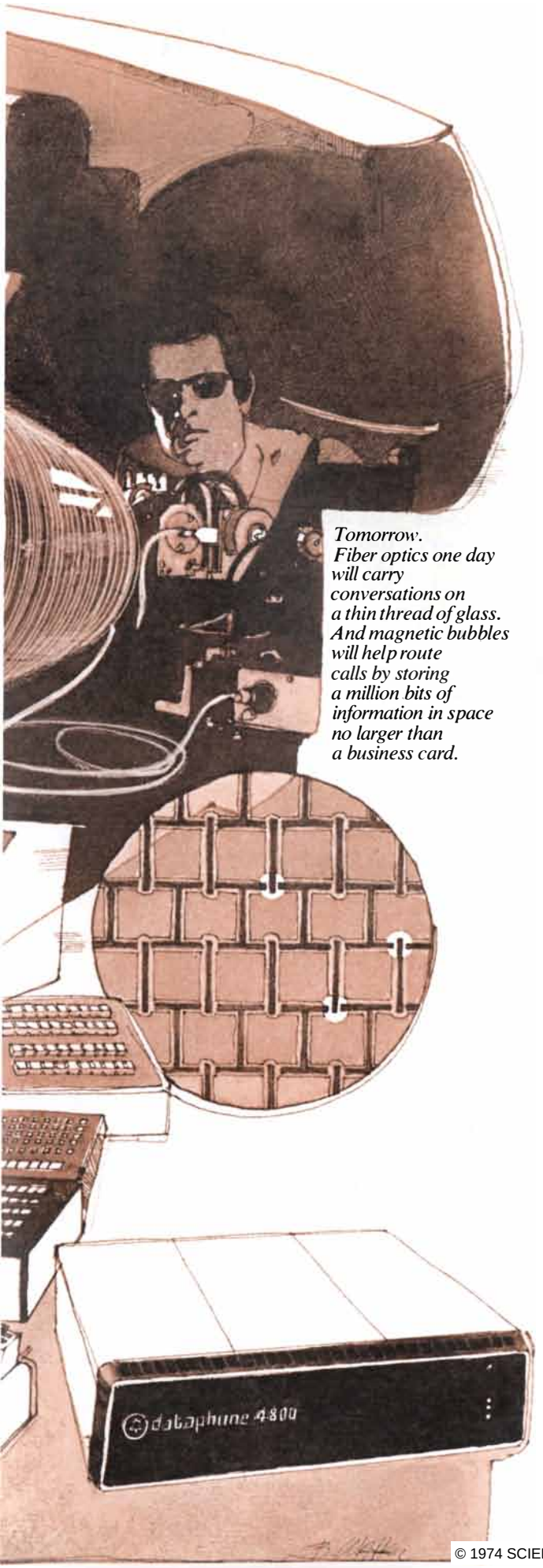

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THE CORTEX OF THE CEREBELLUM

In this part of the brain the pattern of connections between nerve cells has been determined in detail. The pattern is now understood well enough to relate it to the function of the neuronal networks

by Rodolfo R. Llinás

In the study of the brain a perennial goal is to infer function from structure, to relate the behavior of an animal to the form and organization of the cells in its central nervous system. At the highest level this task can be equated with the tantalizing problem of identifying the mind with the brain, a problem whose solution may well elude us for some time to come. On a more modest scale the operation of certain limited regions of the brain can already be interpreted in terms of cellular anatomy. For example, the sensory nerve circuits associated with the retina of the eye and the olfactory organs of the nasal cavity have been traced in detail, and our understanding of these circuits has helped to reveal how visual and olfactory information is processed.

The region of the brain where the correlation of anatomy with function has been determined with the greatest success is the cortex, or outer sheath, of the cerebellum. The cells of this structure have been classified according to their form and their position and orientation in the tissue. The properties of each kind of cell, and in particular their response to stimulation, have been investigated. Perhaps most important, a complete "wiring diagram" of the cerebellar nerve circuit has been drawn, showing how the several types of cells are interconnected. From this knowledge of the individual cell and of the pattern of connections between cells one can begin to predict the behavior of the system as a whole.

Of course, our knowledge of the cerebellum is far from complete. To begin with, a comprehensive explanation of the cerebellum would require an equally comprehensive understanding of other parts of the brain with which the cerebellum communicates; some of those areas remain quite mysterious. Furthermore, our present model of the cerebellum is best suited to describing what happens when a single nerve impulse enters the cortex, and it must be somewhat vague in specifying the effect of a complex pattern of impulses. The model is valuable nevertheless; at the least it offers evidence that the functioning of the brain can be explained simply as the sum of the activities of its component cells, that in the final analysis all mental activity consists of known kinds of interactions between known kinds of nerve cells.

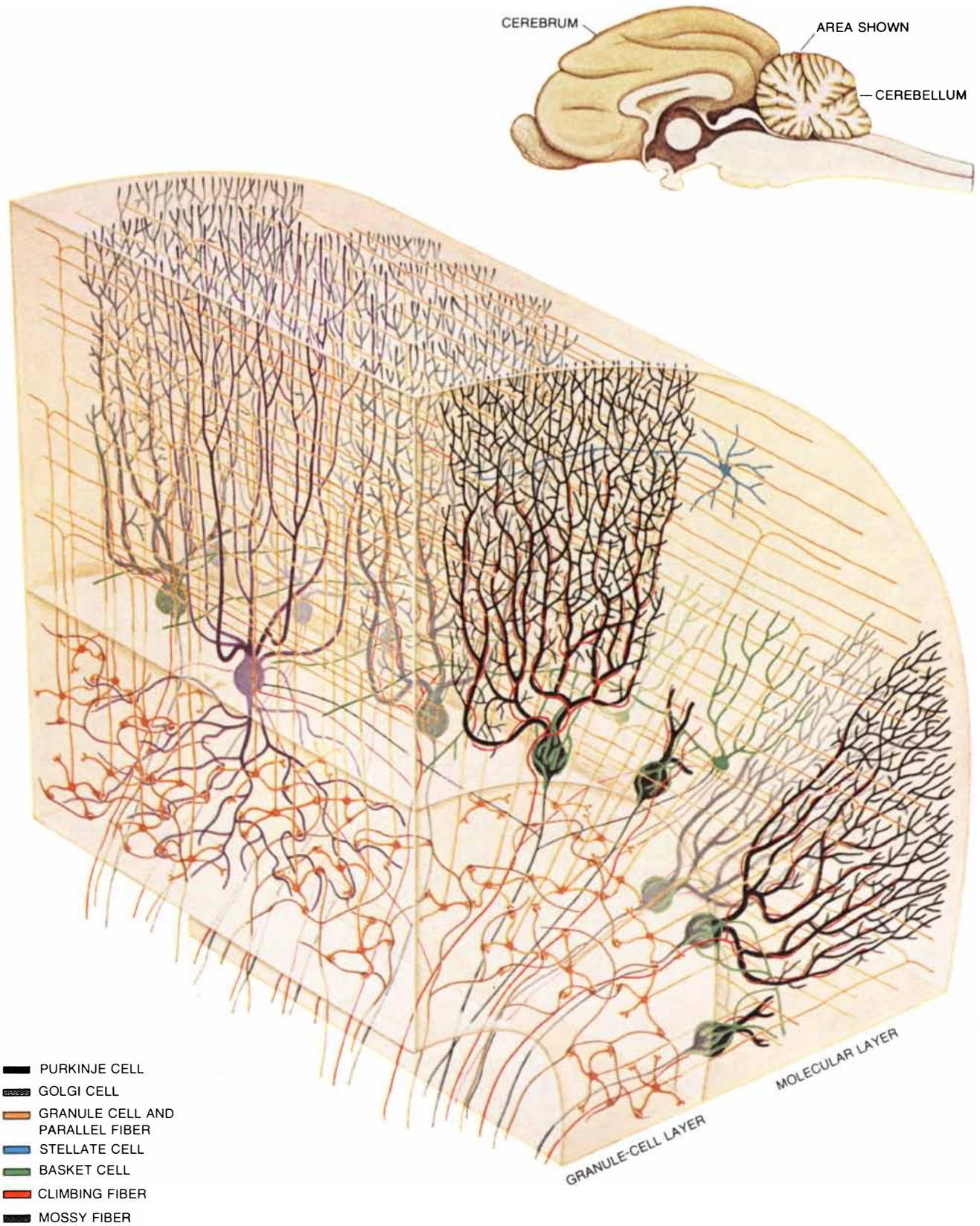
Anatomy of the Cerebellum

The cerebellum lies at the back of the skull behind the brain stem and under the great hemispheres of the cerebrum. Its name is a Latin diminutive of "cerebrum" and means simply "lesser brain." Superficially that is an adequate description of the cerebellum: it is much smaller than the cerebrum but shares certain morphological features with it. As in the cerebrum, the highest functions in the cerebellum are confined to the thin layer of gray matter that makes up the cortex and, as in the cerebrum, this layer is elaborately folded and wrinkled to increase its area. The folds are in fact much deeper and more closely spaced than those of the cerebral cortex. If the cerebellum is split down the middle, the folds form a pattern that resembles a tree, which medieval anatomists termed the *arbor vitae,* or tree of life [*see illustrations on page* 59].

Both the structure and the function of the cerebellum have been known, at least in terms of broad principles, since the end of the 19th century. The challenge to modern investigators has been in combining the two kinds of data and discovering how a particular structure generates the observed behavior.

The fundamentals of cerebellar anatomy were established in 1888 by Santiago Ramón y Cajal of Spain. He employed a staining technique that had been developed in 1873 by Camillo Golgi of Italy, in which the tissue is impregnated with salts of silver, coloring some of the nerve cells deep brown or black. By studying many stained sections of tissue Ramón y Cajal identified the principal neurons, or nerve cells, of the cerebellar cortex and described their arrangement in space. The arrangement itself is remarkable: some elements of the system are arrayed at right angles to others with extraordinary precision and delicacy. Finally, Ramón y Cajal determined the nature of the connections between the neurons and recognized in them a stereotyped pattern, repeated throughout the cortex. The essential accuracy of his observations has been repeatedly confirmed, and the neuronal circuit he described has been found to be a universal feature of the cerebellum from the most primitive vertebrates to the most advanced.

The first reliable clue to the function of the cerebellum was provided by the Italian physiologist Luigi Luciani, who discovered that experimental animals deprived of a cerebellum suffer disturbances of coordination and equilibrium. Other investigators subsequently demonstrated that the cerebellum communicates with both the motor centers of the cerebrum and the proprioceptive organs of the body, the nerves that sense the relative position and tension of the muscles. By the end of the 19th century the English physiologist Charles Sherrington was able to conclude that the cerebellum coordinates the movements of the muscles but does not initiate them. Although



ARCHITECTURE OF THE CORTEX of the cerebellum is diagrammed for a section of tissue from the brain of a cat. The location of the tissue section is indicated in the drawing at top right; the same array of cells is repeated throughout the cortex. Each cell type is identified by color in the key at bottom left. The cortex is organized around the Purkinje cells, whose somas, or cell bodies, define the border between the superficial molecular layer and the deeper granule-cell layer. In the molecular layer are the Purkinje-cell dendrites, which are arrayed in flattened networks like pressed leaves, and the parallel fibers, which pass through the dendrites perpendicularly. This layer also contains the stellate cells and the basket cells, which have similarly flattened arrays of dendrites. In the deeper layer are the granule cells, which give rise to the parallel fibers, and the Golgi cells, which are characterized by a cylindrical dendritic array. Input to the cortex is through the climbing fibers and mossy fibers; output is through the axons of Purkinje cells.

Sherrington's formulation can no longer be accepted entirely, it has been refined rather than refuted [see "The Cerebellum," by Ray S. Snider; SCIENTIFIC AMERICAN, August, 1958].

The Cerebellar Neurons

One reason the cerebellum is so well understood today is that its organization is much simpler than that of most other parts of the brain. The basic circuit of the cortex—with few modifications the circuit described by Ramón y Cajal—involves just seven nerve elements. Two of them conduct nerve impulses into the cortex; they are called the climbing fibers and the mossy fibers. Another serves as the sole output of the system; it is the Purkinje-cell axon. The four remaining nerve elements are the granule cells, the Golgi cells, the basket cells and the stellate cells; they are entirely indigenous to the cerebellar cortex and run short distances between the other cells. The input terminals are often referred to as afferent fibers, the output cells as efferent neurons and the cells that serve as intermediaries as interneurons [*see illustration below*].

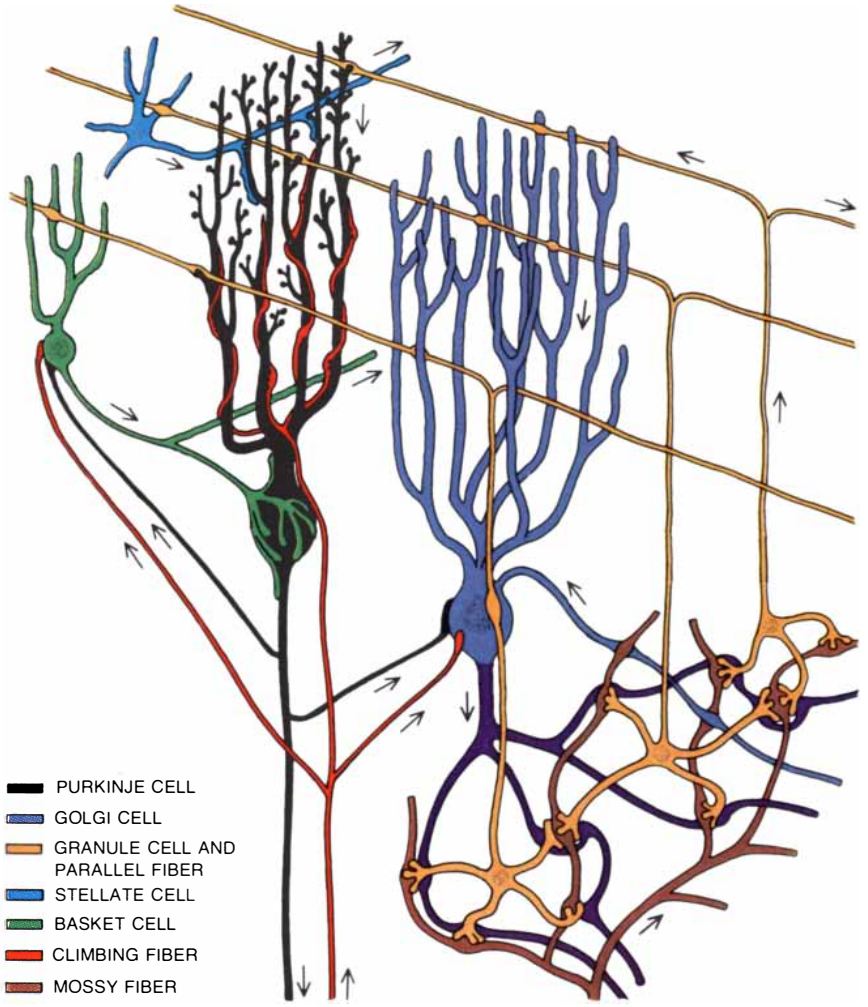
The discovery of a third afferent system, in addition to the climbing fibers and the mossy fibers, has recently been reported by F. E. Bloom and his colleagues at Saint Elizabeths Hospital in Washington. It consists of fibers arising from a structure in the brain stem called the locus ceruleus. Because it is not yet clear how this system is related to the other functions of the cerebellum it will not be considered further here.

Neurons are diverse in form, but they all have certain structures in common. Each has a soma, or cell body, which contains the nucleus and usually a major portion of the cytoplasm as well. Extending from the soma are the dendrites (from the Greek for "tree"), which often branch repeatedly, and the axon, which can be quite long and may or may not branch. For the most part dendrites conduct nerve impulses toward the body of the cell and the axon conducts impulses away from it. The junction where the axon of one cell meets a dendrite of another is a synapse.

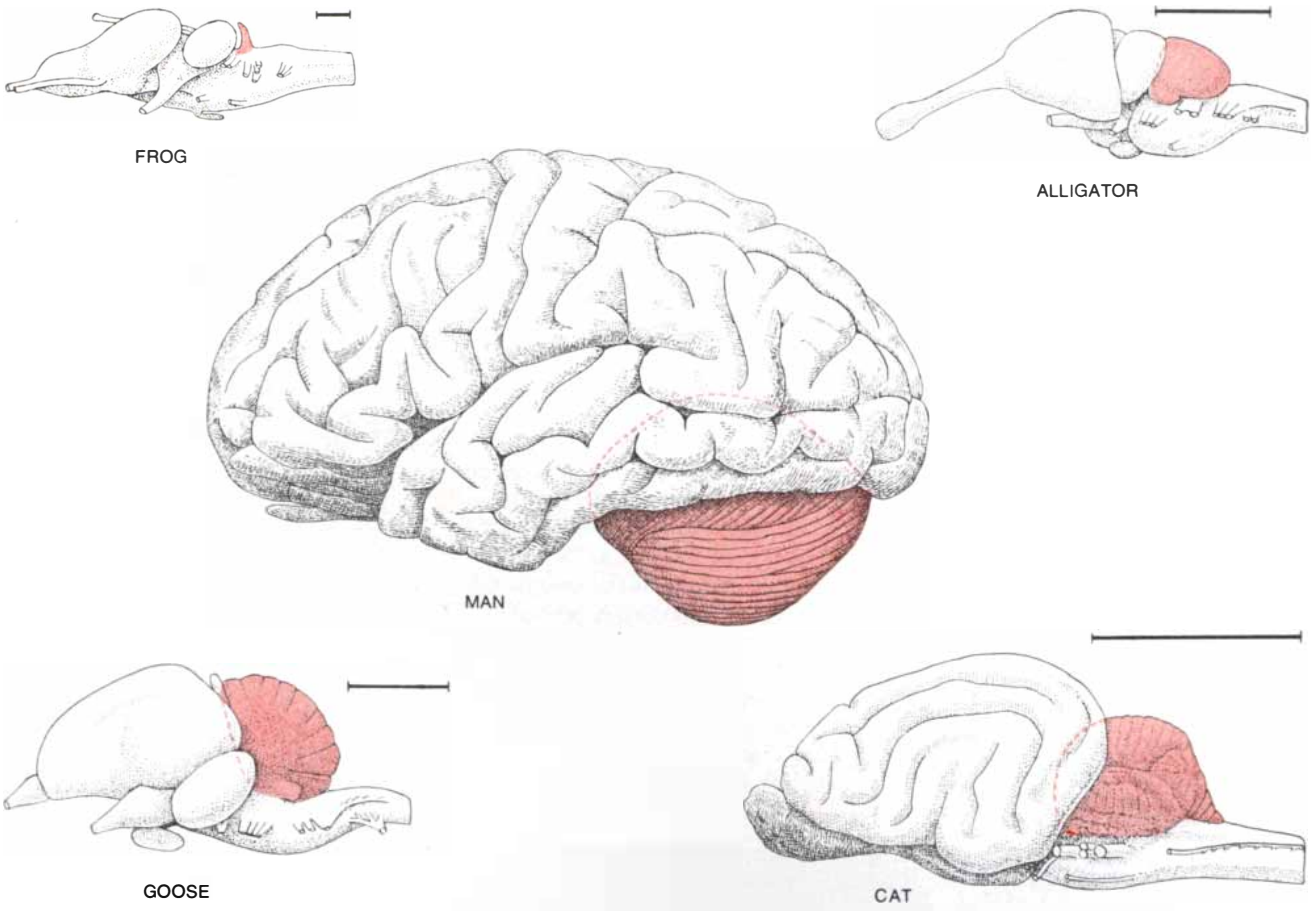
When a nerve impulse reaches the terminal point of the axon, it provokes the release of a transmitter substance, which passes across the synapse and alters the membrane of the dendrite of the next cell in the neural pathway, changing its permeability to certain ions. The resulting flow of ions across the membrane generates a small electric current, which propagates as a local electrical disturbance of the membrane down the dendrite to the soma. If the stimulating neuron is excitatory, and if the stimulation exceeds a threshold, the receiving cell will "fire" and the impulse will be conveyed through the axon to the next synapse. If the first cell is inhibitory, the probability that the receiving cell will fire is reduced.

The Purkinje cells were among the first neurons recognized in the nervous system; they are named for Johannes E. Purkinje, the Czech physiologist who described them in 1837. They are among the most complex of all neurons. Each has a large and extensive dendritic apparatus referring impulses to a bulblike soma, and a long, slender axon [*see illustration on page 60*]. The dendrites of a typical human Purkinje cell may form as many as 100,000 synapses with afferent fibers, more than those of any other cell in the central nervous system.

The Purkinje cells are the pivotal element in the neuronal network of the cerebellar cortex. They are found throughout the cortex, their cell bodies constituting a continuous sheath called the Purkinje-cell layer. The dendrites extend densely above the Purkinje-cell layer, toward the boundary of the cortex; this region is called the molecular layer. The axons extend in the opposite direction, into the deeper portion of the cortex called the granule-cell layer. The axons, in fact, penetrate far beyond this



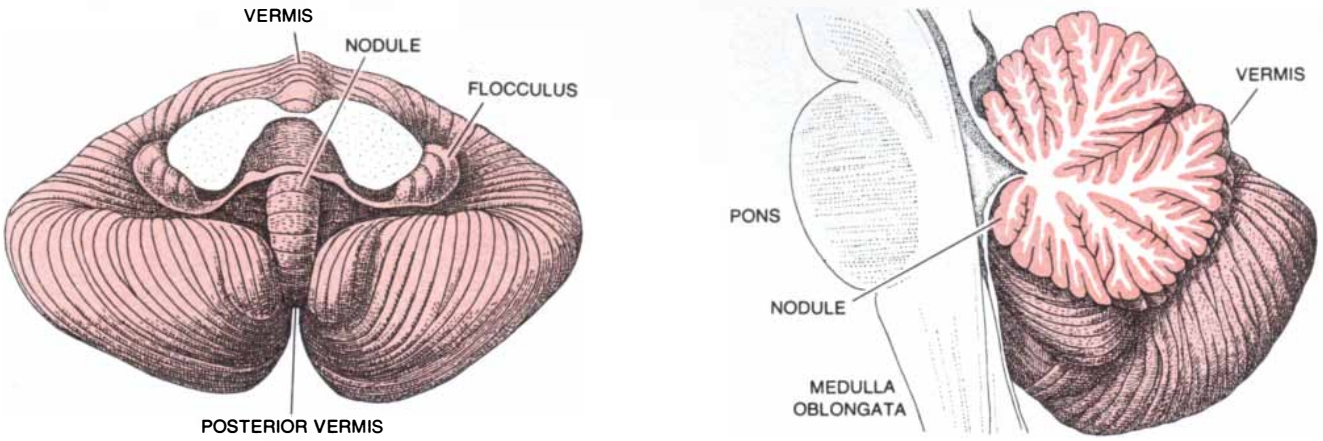
INTERCONNECTION OF NEURONS in the cortex follows an elaborate but stereotyped pattern. Each Purkinje cell is associated with a single climbing fiber and forms many synaptic junctions with it. The climbing fiber also branches to the basket cells and Golgi cells. Mossy fibers come in contact with the terminal "claws" of granule-cell dendrites in a structure called a cerebellar glomerulus. The axons of the granule cells ascend to the molecular layer, where they bifurcate to form parallel fibers. Each parallel fiber comes in contact with many Purkinje cells, but usually it forms only one synapse with each cell. The stellate cells connect the parallel fibers with the dendrites of the Purkinje cell, the basket cells mainly with the Purkinje-cell soma. Most Golgi-cell dendrites form junctions with the parallel fibers but some join the mossy fibers; Golgi-cell axons terminate at the cerebellar glomeruli. Cells are identified in the key at lower left; arrows indicate direction of nerve conduction.



EVOLUTION OF THE CEREBELLUM suggests that its function has become more important during the span of vertebrate history. From the amphibians through the reptiles and birds to the mammals it has become progressively larger, both in actual mass and in proportion to overall brain size. It has also become more convoluted, providing a greater area of cortex. In man it is a large and deeply fissured structure. The cerebellums are shown in color; the scale in relation to the human brain is indicated by horizontal bars.

region; they pass out of the cortex entirely, through the white matter in the core of the cerebellum, and eventually reach isolated lumps of gray matter called cerebellar nuclei. The nuclei are also supplied with side branches of the climbing-fiber and mossy-fiber input systems, so that they receive all the information going to the cortex. In the nuclei the incoming messages are blended with those returning from the cortex and are relayed to other parts of the brain and down the spinal cord to the rest of the body.

The dendrites of the Purkinje cells have an unusual arrangement that is at once the most conspicuous structural element in the cerebellar cortex and an important clue to its functioning. The entire mass of tangled, repeatedly bifurcating branches is confined to a single



HUMAN CEREBELLUM consists of two hemispheres separated by a narrow girdle, the vermis. At left it is viewed from below; the brain stem has been removed to reveal the vermis, flocculus and nodule, which are involved in eye movement, among other functions. At right the cerebellum is sectioned through the vermis. The pattern of cortical folds is called the *arbor vitae* ("tree of life").

plane, as if it had been flattened like a pressed leaf. Moreover, the planes of all the dendrites in a given region are parallel, so that the dendritic arrays of the cells stack up in neat ranks; adjacent cells in a single plane form equally neat, but overlapping, files.

To a large extent this orderly array determines the nature and number of contacts made with other kinds of cells. As has been pointed out by Clement A. Fox of the Wayne State University School of Medicine, the dendrites are organized like a net to "catch" as many incoming signals as possible. Fibers running perpendicular to the plane of the dendrites will intersect a great many Purkinje cells, although they will touch each cell only once or at most a few times. Fibers oriented in this way do in fact constitute one of the afferent systems in the cortex. (Geometric arrays similar to the arrangement of the Purkinje-cell dendrites appear elsewhere in biology where a large surface area must be fitted into a small volume; an example is the antennae of moths.)

The Purkinje cell represents the output system of the cerebellar cortex, but it is not a mere transmitter or repeater of information originating elsewhere. It is part of an indivisible system of neurons whose activity is determined entirely by the way in which the other neurons are connected with the Purkinje cells and with one another.

The Climbing Fiber

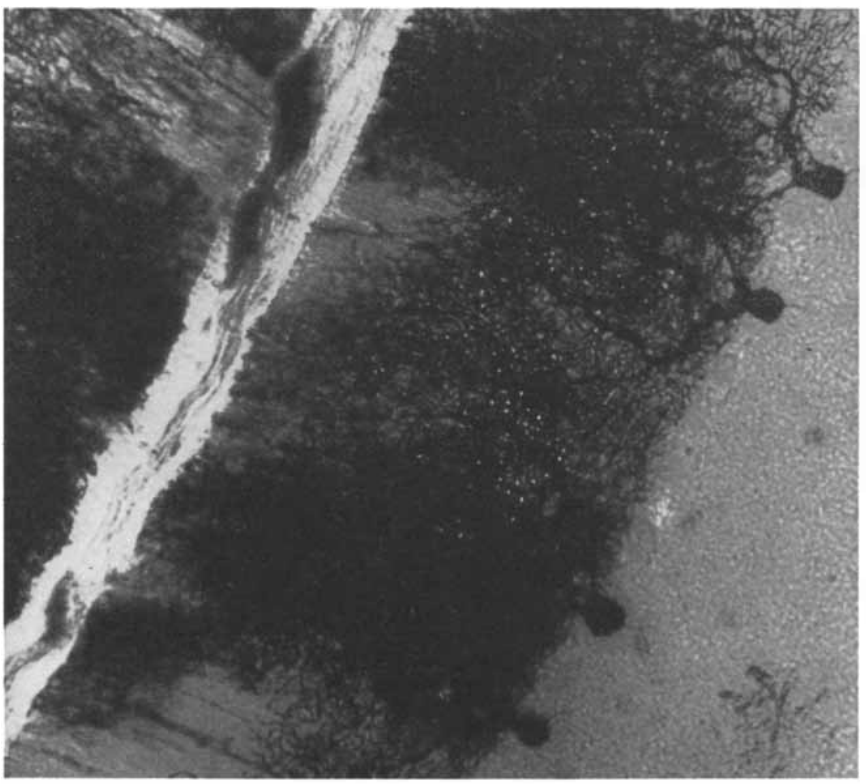
The climbing fibers and the mossy fibers, the two afferent systems that ultimately direct impulses to the Purkinje cells, are distributed throughout the cerebellar cortex in a more or less orderly array. Their presence in all parts of the cortex was demonstrated by Jan Jansen and Alf Brodal and their colleagues at the Anatomical Institute at Oslo in Norway. These workers also showed that the two systems are apparently present in all members of the vertebrate subphylum. The systems are radically different; in some properties they represent opposite extremes among the neurons of the central nervous system.

The climbing fiber is virtually a private line to a given Purkinje cell. It begins outside the cerebellum in other regions of the brain such as the inferior olive, a compact collection of nerve cells alongside the medulla oblongata. The long, ramified axons of these cells extend into the cerebellar nuclei and cortex. In embryonic development the climbing fiber is the first afferent system to reach the Purkinje cell, and once it has "mated" with its particular cell it generally enforces monogamy. The union takes place early in the development of the cerebellum, and the formation of a junction with one climbing fiber apparently discourages others from attaching themselves to the same cell. As the Purkinje cell develops its net of dendrites the climbing fiber follows, matching the intricacy of the dendrites like a vine growing on the trunk and branches of a large tree. This behavior is the root of its name.

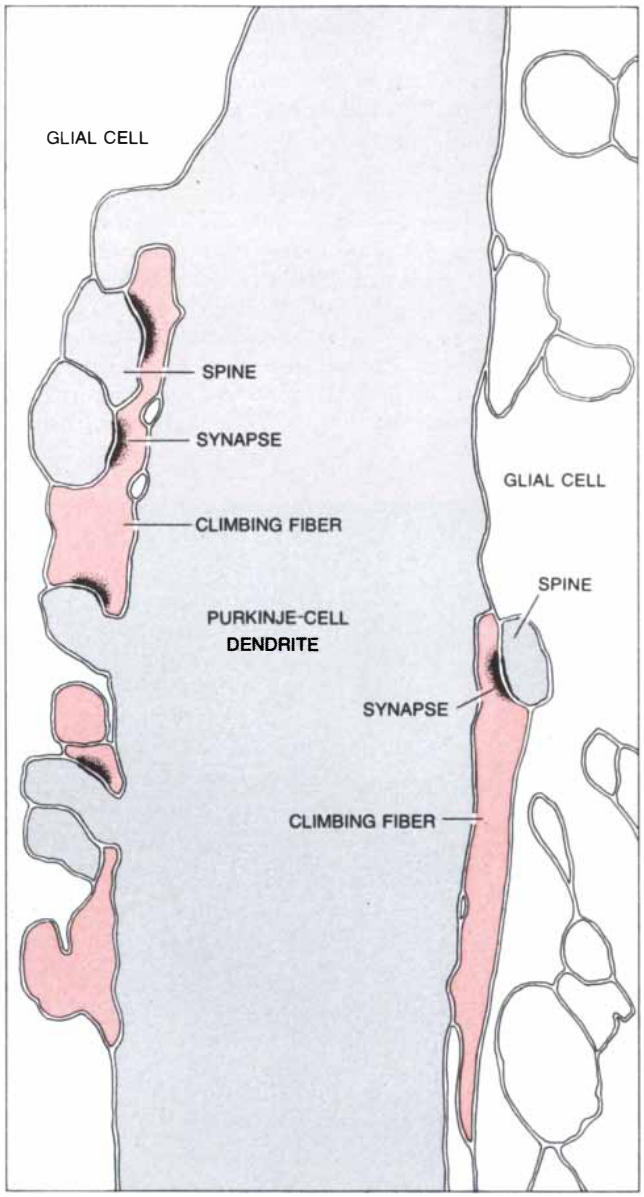
It was once believed the climbing fiber formed synapses with the smooth surface of the Purkinje-cell dendrites. It has now been demonstrated by Luis M. H. Larramendi and his colleagues at the University of Chicago, however, that the two cells are actually in contact only where small spines protrude in groups from the surface of the Purkinje-cell dendrite [*see illustrations on opposite page*]. There are many such spines on any one Purkinje cell. Dean E. Hillman of the University of Iowa has estimated that a Purkinje cell and its climbing fiber are probably in synaptic contact at about 300 points, which is a large number of junctions to be established between a cell and a single afferent fiber.

The action of the climbing fiber on the Purkinje cell was described in 1964 by John C. Eccles, K. Sasaki and me. Working at the Australian National University in Canberra, we found that stimulating a climbing fiber produced an exceedingly powerful excitation of the corresponding Purkinje cell. The Purkinje cell responded with a prolonged burst of high-frequency action potentials, the electrically recorded evidence that a nerve cell is discharging. The intensity of the response was not unexpected, considering the large number of synapses connecting the cells. The excitation was capable of overriding any ongoing activity in the Purkinje cell.

Recordings made with electrodes implanted in Purkinje cells showed that the action potential arises very quickly, then declines slowly and irregularly [*see illustration on page 62*]. The recorded pattern represents the firing of the cell body of the neuron and the generation of



PURKINJE CELLS sprout a dense network of overlapping dendrites, all confined to a single plane and extending above the cell bodies through the molecular layer to the surface of the cortex. In this section of tissue from the brain of a monkey the surface of the cortex is the bright diagonal strip; it is inside a fold and abuts another part of the cortex with its own Purkinje cells. The parallel fibers are not visible; they run perpendicular to the plane of the page. The Purkinje-cell axons are the small fibers extending from the cell bodies toward deeper strata. The tissue was prepared by staining it with silver salts; the photomicrograph was made by Clement A. Fox of the Wayne State University School of Medicine.



CLIMBING FIBER forms numerous synaptic junctions with a Purkinje-cell dendrite through spines that protrude in clusters from the surface of the dendrite. The structures visible in the electron micrograph at left are diagrammed and identified in the drawing at right. The several regions labeled "Climbing fiber" are segments of a single fiber that is wrapped around the dendrite. Nerve impulses are transmitted from the climbing fiber to the dendrite. Glial cells surrounding the synapse are not neurons but serve as a matrix in which the nerve cells are embedded. The photomicrograph was made by Dean E. Hillman of the University of Iowa.

many lesser action potentials in the dendrites as the cell is showered with synaptic transmitters released at many points by the climbing fiber. Because the response is provoked by a single impulse in a single afferent fiber, it is an all-or-nothing phenomenon, that is, it is present in full force or is absent altogether.

The Mossy Fiber

Whereas the climbing fiber generates many connections to a single Purkinje cell, the mossy fiber ultimately excites many Purkinje cells, but through only a few contacts with each of them. Among all the neurons of the central nervous system, the mossy fiber stimulates one of the largest numbers of cells to be activated by a single efferent fiber.

The mossy fibers do not terminate directly on Purkinje cells, as the climbing fibers do, but on small interneurons, the granule cells, which lie immediately under the Purkinje-cell layer. The granule cells serve as intermediaries, greatly increasing the number of Purkinje cells stimulated by a single afferent fiber.

One reason the granule cells can intersect so many Purkinje cells is that the granule cells are themselves exceedingly numerous. Valentino Braitenberg of the Max Planck Institute for Biological Cybernetics in Tübingen has calculated that the number of granule cells in the human cerebellar cortex may be 10 times greater than the number of cells previously believed to make up the entire brain. Sanford L. Palay of the Harvard Medical School has commented: "Of the 10^{10} cells in the brain, 10^{11} are in the granular layer of the cerebellar cortex!"

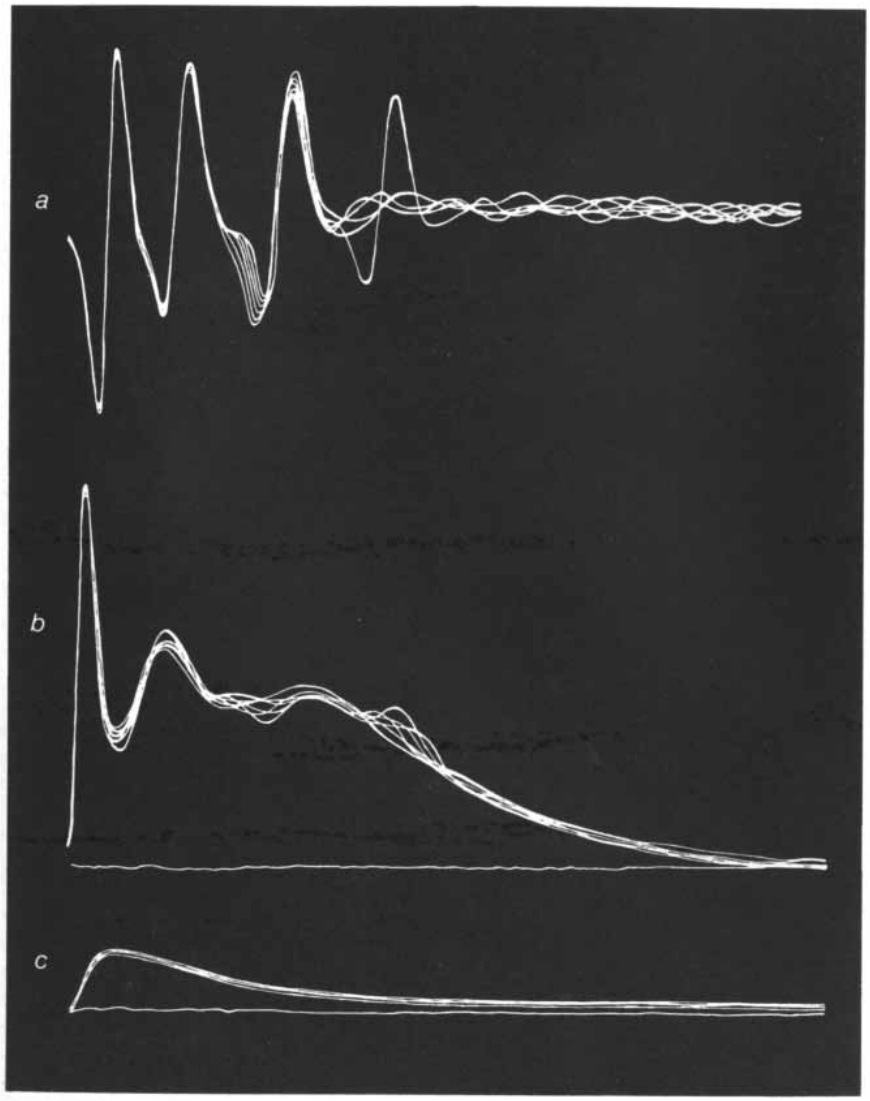
The axon of the granule cell projects upward, past the Purkinje-cell layer and into the molecular layer. There it splits, the two branches taking diametrically opposite directions, so that the axon assumes the form of a capital *T*. Fibers

representing the horizontal portion of the *T* occupy all levels of the molecular layer. The orientation of these fibers is precisely determined: they are all parallel to one another (for that reason they are called parallel fibers), and they are perpendicular to the planes of the flattened Purkinje-cell dendrites [*see illustration on page 57*]. The arrangement of the cells is thus somewhat like an array of telephone poles (the Purkinje cells) strung with many telephone wires (the parallel fibers). The actual conformation is complicated by the curvature of the folds in the cortex.

The parallel fibers come in contact with the Purkinje cells through spines that emerge in enormous numbers from the terminal regions of the Purkinje-cell dendrites, regions called spiny branchlets [*see illustrations on opposite page*]. The junction is formed between the point of a spine and a globular expansion of the parallel fiber; the geometry of the synapse may resemble that of a ball joint, in which the spine penetrates the swollen part of the fiber.

Generally a parallel fiber comes in contact with a given Purkinje cell only once or (rarely) twice; nevertheless, most of the inputs to the Purkinje cells are through the parallel fibers. As I have noted, a single human Purkinje cell can receive as many as 100,000 parallel fibers (compared with a single climbing fiber).

Eccles, Sasaki and I have studied the effects of stimulating the mossy fibers. Like the climbing fiber, the mossy fiber is excitatory, and so is the granule cell it stimulates. Both afferent systems can therefore excite activity in the cerebellar cortex. The influence of the mossy fibers, however, is for obvious reasons diffuse and complex, in contrast to the sharply focused effect of the climbing fiber.



RESPONSE OF A PURKINJE CELL to stimulation by a climbing fiber is recorded electrically. Action potentials (voltages developed across the cell membrane) are measured from outside the cell (*a*) and from inside it (*b*). The response is strong and consistent; several repetitions are superposed here, revealing only small variations. It is an all-or-nothing response; if the climbing fiber fails to fire, only a straight line is recorded. Climbing-fiber stimulation provokes the firing of the Purkinje cell by depolarizing the cell membrane; the phenomenon can be recorded in isolation (*c*) in a damaged cell. The time span of the recordings is about 20 milliseconds. The voltages are not drawn to the same scale; those measured inside the cell (*b, c*) are actually many times larger than those measured outside (*a*).

The Interneurons

Embedded in the matrix of the cerebellar circuitry are two sets of interneurons that, unlike the granule cells, have only short axons. One set is located in the molecular layer and consists of basket cells and stellate cells; the other is in the granule-cell layer and is represented by Golgi cells.

The basket and stellate cells are similar and can be considered members of a single class. Both receive impulses from the parallel fibers and act, through their axons, on Purkinje cells. The principal difference between the two types is that the basket cell establishes synaptic junctions with the Purkinje cell in the lower dendrites and on the soma, whereas the stellate cell is more or less confined to the dendrites. Perhaps the most significant anatomical observation on the basket and stellate cells pertains to the spatial distribution of their axons. They are perpendicular to the parallel fibers and are also perpendicular to the axis of the Purkinje cells. The network of cells in the molecular layer thus consists of three basic types of cell process all of which are mutually perpendicular.

In the granule-cell layer the remaining interneuron, the Golgi cell, also receives impulses from the parallel fibers, but its dendrites form synapses directly with the mossy fibers as well. The Golgi cells are components of a specialized synaptic linkage known as the cerebellar glomerulus, which is the basic functional unit of the granule-cell layer. It consists of a bulge or swelling in a mossy fiber, surrounded by the dendrites of granule cells, which in turn are surrounded by the axons of Golgi cells [*see illustrations on page 64*].

All three kinds of interneuron have been demonstrated to be inhibitory. The inhibitory effect of the basket cell on the soma of the Purkinje cell was initially shown by P. Andersen, Eccles and P. E.

Voorhoeve at the Australian National University in 1963; the inhibition of Purkinje-cell dendrites by stellate cells and the inhibition of granule cells by Golgi cells were demonstrated soon afterward by Eccles, Sasaki and me.

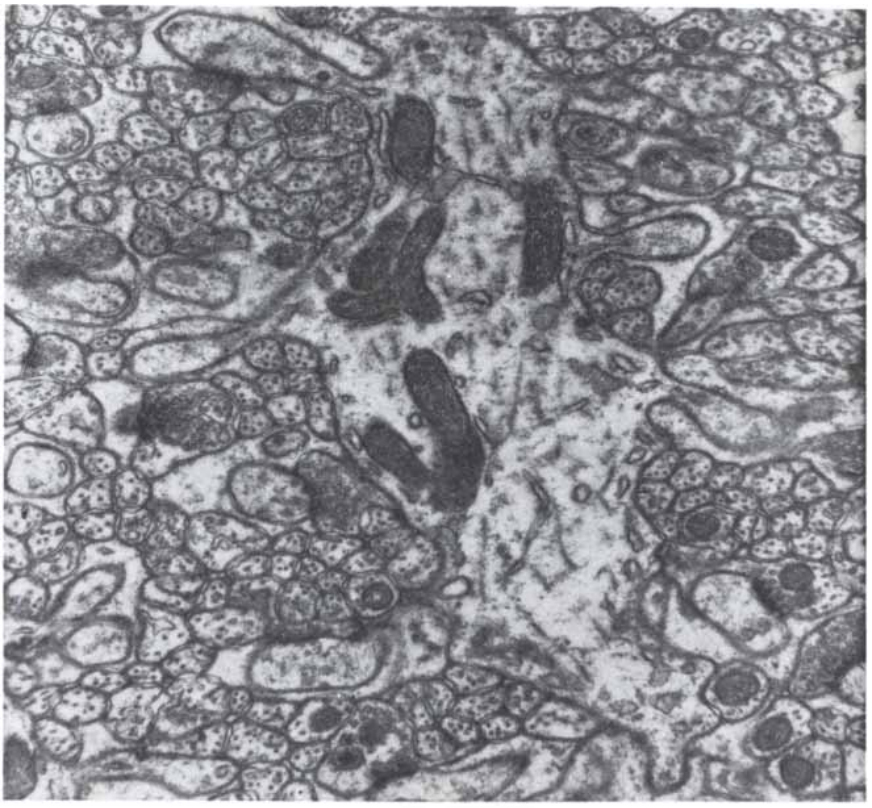
Organization of the Neurons

As we have seen, the activation of the cerebellar cortex through the climbing-fiber system is relatively straightforward: the stimulation of a single climbing fiber elicits a powerful response from a single Purkinje cell. The sequence of events that follows on the stimulation of a mossy fiber is not only more complicated but also inherently less predictable.

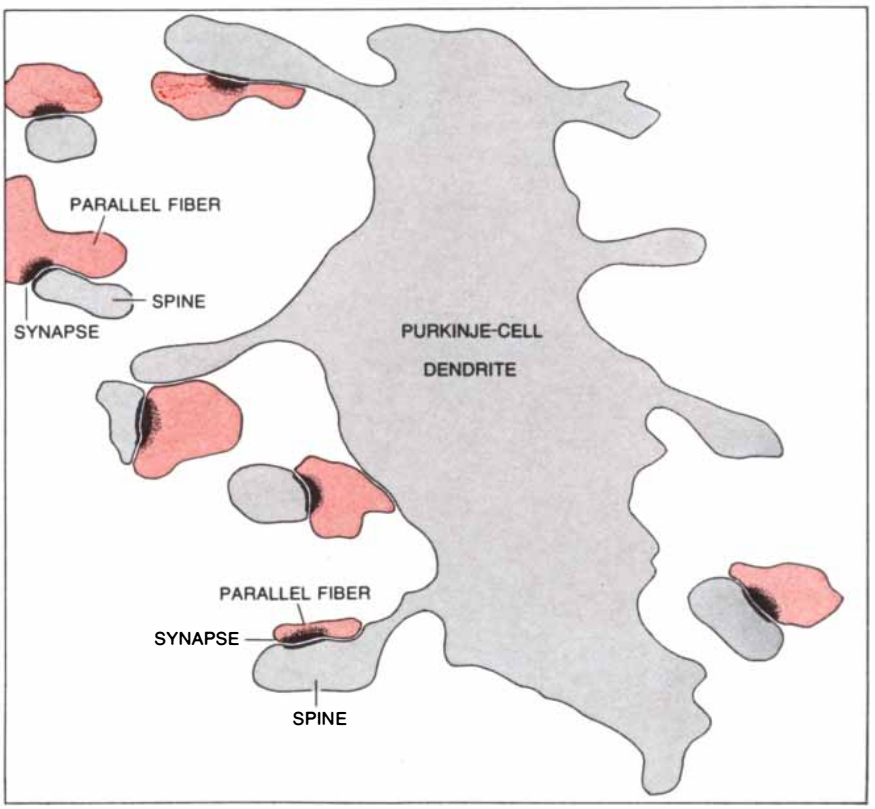
The initial sequence of events was first suggested by János Szentágothai of the Semmelweis University School of Medicine in Budapest: the stimulation of a small bunch of mossy fibers activates, through the granule cells and their parallel fibers, an extensive array of Purkinje cells and all three types of inhibitory interneuron. Subsequent interactions of the neurons tend to limit the extent and duration of the response. The activation of Purkinje cells through the parallel fibers is soon inhibited by the basket cells and the stellate cells, which are activated by the same parallel fibers. Because the axons of the basket and stellate cells run at right angles to the parallel fibers, the inhibition is not confined to the activated Purkinje cells; those on each side of the beam or column of stimulated Purkinje cells are also subject to strong inhibition. The effect of the inhibitory neurons is therefore to sharpen the boundary and increase the contrast between those cells that have been activated and those that have not.

At the same time the parallel fibers and the mossy fibers have activated the Golgi cells at the granule-cell level. The Golgi cells exert their inhibitory effect on the granule cells and thereby quench any further activity in the parallel fibers. This mechanism is one of negative feedback: through the Golgi cell the parallel fiber extinguishes its own stimulus. The net result of these interactions is the brief firing of a relatively large but sharply defined population of Purkinje cells.

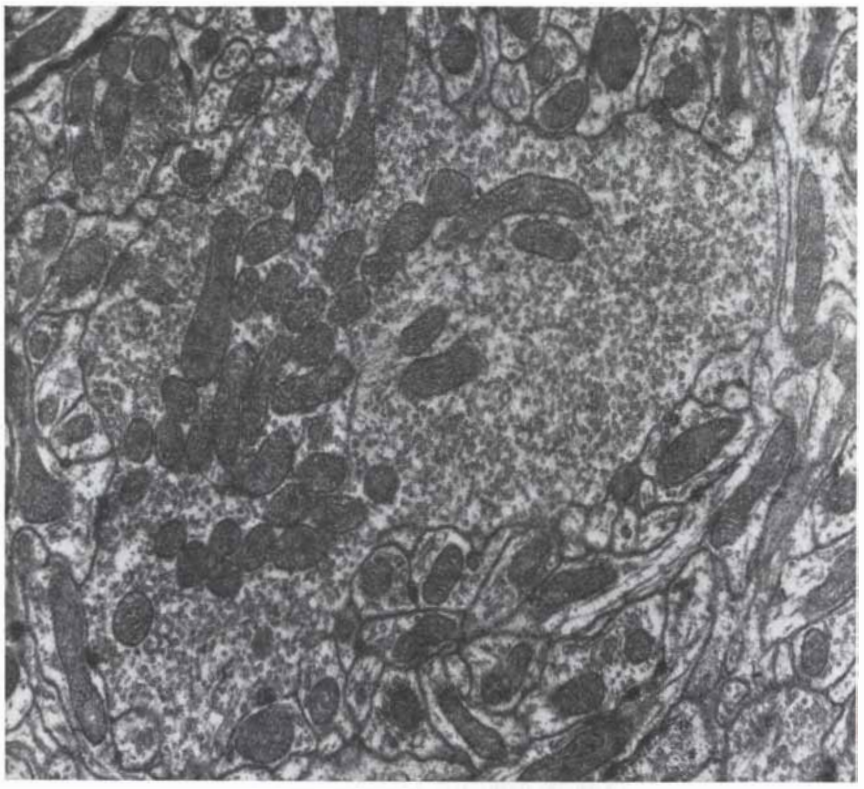
At about the time the functional properties of these neuronal circuits were being elucidated an observation made by Masao Ito and his colleagues at the University of Tokyo changed our perspective on the behavior of the entire system. Ito and his co-workers discovered that the Purkinje cell is itself an inhibitory neuron. The entire output of the elabo-



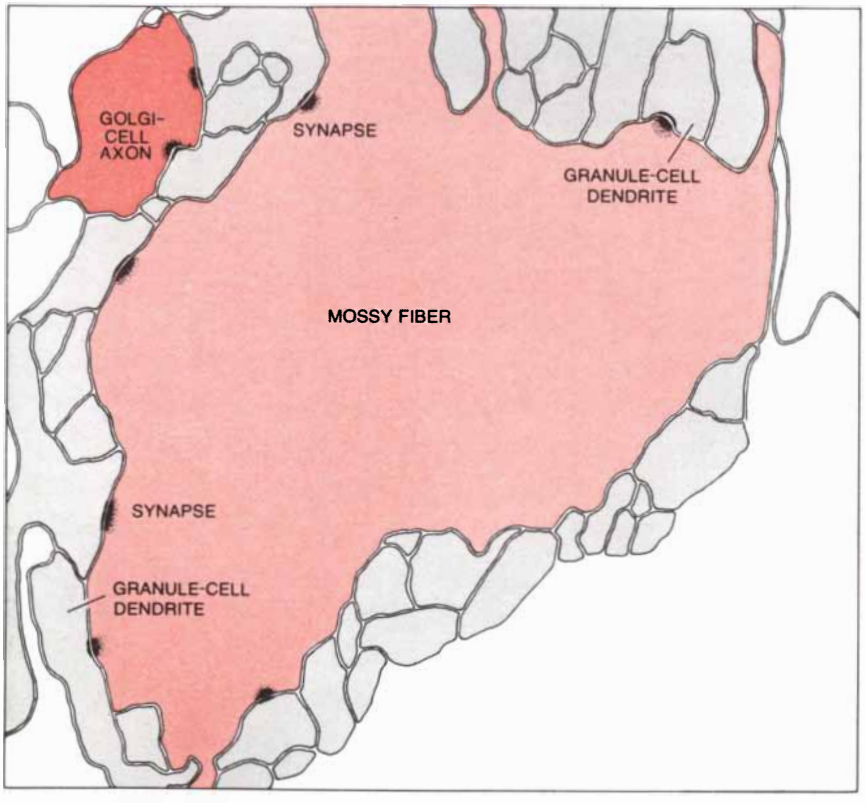
PARALLEL FIBERS attach to a Purkinje-cell dendrite in an electron micrograph made by Hillman. The dendrite is sectioned longitudinally; the parallel fibers are cut transversely.



SYNAPSES between parallel fibers and the Purkinje-cell dendrite are indicated in a diagram identifying the elements of the electron micrograph at the top of the page. The region of the dendrite shown is called a spiny branchlet; the spines form junctions with the parallel fibers. Each parallel fiber ordinarily makes only one contact with a given Purkinje cell.



CEREBELLAR GLOMERULUS is seen in cross section in another electron micrograph made by Hillman. The cells of the mammalian tissue are identified in the diagram below.



MOSSY FIBER forms synapses with the terminal dendrites of many granule cells in the cerebellar glomerulus. In addition the axons of Golgi cells make contact with the same granule-cell dendrites. The glomerulus forms on an enlarged segment of the mossy fiber.

rate neuronal network in the cerebellar cortex is therefore the organized, large-scale inhibition of other neurons in the cerebellar nuclei. Furthermore, it became evident that of the cells residing in the cortex only the granule cells are excitatory; all the rest are inhibitory. This work provided a fundamental insight into the functioning of the cortex. The firing of the nerve cells that give rise to the climbing fibers and the mossy fibers produces rapid activation of the cerebellar nuclei and through them of cerebral and spinal systems. This activity is abruptly terminated by the inhibitory signals from the cortex.

In several ways the model of the cerebellar cortex devised in these early studies was too simplistic. Although it described with some accuracy the neuronal response to an abrupt stimulus, such as an externally applied electrical potential, it was inadequate to describe the activity following the physiological stimuli constantly impinging on the cortex under ordinary circumstances. For example, the inhibitory interneurons of the molecular layer probably do not normally obliterate the activity of entire groups of Purkinje cells while allowing others to fire. It is more likely that they serve to set a threshold of excitability and thereby to regulate the dynamic range of activity in the cortex. The Golgi cell, on the other hand, is probably a central element in cerebellar organization. Through its direct contacts with the climbing fibers and the mossy fibers the Golgi cell probably "selects" what inputs reach the Purkinje-cell layer at a given time.

In spite of its limitations our study provided a foundation for constructing a theory of cerebellar function. The description of the interactions between the neuronal elements of the cortex was comprehensive and detailed, even if it was based on observations made under somewhat artificial circumstances. Furthermore, the study represented the first demonstration of a correlation between structure and function in a major lobe of the brain.

The Function of the Cerebellar Cortex

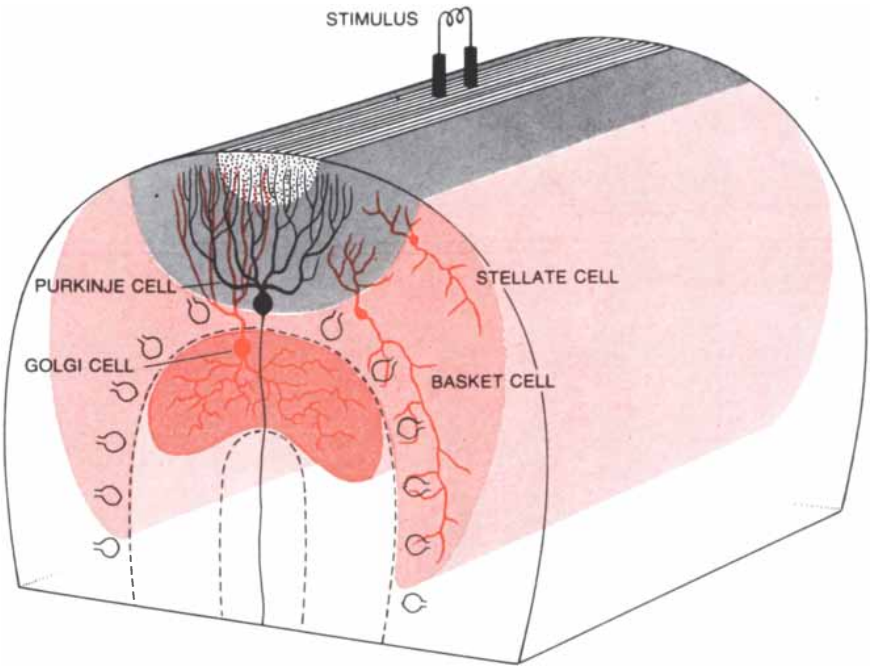
If we are finally to understand the significance of the neuronal circuits in the cerebellar cortex, we must analyze those circuits in terms of the kind of information they ordinarily receive. The techniques available for this task are necessarily less direct and less precise than dissection and staining or probing with an electrode, but they have nevertheless yielded important results. One of

the most profitable techniques has been the mapping of projections onto the cerebellum. This consists in selecting a nerve fiber of known origin or destination outside the cerebellum and determining the point at which it impinges on the cerebellar cortex.

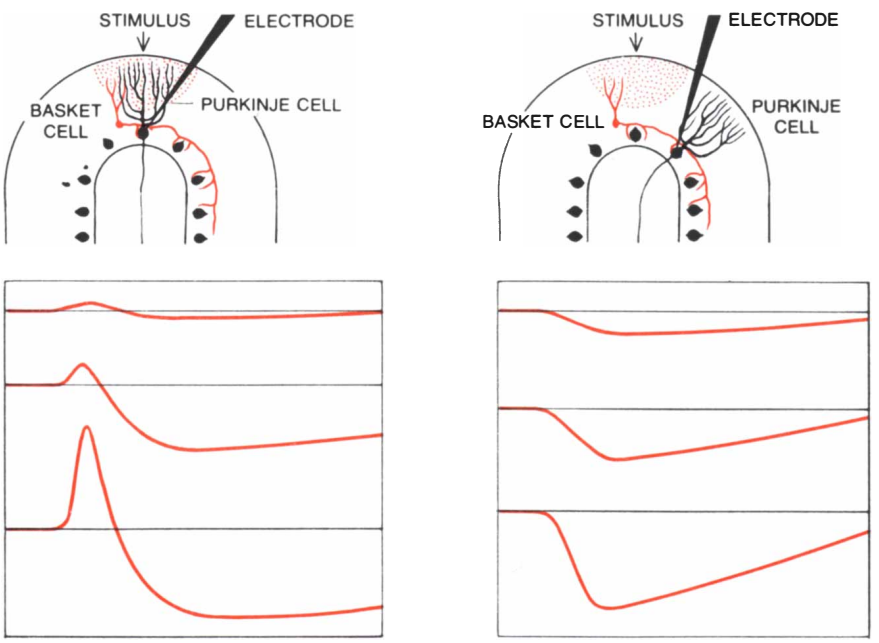
Each of the proprioceptive nerve endings in the skeletal muscles, for example, corresponds to a particular position on the surface of the cerebellum. When the sum of these positions is plotted, the result is a map such as the one that has been compiled over a period of many years by Olov Oscarsson of the University of Lund and by D. Armstrong and R. J. Harvey of the University of Bristol. By recording the projections of the climbing fibers they have discovered that these afferent cells are distributed with remarkable orderliness in the cerebellar cortex: they are organized in strips parallel to the median line and covering large areas distributed over many folds in the cortex [*see bottom illustration on next page*].

These maps confirm the earlier findings of Jan Voogd of the University of Leiden, who studied the effects of small lesions in the inferior olive, one of the principal sources of the climbing fibers. Nerve fibers radiating from a lesion usually degenerate, and Voogd found in this case that patterns of degenerating tissue on the cerebellar cortex assumed the form of long strips oriented from the front of the head to the back, that is, parallel to the median plane. His discovery suggests that the longitudinal strip is an important principle of organization in the projection of the climbing fibers onto the cerebellar cortex. The pattern has been detected in several vertebrate species.

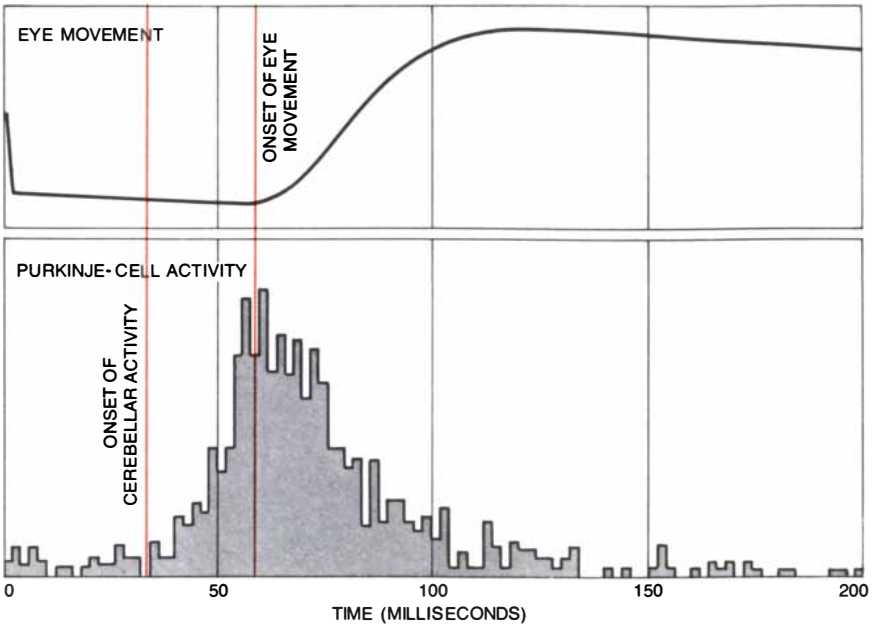
A clue to the significance of this organizational pattern has recently been provided by pharmacological studies of the cortex. The experiments were performed by Y. Lamarre and C. de Montigny of the University of Montreal and by R. A. Volkind and me at the University of Iowa. They involved a drug called harmaline, derived from the herb harmal, which causes tremors; we have shown in the cat that the effects of the drug are traceable to the activation of the inferior olive. An immediate and obvious inference is that the inferior olive, with the fibers it projects to the cerebellar nuclei and the Purkinje cells, is part of a motor command system concerned with muscular movement. There is even a reasonable basis for speculation on what kind of movements are involved. When maps derived from the proprio-



SPATIAL DISTRIBUTION of excitation in the cortex is determined largely by inhibitory neurons. When a brief electrical stimulus is applied to the surface of the cortex, a small bundle of parallel fibers (*stippled area*) is activated and excites the dendrites of all the fibers immediately under it (*gray*). The stimulated fibers excite Purkinje cells, stellate cells, basket cells and Golgi cells. The firing of the Purkinje cells constitutes the sole output of the cortex; the other neurons serve to define which Purkinje cells can fire. Because the axons of basket cells and stellate cells extend at right angles to the parallel fibers in the molecular layer, they inhibit Purkinje cells in a wide area on both sides of the excited region (*light color*). The Golgi cells generate an area of inhibition in the granule cells directly under the activated array of parallel fibers (*dark color*). Because the parallel fibers are the axons of the granule cells, inhibition by Golgi cells tends to terminate the excitation.

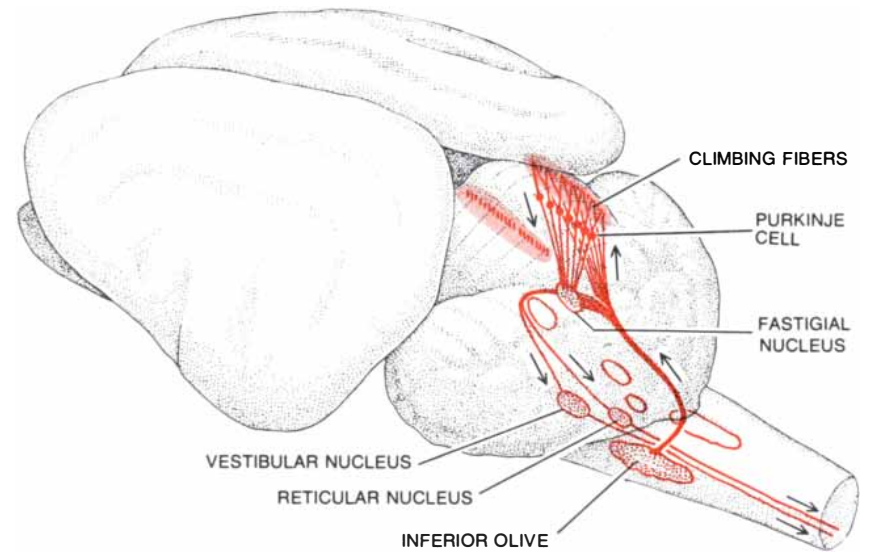


STIMULATION AND INHIBITION of Purkinje cells follow an established temporal sequence. When the response of a cell directly under the stimulated area is recorded (*left*), a brief period of activation is observed (*upward deflection*), followed by a longer period of inhibition (*downward deflection*). The activation results from the direct stimulation of the Purkinje cell by parallel fibers, the inhibition from the action of basket cells and stellate cells. The magnitude of the response varies with the intensity of the stimulation. When the response of a laterally located Purkinje cell is monitored (*right*), only the inhibition is observed, since only basket-cell axons, not stimulated parallel fibers, reach Purkinje cells.



RAPID EYE MOVEMENTS called saccades are associated with activity in the cerebellar cortex. The top graph is an averaged record of 100 saccades; the bottom graph records the activity of a single Purkinje cell during the same 100 eye movements. Purkinje-cell activity begins to increase about 25 milliseconds before the movement is initiated, which suggests that the cerebellum can coordinate or correct such movements before they are generated.

ceptive sensors are superposed on the longitudinal strips that are associated with the climbing fibers, it is found that the climbing-fiber patterns overlap the projections of several areas of the body. It is the current hypothesis, therefore, that the climbing-fiber system is concerned with synchronous movements of groups of muscles, probably involving more than one limb. There is also reason to believe it mainly influences rapid movements. The inhibition of the cerebellar nuclei by the Purkinje cells should follow very soon after the activation of the nuclei, generating a powerful but brief command signal.



PROJECTION OF CLIMBING FIBERS onto the cerebellar cortex reveals an orderly distribution. The fibers originate in the two inferior olives of the brain stem. Fibers from each olive terminate in the opposite hemisphere of the cerebellum. There they are organized in longitudinal strips covering many cortical folds. The length and orientation of these strips suggest that the climbing-fiber system participates in the regulation of movements that involve several limbs, since each strip extends across areas known to be associated with several parts of the body. Branches of the climbing fibers also reach the cerebellar nuclei (the fastigial nucleus is shown here) and are joined there by the axons of Purkinje cells from the cortex. The output of the fastigial nucleus is applied to the vestibular and reticular nuclei.

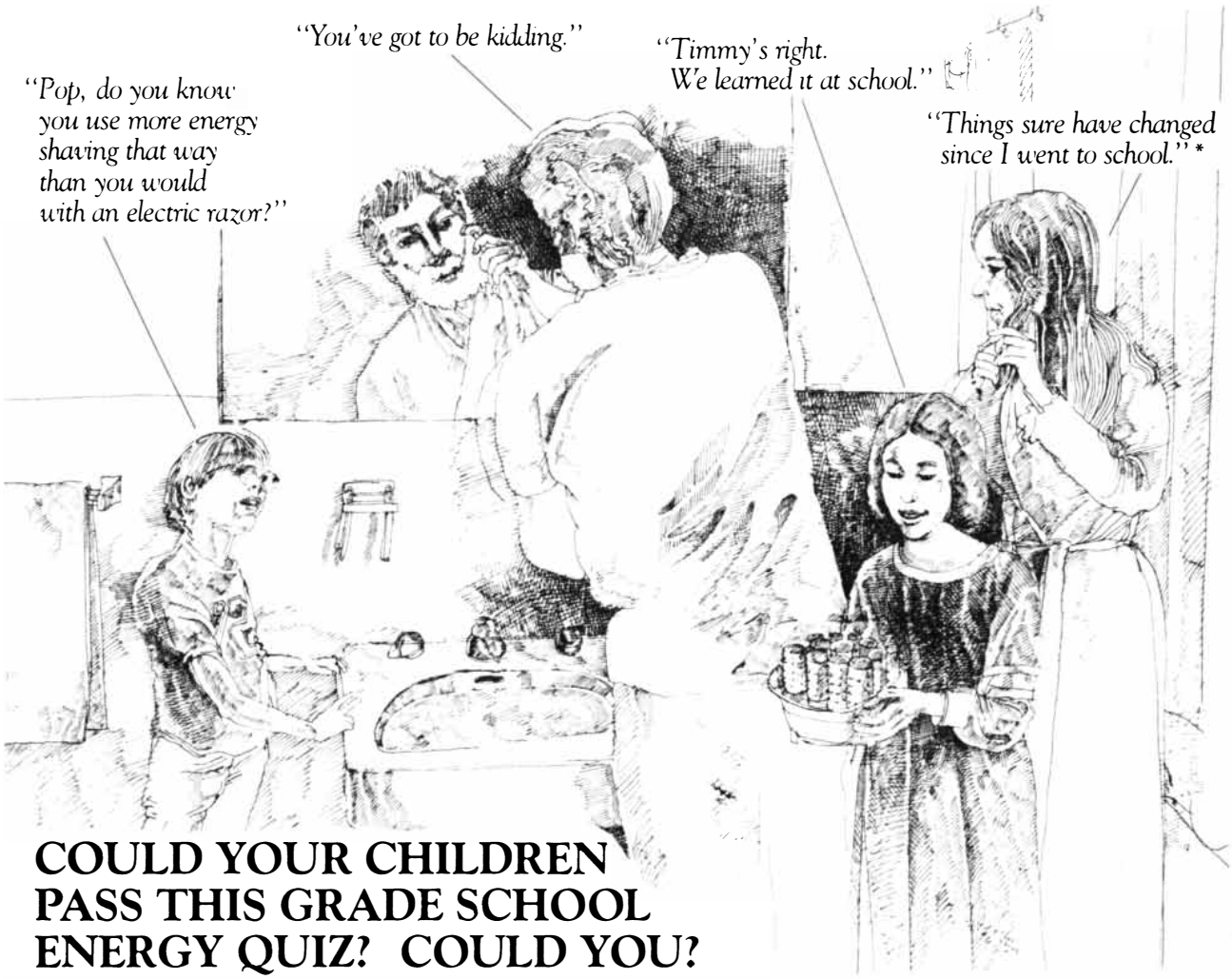
A comprehensive analysis of the mossy-fiber system is more difficult to achieve. The effects of mossy-fiber stimulation are so different from those of the climbing fibers that it is possible the two systems are "time-sharing" the Purkinje cells, each employing them for quite different purposes. Not only do the mossy fibers activate large areas of the cortex instead of individual cells; they also enlist the aid of the inhibitory interneurons, which may modulate and detect patterns in incoming signals. The Golgi cells in particular may be involved in determining what kinds of information reach the cortex through the parallel fibers; moreover, in any time-sharing arrangement they could apportion the Purkinje cells between the two systems.

An example of a motor behavior that is linked with the mossy-fiber system has recently been encountered in studies of visual coordination. In organizing the delicate and precise movements of the eyes the cerebellum is evidently essential; cerebellar dysfunction often disrupts such movements. Two regions of the cerebellum are known to participate in these functions. One is the flocculonodular area; it regulates the position of the eyes with respect to the orientation of the head and body, enabling one to stare at a fixed point while moving. The other is the cerebellar vermis, which is believed to control the rapid eye movements called saccades, which are important in visual tracking.

In a recent series of experiments at the Air Force School of Aerospace Medicine, James W. Wolfe and I showed that the activation of Purkinje cells by mossy fibers increases about 25 milliseconds before an eye movement begins [*see top illustration at left*]. The implication of this discovery is that cerebellar regulation of movement through the mossy-fiber system is capable of correcting mistakes before they have reached the muscles and have been expressed in actual movement. The cerebellum appears to correct these movements by acting as a brake.

Motor Coordination

There is no longer any doubt that the cerebellum is a central control point for the organization of movement. It does not initiate movement, and indeed movement can be generated in the absence of a cerebellum. It modulates or reorganizes motor commands, and by coordinating diverse signals it obtains the maximum efficiency from them. It is there-



COULD YOUR CHILDREN PASS THIS GRADE SCHOOL ENERGY QUIZ? COULD YOU?

1. The average American uses ☐2 ☐4 ☐8 times as much energy as the average person in the rest of the world.

2. Which gives you more light from the same amount of energy: ☐one 75-watt bulb ☐three 25-watt bulbs?

3. The most abundant energy resource in this country is ☐natural gas ☐coal ☐oil.

4. Most car trips in the U.S. are ☐under 5 miles ☐5 to 10 miles ☐over 10 miles.

Chances are, when you were in school, nobody asked questions like these. Because nobody thought the answers were important.

But children today are facing an increasingly energy-conscious, environment-conscious way of life. They must have the answers. And the sooner the better.

One promising approach to energy education is a pilot program for elementary and secondary school students developed by the Bolton Institute of Washington, D.C. The idea is to get youngsters involved in energy-saving activities at home and through community workshops. It is being tested now in the New England states.

But there's much more to be done. Energy education needs the support of all of us to really take hold. That means community leaders, business people, teachers–and parents.

We're offering two booklets we think you and your children will find stimulating and fun: "Energy Conservation Experiments You Can Do", published by the Thomas Alva Edison Foundation; and "The Energy Challenge: What Can We Do?", published by Energy Conservation Research. For copies, write Conoco, Dept. C54, GPO Box 29, New York, New York 10001. And if you'd like to know more about the Bolton program and how it might be applied to your community, write directly to the Bolton Institute, 1835 K Street N.W., Washington, D.C. 20006.

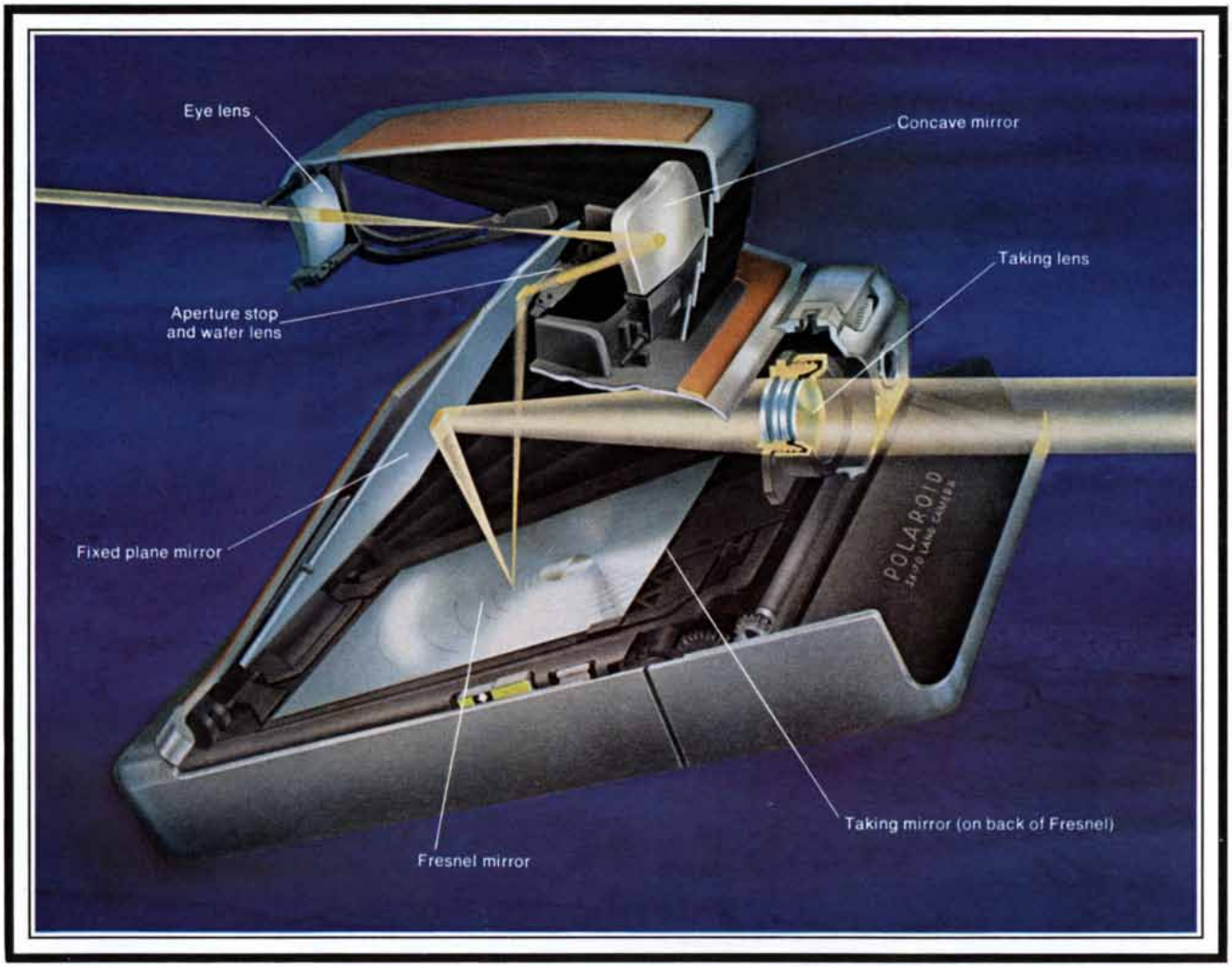
Answers to quiz:
1. 8 times. **2.** One 75-watt bulb. **3.** Coal. **4.** Under 5 miles.

*We're not trying to tell you how to shave—we'd hope nobody would. We just thought you'd like the facts to choose for yourself.

Continental Oil Company conoco

THE STORY OF THE POLAROID SX-70 VIEWING SYSTEM.

We were confronted with an optical dilemma...



Then we invented ways to resolve it.

The concept of the SX-70 Land camera presented our optical designers with a staggering array of technical challenges. The difficulties arose out of the basic requirements set for the camera design—that it be a pocket-sized camera, sophisticated yet easy to operate, with a minimum of mechanical interference between the user and his subject.

We knew the basic, roughly triangular shape of the camera at a fairly early stage and therefore the path of light to the film. The question that remained was how the user would view the subject. With a camera capable of focusing to 10.4 inches, it is most desirable to view the subject through the picture-taking lens—a single-lens reflex design. This concept has a compelling simplicity, but we found it extraordinarily difficult to achieve in a folding pocket-sized camera.

The problems were related to the fact that the light from the camera lens would have to be directed toward the viewfinder on a path that diverges from the optical centerline. (A direct viewing route would have required a hole in a mirror . . . with a resultant "hole" in the picture.) This off-axis light path introduces severe distortion and other aberrations which require complex optical surfaces to correct. Additional problems stemmed from our requirements that the viewing image be right side up with no reversals, that it appear to be the approximate size of the subject as seen with the naked eye, and that the user would look toward the subject (rather than down) through the viewer. Even if we could design a workable system, we had no assurance that we could manufacture, test and assemble the components economically and accurately—no one had ever tried before.

Ripples on wobbles on grooves: our strange and wonderful Fresnel mirror.

The solutions to the host of problems faced by our designers have made photographic history . . . as the entire SX-70 has. Consider the path of light through the viewing system:

Light passes through the taking lens, strikes a fixed plane mirror on the back of the camera and is reflected down onto a Fresnel mirror covering the film. (This Fresnel has a plane taking mirror under it which pops up against the fixed mirror to take the picture.)

A Fresnel mirror is essentially a curved mirror which has been cut in circular segments and squashed flat without losing its effective curvature, and, *per se,* is not new. For the SX-70, however, we needed a rather special Fresnel mirror.

First, it has to take light falling on it from overhead and reflect it at an angle toward a point off the optical centerline. This off-axis nature of the light path required us to locate the center of the Fresnel rings ¾ inch away from the center of the mirror itself.

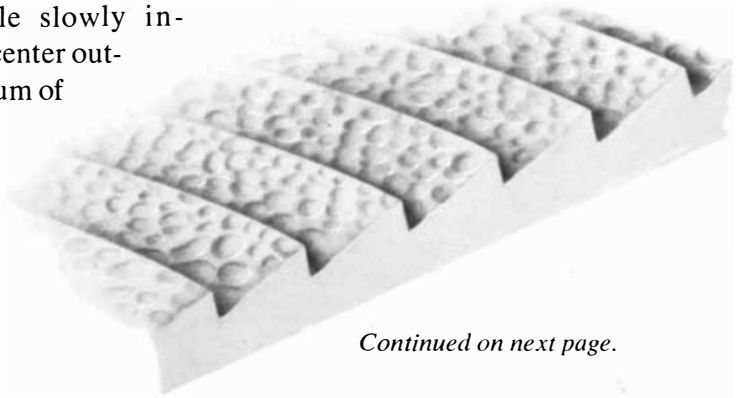
To control the off-axis astigmatism, we cut each circular groove in our master Fresnel mirror with a wobbling tool, so that the pitch was steeper near the sides of the camera. By design, the wobble slowly increased from the center outward, to a maximum of about 1 degree.

But the Fresnel mirror had to do even more. Like the ground glass of a view camera it had to provide a surface on which the image would form, so that when the image was out of focus it would show an unmistakable blur. To achieve this we had to deform the surface of each tiny Fresnel groove (only .005 inches wide) by superimposing precisely controlled ripples on it. These ripples had to be just right to provide accurate focus without scattering and wasting light. The technique which finally produced ideal ripples was to spray a fine mist of solvent on a plastic master Fresnel mirror. Each droplet dissolved a minute amount of plastic and then evaporated, leaving a tiny deformation (see below).

(One man spent hours at a time for several months under a paint hood searching for the solvent/additive combination that had the proper volatility for creating uniform ripples of the correct size. "I felt," he said, "like Edison, trying hundreds of materials for his incandescent filament until one good one emerged.")

The brightness of the resulting SX-70 viewfinder image actually surpasses that of many conventional reflex cameras with much larger lens apertures. The final Fresnel mirror is a piece of molded plastic only 1/100 inch thick; it is made reflective by an evaporated aluminum coating.

Light bouncing off this wavy, grooved surface rebounds again



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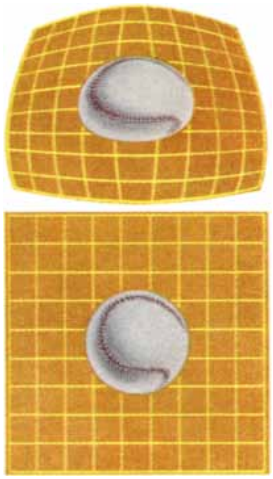
off the top of the plane mirror, performing the necessary image reversal. It exits the camera chamber by way of a small aperture stop, 1/10 inch in diameter. Here, at the top of the camera, are located the three viewfinder elements—one mirror and two lenses—which require the use of complex non-spherical surfaces never before seen in a camera.

We made lenses with light bulbs, computers and plastic wrap.

The mirror is a sophisticated curved surface which is described by an eighth-order polynomial. Its aspheric shape is essential if the off-axis light bundle is not to produce an image that is squashed in at the



top. Correcting this squashed effect (above) requires that the mirror have less curvature at the top than at the bottom. But an undesirable consequence of this shape is that the image formed by the top of the mirror is nearer to the eye than the image formed by the bottom.

It is the eyelens' task to correct this focus difference. In perfecting the design we represented the subject area with a grid of 25 tiny lights, five across and five down, and worked out corrections for each light. Then through computer optimization we arrived at an aspheric lens surface which would yield the least distortion and blur.

Faced with actually making such a surface, we produced one early prototype by filling a box with water (later epoxy) and covering it with plastic food wrap.

When the box was tilted its surface became a continuous, smooth concave-convex surface (above) of the kind we needed.

The mirror and the eyelens together, left residual aberrations, particularly coma, in the viewer's image. To correct these we added the "wafer lens" near the viewfinder's aperture stop.

Like the eyelens, the wafer is concave over part of its surface and convex elsewhere. It contains enormous power variations (more than 12 diopters) in a space only 3/16 inch in diameter.

Since the aperture stop is imaged on the viewer's eye, locating the wafer lens there is optically the equivalent of equipping each SX-70 user with a highly-sophisticated aspheric contact lens.

The aspheric surfaces on the eyelens and wafer are not even figures of revolution, and to make the master lens shapes we had to extend the technology used for shaping aspheres. The production versions of the concave mirror, eyelens and wafer lens are made of molded plastic.

Designing and refining this optical maze kept us busy for three years.

We explored the very nature of human vision, learning which aberrations the eye can tolerate and which interfere seriously with seeing the image. We probed the uncharted terrain of tilted aspheric optics, and found we were dealing with rapidly varying aberrations of unusual complexity. We pushed the limits of the plastic injection molding process to new levels of sophistication in defining and mass producing complex optical shapes. We even found a way to include a split-image rangefinder.

All of this exotic technology assumes such a low profile that the user is hardly aware of it: You pick up the SX-70. Focus and frame your subject. Push a button. And the picture you get is the picture you saw.

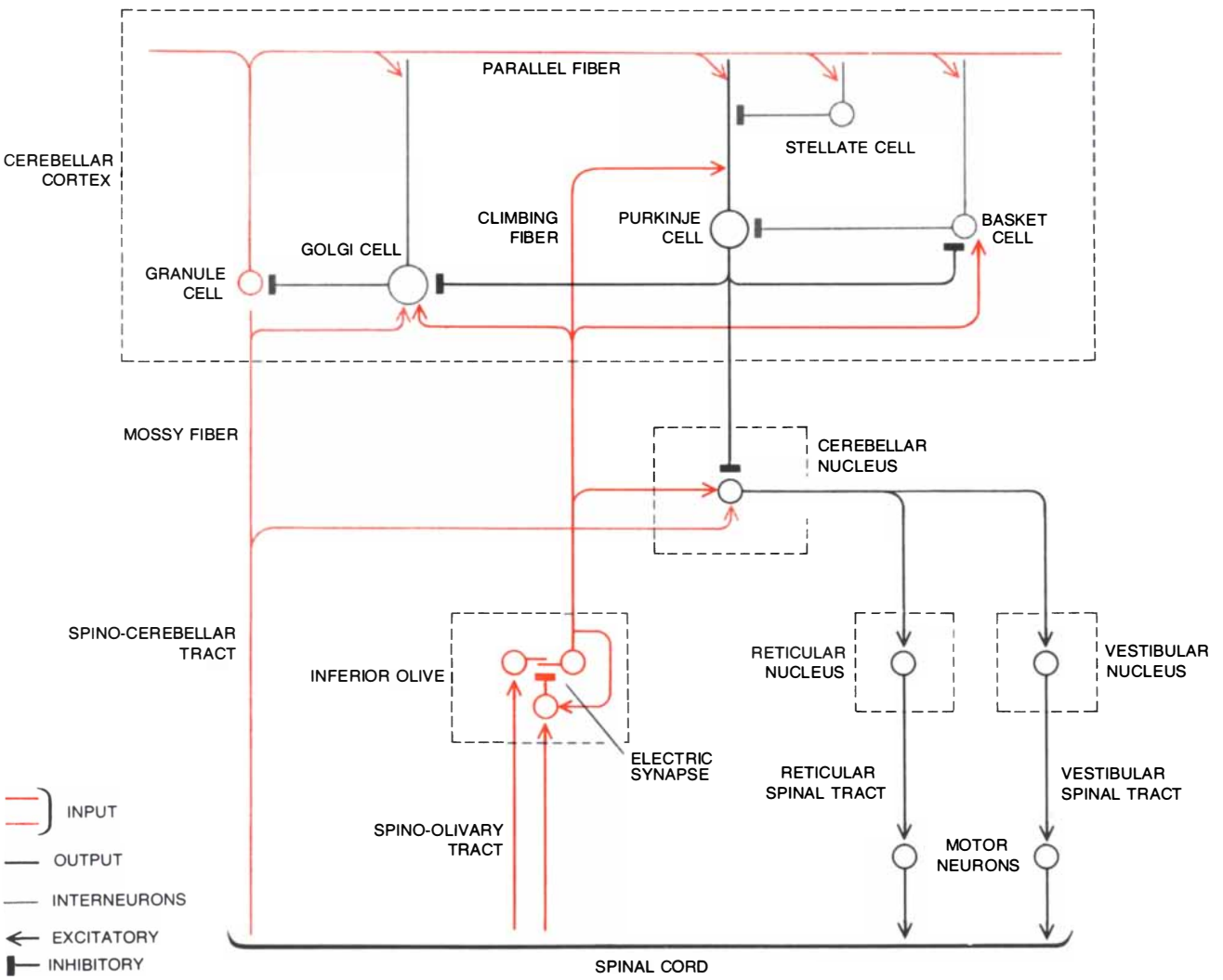
Easy for you. Difficult for us.

The SX-70 System from Polaroid

fore an organ of regulation in the highest sense. It may in fact regulate more than motor performance. R. Nieuwenhuys and C. Nicholson of the Catholic University of Nijmegen have shown that in electric fish (family Mormyridae) employing an electric field as a sensory organ the cerebellum attains enormous size and fills most of the cranial cavity.

Without question the cerebellum is far more sophisticated than the simple control box, comparing muscle position with brain command, that Sherrington and his contemporaries supposed it to be. Israel Gelfand, M. L. Shik and their associates at the Institute of Information Transmission Systems in Moscow have shown that the cerebellum is capable of coordinating movement even in the absence of all information from the periphery of the body. They removed the forebrain and blocked proprioceptive sensation in experimental animals; as long as the cerebellum remained intact locomotion was possible, but it was disrupted when the cerebellum was removed. A series of experiments conducted by Anders Lundberg and his colleagues at the University of Göteborg provides a further indication that some cerebellar activity is concerned with the internal state of the central nervous system. They found that one of the main afferent tracts leading to the cerebellum, the ventral spinocerebellar tract, conveys information not about the state of the body or the external environment but about the activity of inhibitory interneurons in the spinal cord. Such an internal monitoring mechanism might be a necessity in a system intended to refine or revise motor commands before they reach the muscles, such as is observed in the cerebellar control of eye movement.

Excellence in motor coordination is obviously an adaptive advantage, and evidently it is enough of an advantage to sustain the development of a specialized brain center committed primarily to that purpose. The success of the motor coordination center is suggested by the calculations of Sherwood L. Washburn and R. S. Harding of the University of California at Berkeley. They report that the cerebellum has enlarged between threefold and fourfold in the past million years of human evolution.



SCHEMATIC "WIRING DIAGRAM" of the cerebellar cortex and the brain centers with which it communicates relates the structure of the nerve-cell circuits to their function. The types of cells and synapses are identified in the key at lower left. Input to the cortex is through the climbing fibers and mossy fibers, both of which also send branches to the cerebellar nuclei. In the cortex both fibers ultimately act on the Purkinje cells; in addition the response of these cells is influenced by three kinds of interneurons, all of them inhibitory. Since the Purkinje cell is also inhibitory its effect on the cerebellar nuclei is to prevent the transmission of nerve impulses from the climbing fibers and mossy fibers that would otherwise reach the motor neurons and generate movement. Thus the cortex appears to be an organ of regulation, empowered to select certain motor commands for transmittal and to veto all others.

HIGH-ENERGY REACTIONS OF CARBON

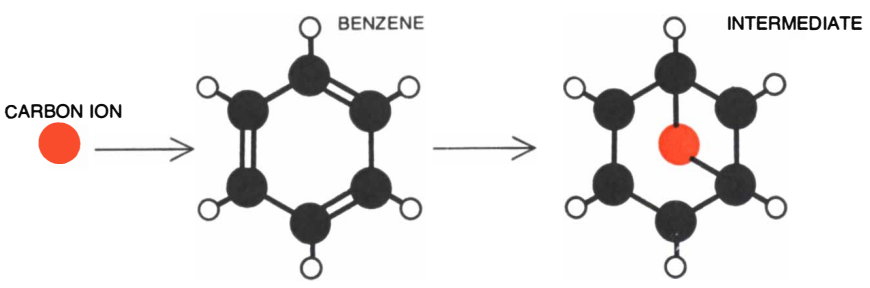
Much of the carbon chemistry in the universe takes place at high energies. Experiments with accelerated carbon ions point to processes that may have played a role in the emergence of life

by Richard M. Lemmon and Wallace R. Erwin

No element is more basic to life than carbon. If one disregards water, living cells are almost entirely an assemblage of carbon compounds. In the chemical processes of life the reactions of carbon take place at modest temperatures, which is another way of saying that they take place at modest energies. In living cells these reactions proceed at temperatures near 38 degrees Celsius (100 degrees Fahrenheit). Even in laboratory studies of carbon compounds a chemist rarely employs temperatures above 300 degrees C. Although these low-energy carbon reactions are obviously of great importance to us, the recent discovery of many complex carbon compounds in interstellar space makes it clear that the carbon chemistry of the universe is almost entirely a high-energy chemistry. The earth is constantly bombarded by high-energy carbon atoms in cosmic rays and in the "wind" flowing outward from the sun's corona. It is entirely possible that the emergence of life on our planet depended on some key organic reactions promoted by these high-energy carbon atoms. In order to gain any understanding of this possibility it is necessary to investigate high-energy carbon reactions in the laboratory.

Over the past few years we and our colleagues at the Lawrence Berkeley Laboratory of the University of California have been producing such reactions by means of a chemical accelerator. Carbon ions are accelerated in an electrostatic field and aimed at selected target molecules. By analyzing the products of the reactions we are beginning to gain some knowledge of the mechanisms by which high-energy carbon atoms form new carbon compounds.

There is much evidence for the pervasiveness of high-energy carbon chemistry in the universe. Radio astronomers have now found some 20 carbon compounds in interstellar space. Some of these compounds may well have been created in collisions involving high-energy carbon atoms such as those in cosmic rays and the solar wind. It is clear that the carbon atoms of the solar wind have played an important role in the chemistry of the moon's surface [see "The Carbon Chemistry of the Moon," by Geoffrey Eglinton, James R. Maxwell and Colin T. Pillinger; SCIENTIFIC AMERICAN, October, 1972]. The Apollo missions to the moon have provided us with a good estimate of the density of solar-wind carbon atoms striking the moon: approximately 100,000 atoms per square centimeter per second. The number of carbon atoms reaching the earth's atmosphere is likely to be much lower because of the shielding effect of the earth's magnetic field. If we assume, however, that the earth's atmosphere receives only a tenth as many carbon atoms as the moon does, our planet would pick up more than 30 tons of solar-wind carbon per year. Multiply that by the age of the earth (4.5 billion years) and the total weight of the solar-wind carbon that may have accumulated on our planet is 135 billion tons—roughly as much as the total amount of carbon in all living matter on the earth today.

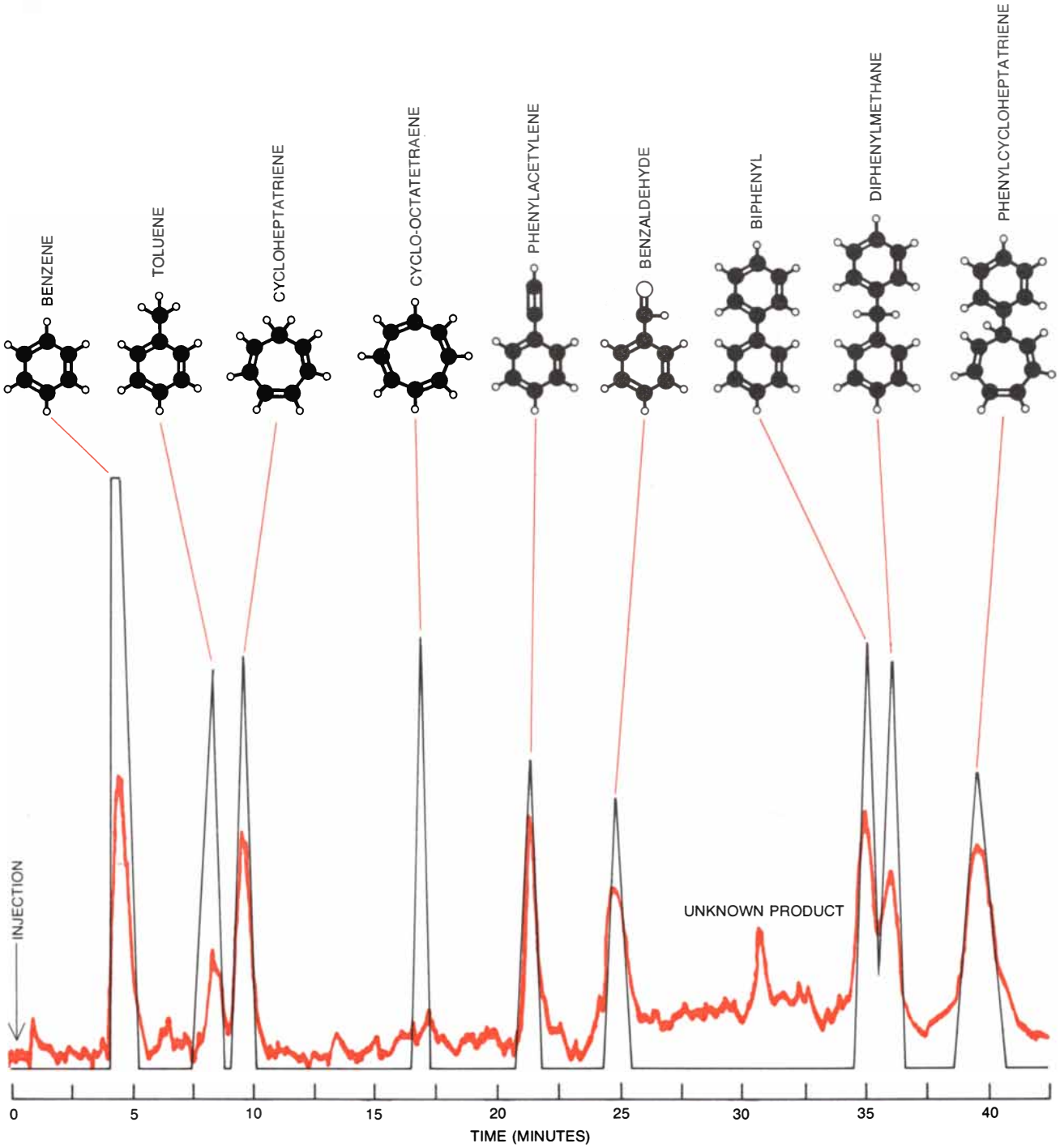


HYPOTHETICAL BRIDGED INTERMEDIATE incorporating seven atoms of carbon is believed to be formed when a high-energy carbon ion strikes a benzene molecule. The possibility of such an intermediate was not envisioned prior to studies with ion accelerators.

Whether or not high-energy carbon reactions were involved in the emergence of life, there are good reasons for the fact that our biology and very likely any other biology that may exist in the universe is based on carbon. The element is unique in its ability to form compounds. Its uniqueness is apparent from its special position in the periodic table of the chemical elements [*see illustration on page 75*]. Carbon is the smallest atom in the group of elements halfway between the electropositive elements (those that give up electrons to form chemical bonds) and the electronegative elements (those that take up electrons to form chemical bonds). Carbon has four electrons in the outermost shell of its electron cloud, and it has an equal tendency to gain or lose those four bond-forming electrons. It thus forms stable compounds with both sodium and chlorine.

As the smallest atom in its group in the periodic table carbon is also capable of forming particularly strong bonds. Because the carbon atom is small its electron cloud can approach the positively charged nucleus of another atom rather closely. The closer the approach is, the

stronger are the bonds that are formed. The combination of these two properties—small size and electrical "halfwayness"—confers unique bond-forming abilities on carbon. One result is that carbon forms strong bonds not only with many other elements but also with itself. Carbon atoms can link up in chains, and when the chains are joined at their ends, they form rings. The chains and rings can have carbon-atom branches on them and carbon-atom links between them, with almost no restriction on the total number of carbon atoms. Add to this the ease with which carbon atoms can link up with atoms such as hydrogen, oxygen, nitrogen, phosphorus and sulfur and one can visualize the virtually limitless possibilities for carbon molecules. Living systems gain their marvelous complexity from the enormous number of



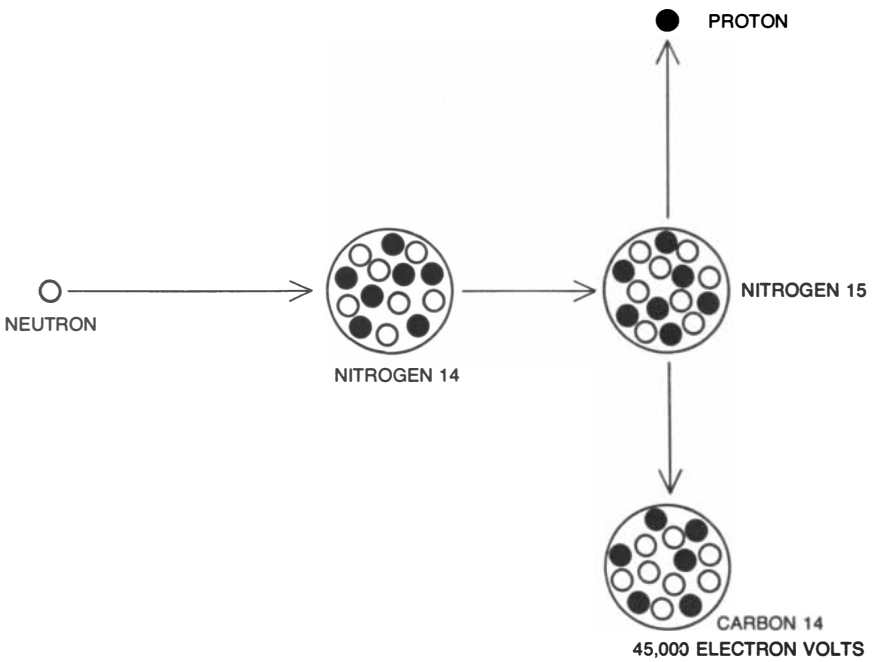
PRODUCTS FORMED BY IRRADIATION OF BENZENE with high-energy carbon-14 ions are identified by means of a gas chromatograph and a radioactivity counter. Since carbon 14 is radioactive, any new compound it becomes part of also will be radioactive. The colored line shows the radioactive peaks of the products formed by the reactions of carbon 14 and benzene. The peaks on the black line are the mass peaks of known compounds added to the sample before it entered the chromatograph. The identity of a radioactive product is established by the coincidence of a colored peak and a black peak. Additional chemical tests are carried out to confirm the identity of the products. Note that cyclo-octatetraene does not have a corresponding radioactive peak, which means little or none of this compound was formed. One major radioactive peak and several minor ones are as yet unidentified.

carbon compounds available for their construction, and it is difficult for the modern chemist to envision life based on any element but carbon. As life has evolved, many new carbon compounds have been formed. More than a million carbon compounds, both natural and synthetic, are known, but billions are possible and the universe probably harbors billions.

Although a single carbon atom is highly reactive, a mass of carbon atoms such as one finds in the graphite of a pencil lead is not particularly reactive because the carbon atoms are already combined with one another. The primary means by which chemists induce chemical reactivity is the application of heat. The higher the temperature is, the faster a molecule will move and the faster its atoms will vibrate. If the temperature is high enough, the molecule will move fast enough so that when it strikes another molecule the kinetic energy will promote a reaction between the two molecules. The high temperature may also cause a molecule to vibrate to the extent that its atoms fly apart, giving the released individual atoms a chance to enter into new combinations. In general the application of heat causes the weakest bonds to break first. At room temperature a pencil lead is inert, but if one heats it enough, its carbon atoms are jostled apart and readily combine with the oxygen in air to form carbon dioxide.

Light is another form of energy the chemist uses to promote reactions. It has long been known that sunlight promotes reactions such as bleaching or tanning, even when little or no heating is involved. We now know that the absorption of light quanta by a molecule can be even more effective than heat in putting the molecule into an energy-rich, reactive state. In contrast to what happens when heat is applied, the absorption of light can cause the breakage of a molecule's stronger bonds because the light is often selectively absorbed by those bonds.

In the past two decades chemists have been promoting reactions of carbon and of other elements at energies much higher than those that can be achieved with either heat or light, energies that are more characteristic of those found in the particles of cosmic rays and the solar wind. One method is to take advantage of the very high energy, or high velocity, of atoms created in nuclear reactions. A typical example in nature is the process that takes place when an atom of the radioactive isotope carbon 14 is born in the earth's upper atmosphere. This particular nuclear reaction is responsible for the small amount of carbon 14 found in all living things and is the basis for the widely used carbon-14 dating method. Carbon 14 is formed when neutrons, which are produced by cosmic rays that steadily bombard the earth, react with atmospheric nitrogen.



CARBON 14 IS FORMED in the earth's upper atmosphere when a neutron from cosmic rays strikes the nucleus of a nitrogen atom, which consists of seven protons (*black circles*) and seven neutrons (*open circles*). The result is an unstable nucleus consisting of seven protons and eight neutrons, which disintegrates into a proton and a carbon-14 nucleus.

When a neutron enters the nucleus of a nitrogen atom, the resulting transient complex is unstable. It disintegrates into a proton, which is a charged hydrogen atom, and a carbon-14 atom. When the unstable complex ejects the proton in one direction, the carbon recoils in the opposite direction with an energy of 45,000 electron volts (the energy that any singly charged ion would acquire if it moved from an electrode at ground potential to an electrode that had a charge of 45,000 volts). The energy of an ordinary carbon-carbon bond is about 3.4 electron volts; therefore a 45,000-volt atom is capable of breaking 45,000 divided by 3.4, or about 13,000, carbon bonds before all its velocity is lost. Such an atom can break the strongest bond in any molecule it strikes. Hence a recoiling carbon atom may produce compounds that could not be prepared by the application of heat or light.

The general technique of recoil studies is simple. If one wants to know how recoiling carbon atoms react with the molecules of a given compound, one mixes the compound with any nitrogen-containing substance and puts the mixture in a nuclear reactor. The neutrons from the reactor collide with the nuclei of the nitrogen atoms, and the resulting carbon-14 atoms recoil through the mass of the compound until they are slowed to a velocity, or energy, at which they can form new chemical bonds. That energy, which is at most only a few tens of electron volts, is low compared with the energy of a newly created carbon-14 atom. It is, however, very high in comparison with chemical-bond energies and with the maximum energies that chemists can give to an organic compound by the application of heat, which are less than .1 electron volt per atom.

Since the recoiling carbon atoms are radioactive, the products into which they are incorporated are also radioactive. This is helpful to the chemist both for finding the new products and for finding the exact position of the carbon-14 atom in the molecule of a product. Other nuclear reactions have also been used as a source of high-energy carbon atoms. The study of the reactions of reactor-produced high-energy atoms is familiarly known as hot-atom chemistry.

Another way of imparting high energies to atoms is to use an accelerating machine such as a cyclotron. Physicists have used accelerators for several decades to examine nuclear reactions; the energies involved are in the millions or billions of electron volts. More recently chemists have been building accelerating devices that enable them to study

	ELECTROPOSITIVE			ELECTRONEGATIVE			
GROUP I	II	III	IV	V	VI	VII
1 H HYDROGEN						
3 Li LITHIUM	4 Be BERYLLIUM	5 B BORON	6 C CARBON	7 N NITROGEN	8 O OXYGEN	9 F FLUORINE
11 Na SODIUM	12 Mg MAGNESIUM	13 Al ALUMINUM	14 Si SILICON	15 P PHOSPHORUS	16 S SULFUR	17 Cl CHLORINE

FIRST THREE ROWS OF PERIODIC TABLE are shown. (Noble-gas elements helium and neon have been omitted.) The Roman numerals designate groups of elements with similar chemical properties. Carbon is the smallest atom in the central group. Electropositive elements tend to give up electrons in their outer shell to form chemical bonds, whereas electronegative elements tend to take up electrons to fill their outer shell. Carbon, with four electrons in its outer shell, has an equal tendency to gain or lose these electrons. This confers on carbon the unique ability to form strong bonds with many other elements and also with other carbon atoms.

the reactions of atoms at the more modest energies where chemical interactions can take place [see "Chemical Accelerators," by Richard Wolfgang; SCIENTIFIC AMERICAN, October, 1968]. Such devices enable the experimenter to choose the energy, down to a few electron volts, with which an energetic atom will strike target molecules. The random destruction of the target molecules during the slowing down of a recoiling atom may thus be avoided. One such device is in use in our laboratory, and we shall describe our research with it as an illustration of the kind of information that can be obtained from energetic carbon reactions. For the progress of this work we are indebted to many former collaborators and to our current co-workers Glenn A. Fisher and Benjamin Gordon.

To form a beam of energetic carbon atoms one admits either carbon dioxide (CO_2) or methane (CH_4) containing carbon-14 atoms into a chamber where the molecules can be ionized [*see illustrations on next page*]. Here, between the anode and the cathode, a cloud of ions (charged molecules) is formed. The ions are expelled out of the region of their formation by an electric field of 5,000 volts. To control the ion beam one uses electrostatic lenses: metal plates of various forms on which electric charges are imposed. These lenses shape, magnify and demagnify the ion beam in ways quite analogous to the effects of optical lenses on a beam of light.

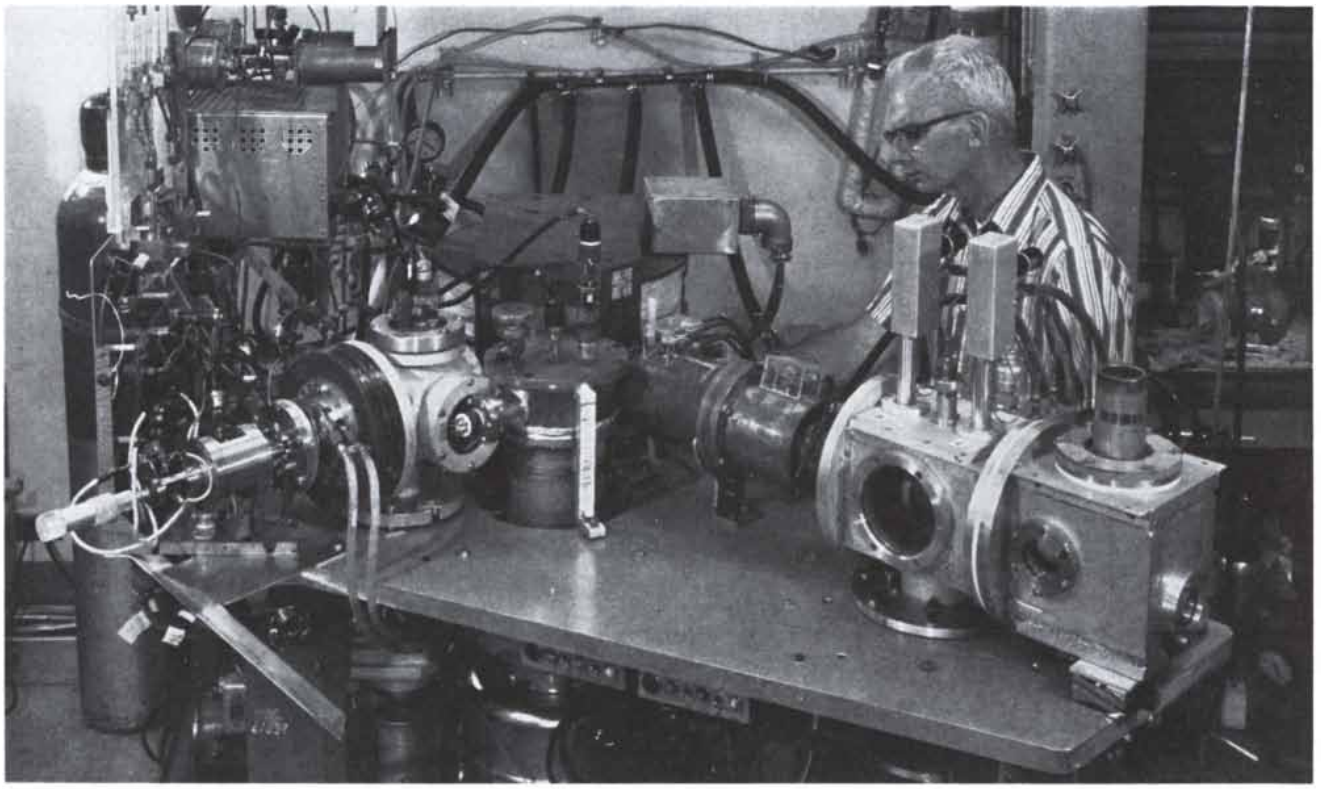
The beam that emerges from the ion source is made up of carbon in many different forms. Some of it is carbon-14 ions, some is ions incorporating oxygen (if carbon dioxide was the starting material) and some is ions incorporating hydrogen (if methane was the starting material). As the ions travel through the magnetic fields the heavier ions are bent less than the lighter ones. By adjusting the strength of the magnetic field one can select the kind of ion one wants to have emerge. Most of our work has been with carbon-14 ions. The intensity of the beam is usually about one microampere; although this does not sound like much of a current, it represents some 6×10^{12} ions per second. The beam then passes through a series of decelerating lenses, doughnut-shaped plates on which positive voltages are imposed. These lenses enable us to set the energy with which the ions strike the target at energies anywhere from their initial 5,000 electron volts down to two electron volts.

The path the ions travel must be kept at a high vacuum. Without such a vacuum the ions would strike gas molecules in the path and be scattered. In order to keep the target material from evaporating and spoiling the vacuum, the material must be held at a very low temperature. A convenient way to do so is to steadily bleed in a vapor of the target material and to freeze it on the surface of the target area, which is held at the temperature of liquid nitrogen (−196 degrees C.). This procedure has the added advantage of presenting a constantly fresh supply of target molecules to the bombarding carbon ions. Once a new product is formed it is not likely to react with additional carbon ions; it is quickly buried under the incoming target material.

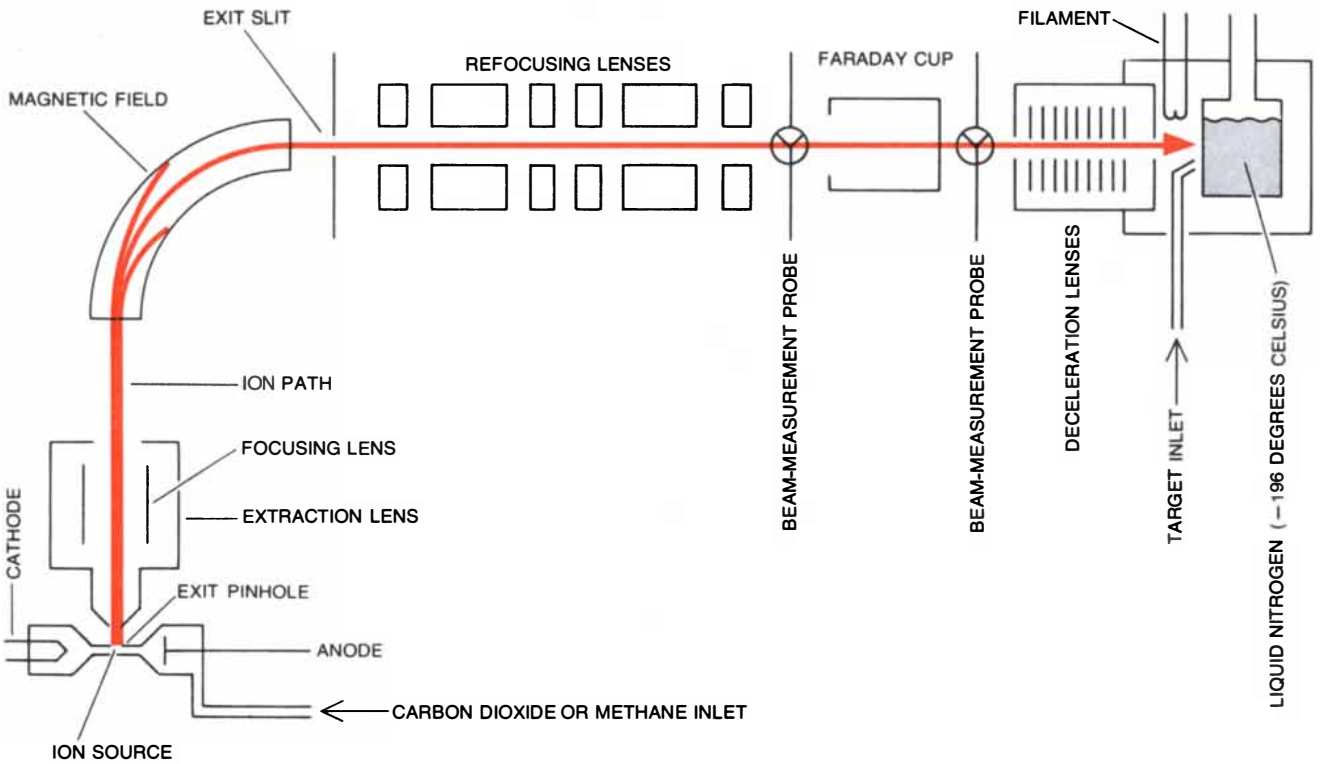
The steady stream of positively charged ions on the target surface could build up positive charge that would repel subsequent incoming ions. That undesirable state of affairs is circumvented by placing near the target a small, hot tungsten filament, which provides electrons (that is, negative charges) at a rate sufficient to balance the positive charges of the incoming ions.

We learn what has happened to our energetic carbon-14 ions by determining what kinds of products incorporating radioactive carbon are formed. To do so we separate and identify the products by the simple and powerful technique of gas chromatography combined with a radioactivity detector. The radioactive products are introduced, usually as a benzene solution, into the column of the gas chromatograph: a metal tube about a quarter of an inch in diameter and several feet in length. The tube is filled with an inert solid, the particles of which are coated with an oily liquid.

The gas-chromatograph column is heated to a temperature that experience



CARBON-ION ACCELERATOR at the Lawrence Berkeley Laboratory of the University of California appears in this photograph. The ions are generated in the apparatus at left. The beam of ions is bent by a magnet and strikes the target in the box at the right.



SCHEMATIC REPRESENTATION of the Berkeley carbon-ion accelerator shows how energetic carbon ions are produced. Methane or carbon dioxide containing carbon-14 atoms is admitted into the ion-source chamber, where carbon-14 and other ions are formed by the electrons emitted from the cathode. The ions are accelerated toward the magnetic field by a high positive voltage on the ion source. The ion beam passes through a magnetic field that has been adjusted to allow only the carbon-14 ions to pass through. Heavier and lighter ions strike the sides of the magnetic-field chamber. The carbon-14 ions pass through refocusing lenses and measuring devices. The Faraday cup measures the intensity of the carbon-14 beam, and two *Y*-shaped probes measure the beam's profile, or cross section. The interior of the accelerator is kept at a high vacuum. In order to maintain the vacuum the target material is bled in slowly as a vapor that immediately condenses on the surface of a target plate kept at −196 degrees Celsius by liquid nitrogen.

has shown gives the best separations. A sample is carried through the column by a stream of helium gas, and depending on the affinity of the constituent compounds for the oily liquid, or on their solubility in it, they move through the column at different rates. As the compounds emerge from the column their presence is recorded by a thermal-conductivity detector. This device records the difference in heat loss between a filament bathed in pure helium and another filament that is exposed to the helium stream emerging from the column. Helium is a better conductor of heat than any gaseous organic compound, so that the presence of any quantity of such a compound in the helium stream reduces the rate of heat loss from the filament. The hotter filament is a poorer conductor of electricity, and this greater resistance is converted to an electrical signal that is displayed as a line on the advancing paper strip of a recorder. The helium stream is then led to the radioactivity detector. Any radioactivity that is present is recorded by a separate pen.

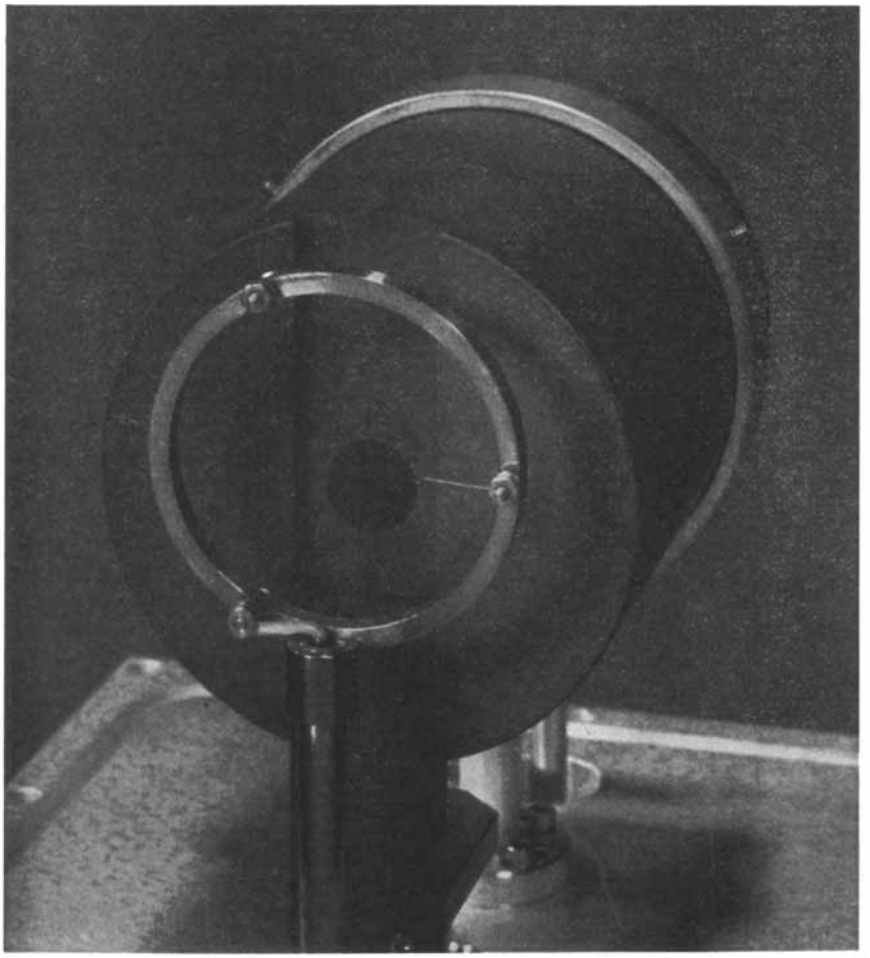
From chemical knowledge or intuition we can expect that a certain compound will be formed when carbon ions strike a particular target. To determine if the compound is present we need only add a known sample of the suspected compound to the target at the conclusion of the bombardment. Because the added sample is not radioactive it appears only as a peak in the recording from the thermal-conductivity detector. If the same compound had been formed in the target during the irradiation, it would incorporate carbon 14 and would give us a peak in the radioactivity recording. Not enough of the product would have been formed, however, for it to affect the peak in the thermal-conductivity recording. Thus if we get a coincidence of a radioactive peak with the thermal-conductivity peak of a known added compound, we have provisionally identified the radioactive product, that is, we have shown it to be identical with the added compound. The procedure becomes very reliable if the coincidence of the two peaks is repeated on other columns that are packed with other kinds of oily liquids.

Finally we direct the gas stream from the gas-chromatograph column into a cold trap: a glass tube immersed in liquid nitrogen or dry ice. The low temperature freezes and traps the organic compounds but allows the helium to flow out as a gas. The frozen compounds can then be recovered and subjected to chemical tests or further gas chromatography. The chemical tests can be directed not only to the question of the identity of the product but also to the location within the product molecules of the carbon-14 atoms that caused the products to be formed.

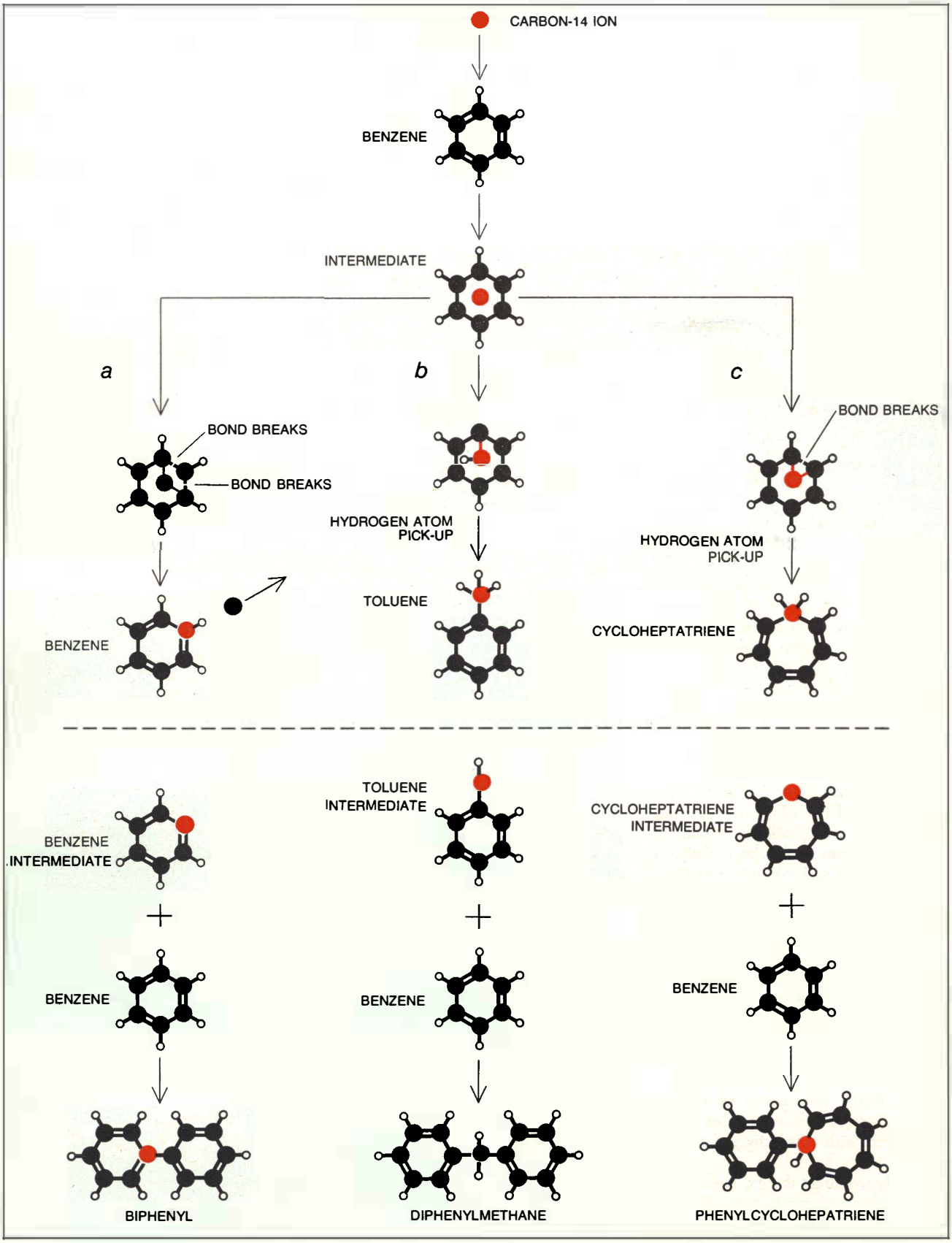
Most of our studies on the high-energy reactions of carbon have been done with the organic chemist's favorite molecule: benzene. This relatively simple hydrocarbon, C_6H_6, is the parent molecule from which a vast number of natural and synthetic compounds are formed. It has great theoretical and practical interest to organic chemists. What happens when an energetic carbon atom strikes it?

The first thing we discovered was that an accelerated carbon-14 ion reacted with the benzene to yield benzene incorporating carbon 14. The result was unexpected, because somehow the carbon 14 had to remove a carbon atom from the benzene and then remain behind as part of the benzene ring. One might imagine that carbon atoms are hard, impenetrable spheres, something like tiny billiard balls. The incoming carbon-14 atom might strike one of the carbons in the benzene ring head on, giving up all its forward momentum and energy to the atom it had hit. That atom would be knocked away, leaving the carbon-14 atom behind as part of a new ring of six carbons.

In our experiments about one in 30 of the incoming atoms is incorporated into a new benzene molecule. That is a much higher fraction than would be expected from the billiard-ball model, in which the probability of such perfect center-to-center, complete-momentum-transfer hits is far below one in 30. From what we know about the collisions of atoms they do not in general behave like little hard spheres. The complex forces of repulsion and attraction that come into play as atoms approach one another make them somewhat soft and sticky; they can be likened to balls of putty, some harder and some softer. If one throws a putty ball at a ring of six putty balls stuck to one another, it is extremely unlikely that the thrown putty ball



BRANCHED-WIRE PROBE is moved up and down to measure the shape of the cross section of the carbon-ion beam in the ion accelerator. The Faraday cup behind the probe measures the beam's overall intensity. Cup is removed to allow the beam to reach the target.



POSSIBLE MECHANISMS involved in the formation of new products when benzene is irradiated with high-energy carbon-14 ions are shown. The first step involves the formation of an energy-rich, seven-member intermediate, which then can undergo internal rearrangements to form benzene containing radioactive carbon 14 (*a*), toluene (*b*) or cycloheptatriene (*c*). Below the broken line are shown three possible reactive intermediates that can combine with benzene to form more complex aromatic compounds. The radioactive carbon-14 atom can appear in other positions in these products as a result of additional processes and carbon-atom rearrangements.

will replace one of the six balls to form a new six-membered ring.

Both statistics and atomic theory therefore tell us that the incoming carbon atom could not simply replace one of the benzene molecule's carbons by a colliding-billiard-ball process. So do our data, which show that the yield of benzene incorporating carbon 14 is independent of the energy with which the carbon struck the benzene. We found that one in 30 incoming carbon-14 ions is incorporated into new benzene molecules regardless of whether the carbon atoms hit at a high energy (5,000 electron volts) or a low one (two electron volts).

The carbon-carbon bond in benzene has a strength, or energy value, of more than four electron volts. Two carbon-carbon bonds must be broken in order to free one of the benzene molecule's carbon atoms. The two-electron-volt bombardment would therefore not be expected to produce a benzene with carbon 14 by the billiard-ball mechanism. Nonetheless, the reaction occurs at ion-beam energies as low as two electron volts.

In addition to benzene, one of the carbon-14-containing products of bombarding benzene with carbon-14 atoms is phenylacetylene, a molecule that has eight carbons. This brought up the possibility that the benzene containing carbon 14 was formed from an eight-carbon intermediate. For such an intermediate to be formed the incoming carbon ion would have to knock a carbon atom out of a benzene molecule, form a two-carbon fragment and go on to form a two-carbon bridge across another benzene molecule. We were able to rule out this notion by bombarding a compound, dimethyl benzene, that has two methyl (CH_3) groups attached to adjacent carbons in the benzene ring. If an intermediate with a two-carbon bridge was formed, the two carbon atoms carrying the methyl groups could be split out, leaving a new six-carbon benzene ring. On the other hand, if only a one-carbon bridge was formed, there would be no benzene with carbon 14. When we ran the experiment, we found no carbon-14 benzene among the products.

Both theoretical considerations and experimental results point to the presence of a seven-carbon intermediate, of whose existence we had no idea when we first undertook the work. It appears likely that this and other seven-carbon intermediates play a role in the reactions of energetic carbon in the solar wind; indeed, it may be that such intermediates are formed whenever a solar-wind carbon atom strikes, with the appropriate energy, any molecule with a benzene ring.

In our experiments two compounds with seven carbon atoms, toluene and cycloheptatriene, were formed. Toluene appears to result mainly from the establishment of a new carbon-carbon bond between the slowed-down carbon-14 ion and a benzene molecule, followed by the picking up of hydrogen atoms from an adjacent benzene. Cycloheptatriene appears to result from the insertion of a carbon ion between two carbons of the benzene ring. Another product is biphenyl, which consists of two benzene rings joined together. It probably results from a reaction between a benzene that contains a carbon-14 atom and another benzene molecule. The products diphenylmethane and phenylcycloheptatriene are also formed when seven-carbon intermediates react with benzene.

The eight-carbon phenylacetylene does appear to be the result of a process in which an incoming carbon ion strips one carbon atom from a benzene and the two-carbon fragment reacts with another benzene molecule. When the energy of the carbon-14 beam is decreased below 100 electron volts, the yield of phenylacetylene drops sharply. This result suggests that at lower energies the carbon-14 ion does not have enough velocity to strip a carbon atom from the benzene molecule.

We analyzed samples of all our major products by chemical degradation procedures in order to determine the positions of the carbon 14 in the product molecules. We found that in the toluene formed from benzene bombarded by high-energy carbon-14 ions 85 percent of the carbon 14 was in the methyl group and only 15 percent was in the benzene ring. This indicates that toluene is not entirely formed from benzene by the simple establishment of a new carbon-carbon bond. There also appears to be an energy-rich, seven-carbon ring intermediate related to cycloheptatriene. This intermediate uses its excess energy to "switch" hydrogen atoms and electrons around so that some of the carbon 14 appears in the ring of the toluene product. We also measured the distribution of carbon 14 in other products. In general the percentage distribution of carbon 14 does not change over a wide range of carbon-14-ion energies; it is virtually the same for all energies from 5,000 electron volts to about six electron volts. The reason is that the carbon-14 ion must be first slowed down to five electron volts or less before it will form a bond with benzene. The higher-energy carbon-14 ions lose energy by fragmenting benzene molecules.

When the carbon-14 ion is given an energy of five electron volts, there is a sudden increase in the amount of carbon 14 appearing in the benzene ring of some of the products. In the toluene the fraction of carbon 14 in the ring jumps from 15 percent to 40 percent. It appears that at energies of five electron volts or less only first-collision reactions occur, that is, the carbon 14 does not collide with other molecules before it forms an intermediate with a benzene molecule. The five-electron-volt energy level seems to be the maximum the seven-carbon intermediate can tolerate without breaking into fragments.

At an energy level of two electron volts we also have first-collision reactions, but there is much less energy available for rearranging the position of the carbon atoms in the benzene ring. Only 6 percent of the carbon 14 is found in the ring when toluene is formed. In fact, all the reaction products we have analyzed show maximum rearrangement when they are bombarded with carbon-14 ions at five electron volts. The minimum rearrangement comes at two electron volts. These observations reveal chemical mechanisms that could only have been uncovered by studies of reactions at high energies.

Although we have identified the major products of bombarding benzene with energetic carbon ions, there are many minor products we have not yet identified. We believe some of the products are novel and are not known in contemporary carbon chemistry. It may even be possible that some of these molecules may have been important for the emergence of life. For example, a high-energy process may have been necessary for the first appearance on the prebiological earth of a particular molecule that was indispensable for the emergence of living matter. Once made, that molecule may have been able to replicate itself by autocatalysis, the process by which the presence of a particular molecule greatly speeds the production of like molecules. Our continued efforts will be toward establishing the identity of the novel high-energy products and the mechanisms by which they are formed. We are confident that such research will tell us much about the carbon chemistry that goes on in our energy-rich universe.

SUGARCANE LEAVES that show the same symptoms of eyespot disease developed the symptoms through two different processes. The leaf at the left is infected with the fungus *Helminthosporium sacchari*. There are eye-shaped spots where the fungus has colonized the leaf, and from each spot a reddish-brown runner extends along the leaf. The leaf at the right was not exposed to the fungus. It was injected, at two sites near the bottom of the picture, with an extract of a culture of the fungus. The extract contained helminthosporoside, a host-specific toxin that was isolated by the author and his colleagues. Leaf segments in the photograph are about natural size.

A Mechanism of Disease Resistance in Plants

What makes some plants susceptible to a disease and others resistant? Study of a fungus affecting sugarcane reveals a molecular mechanism that may function in many diseases that reduce the world's food crops

by Gary A. Strobel

There are many causes of the present imbalance between the world's need for food and the amount of food available, but one of the most serious—and potentially one of the remediable—is the toll of plant disease. Every year the yield of just about all the world's agricultural crops is reduced, in the field or in storage, as the result of diseases caused by such varied pathogens as fungi, bacteria and viruses. Diseases caused by fungi alone annually destroy food that could have fed 300 million people. From time to time an epidemic strikes a single crop in a limited region, sometimes with devastating effect. The Irish potato famine of the 1840's is the most notable historical example, but there has been an instance closer to home: the decimation of the U.S. corn crop in the summer of 1970 by a fungus disease, the Southern corn leaf blight. That epidemic occasioned a billion-dollar loss of livestock feed, the largest known loss to a plant disease in such a short time.

Plant breeders, in cooperation with plant pathologists, have done a great deal to improve the yield of food plants by selecting varieties that are resistant to disease, that yield well and that are adapted to specific climates, soils and farming methods. What has been accomplished, however, has not been enough. Selection through breeding is a slow process. Moreover, the triumphant dissemination of a new and apparently successful variety can itself be a hazard: a single variety can come to constitute a large fraction of the crop and then turn out to be susceptible to a hitherto unknown or unimportant disease. That was the case in the U.S. in 1970. Corn with the "Texas male-sterile cytoplasm," which had been selected and popularized for the ease with which it could be bred, was particularly susceptible to a single race of the fungus, *Helminthosporium maydis,* that causes Southern leaf blight.

The trouble is that agronomists and plant pathologists still know very little about how plant pathogens function, how they interrelate with a plant and what makes some plant varieties susceptible to them and other varieties resistant. Pathologists and breeders speak of identifying genes for resistance to a disease and incorporating those genes in desirable varieties, which simply means that resistant plants are identified by testing with pathogens and then crossed with plants that have other desirable characteristics until a successful disease-resistant plant is produced. Although plant genes for resistance are therefore known in a sense, we know very little about how they work. The same is true of the genes that regulate the pathogenicity of the various causative organisms. Yet it is the proteins, glycoproteins and other products of those genes in plants and in pathogens that interact to determine resistance or susceptibility.

For some time it has seemed to me that learning something about the molecular events governing the interaction of such products would be intellectually stimulating as well as potentially useful. Recently my colleagues and I at Montana State University have been able for the first time to isolate and characterize a host-specific toxin: a substance, released by the fungus *Helminthosporium sacchari,* that causes the eyespot disease of sugarcane. Moreover, we have been able to learn why it attacks sugarcane in particular and, among cane plants, only certain susceptible ones.

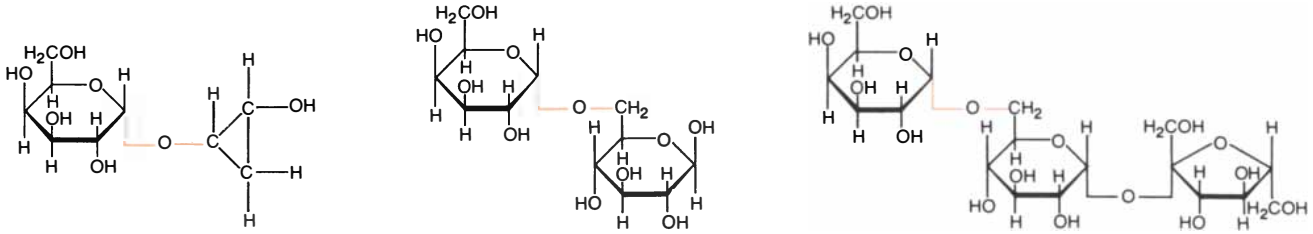
I began, actually, by deciding to study susceptibility rather than resistance. Even though there are thousands of pathogens in nature, a particular plant may have perhaps only twoscore potential pathogens and is ordinarily attacked by only one or two pathogenic agents at any given time; that is, resistance to a particular pathogen is generally the rule rather than the exception. It therefore seemed to me that one could approach the phenomenon of plant disease resistance by thoroughly investigating the inverse phenomenon of susceptibility. To do that I needed a model disease system in which to examine the gene products that interact in the host-pathogen relationship.

In the late 1960's Gary W. Steiner and Ralph S. Byther of the Hawaiian Sugar Planters Association experiment station in Hawaii were studying the eyespot disease, which is present in all important cane-growing regions and is one of the major leaf-spotting diseases of the crop. The spores of the fungus land on a leaf and germinate, and the germ tubes penetrate the leaf. The symptoms that develop are characteristic and striking. A distinctive eye-shaped lesion develops at the initial site of fungus infection, and from it a reddish-brown runner extends some 10 to 20 inches up the leaf. The fungus remains confined to the eye-shaped lesion and does not colonize the runner area. This suggested to Steiner and Byther that the fungus might be releasing in the lesion a compound that was both mobile in the plant and toxic to it. Their suspicions were confirmed when they made an extract of a culture medium of the fungal pathogen and in-

SUGARCANE is a giant perennial grass; a mature plant is from 10 to about 25 feet tall. This is a young plant; a mature one consists of clumps of stalks, each about one and a half or two inches in diameter with sword-shaped leaves and with a tassel of small flowerets at the tip. The stalk is chopped and macerated, and the extract is refined into pure sucrose and other products. Commercial cane is ordinarily propagated by planting cuttings of stalks obtained by intensive crossbreeding of various species of the genus *Saccharum*. There is a shoot bud at each node of the stalk that grows to produce a primary stalk of a new plant.

jected it into cane leaves. The extract produced all the symptoms normally associated with the disease, and it produced the symptoms only in the same clones (descendants of a single plant) of sugarcane that are susceptible to the fungus itself and not in the clones that are resistant to the fungus. Moreover, the extract did not cause symptoms in any other plant or animal that was tested; in plant-pathological terms, the extract contained a host-specific toxin. Although no host-specific toxin had ever been isolated and characterized, Robert P. Scheffer and his group at Michigan State University had shown that it must be some such gene product of the pathogen itself that was primarily responsible for the ability of certain pathogens to cause disease symptoms. The eyespot disease appeared to be a good model for the study of a host-specific toxin.

I arranged for Steiner to spend some time in my laboratory at Montana State and acquired a number of resistant and susceptible clones of sugarcane from the Department of Agriculture. (Both Steiner and the cane survived the transition from subtropical climates to the Montana winter by staying indoors.) Our goal was to isolate the toxin from *H. sacchari* and determine its structure. To do so we needed a quantitative test with which to evaluate the effectiveness of successive extractions and separations. The bioassay we developed was simple. We put a sample of the extract to be assayed on a susceptible leaf. After about 24 hours we measured the length of the runner the extract generated. It turned out that the log of the toxin concentration was proportional to the length of the runner. By trial and error, checking each step with the bioassay test, we devised a purification scheme that involved solvent extraction, column chromatography and paper chromatography, and eventually we separated a powerful toxic material that contained no contaminating compounds. This material was subjected to analytical procedures (infrared, nuclear magnetic resonance and mass spectroscopy) that have led us to a proposed structure: a complex sugar designated 2-hydroxycyclopropyl-alpha-D-galactopyranoside [*see top illustration on opposite page*]. The molecule bears a close resemblance to two common plant galactosides: melibiose, a disaccharide (two-sugar compound), and raffinose, a trisaccharide. As little as from 10^{-12} to 10^{-15} gram of the purified toxin could produce a small runner half an inch long on a susceptible leaf. The toxin had all the properties of host spec-



HELMINTHOSPOROSIDE

MELIBIOSE

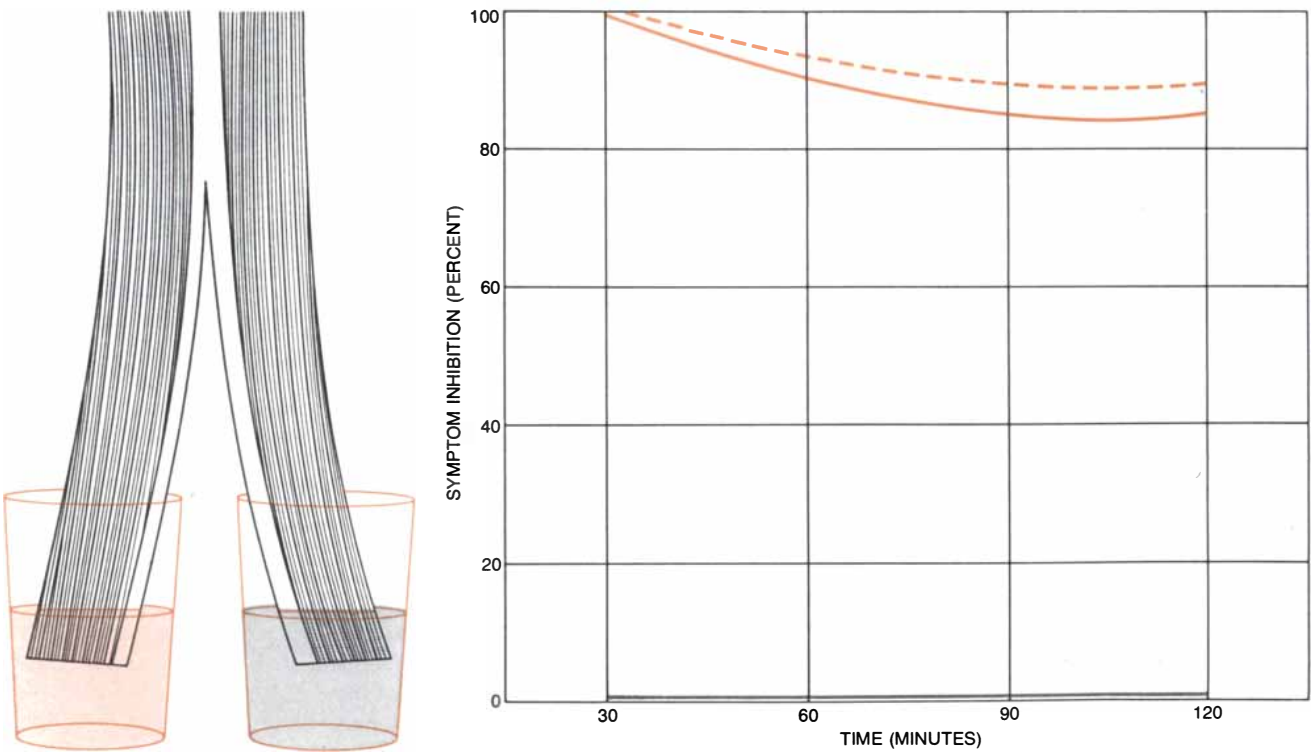
RAFFINOSE

HELMINTHOSPOROSIDE, the toxin that was isolated from the fungus *Helminthosporium sacchari*, is an alpha-galactoside: a compound in which the monosaccharide galactose (*hexagonal form*) is linked by an alpha-galactosidic bond (*color*) to another group, in this case a three-carbon hydroxycyclopropyl ring. The toxin, which causes the eyespot disease, is related to two common plant alpha-galactosides: the disaccharide melibiose (galactose and glucose) and the trisaccharide raffinose (galactose, glucose and fructose).

ificity exhibited by the fungus, producing runners on the same susceptible clones and failing to produce them on clones that are resistant to the fungus.

We called the toxin helminthosporoside and went on to find out if it was present in naturally infected leaves. In other words, did it really cause disease symptoms in nature or was it an artifact produced by culturing the fungus? Areas of leaves showing symptoms were collected from infected plants in Hawaii. When an extract of the leaf material was chromatographed and the active substance was isolated, the toxin was found to be present in infected leaves but not in healthy leaves. And it was present in large enough quantities to account for the symptoms produced in natural infection. It seemed clear, therefore, that helminthosporoside was the fungus product primarily responsible for symptoms in diseased plants.

Armed with the fact that the toxin is host-specific, Steiner and Byther soon found an important practical application for helminthosporoside. Plant breeders at the Hawaiian Sugar Planters Association continually seek to improve the yield of sugar per acre by crossing cane plants from all over the world and then selecting from among the progeny those clones that have the desirable commercial properties: disease resistance, a high yield of sugar and the particular agronomic properties suited to the soil and climate of Hawaii. The process of selecting disease-resistant plants from among the thousands growing in the greenhouse flats can be a cumbersome task involving tedious inoculation with

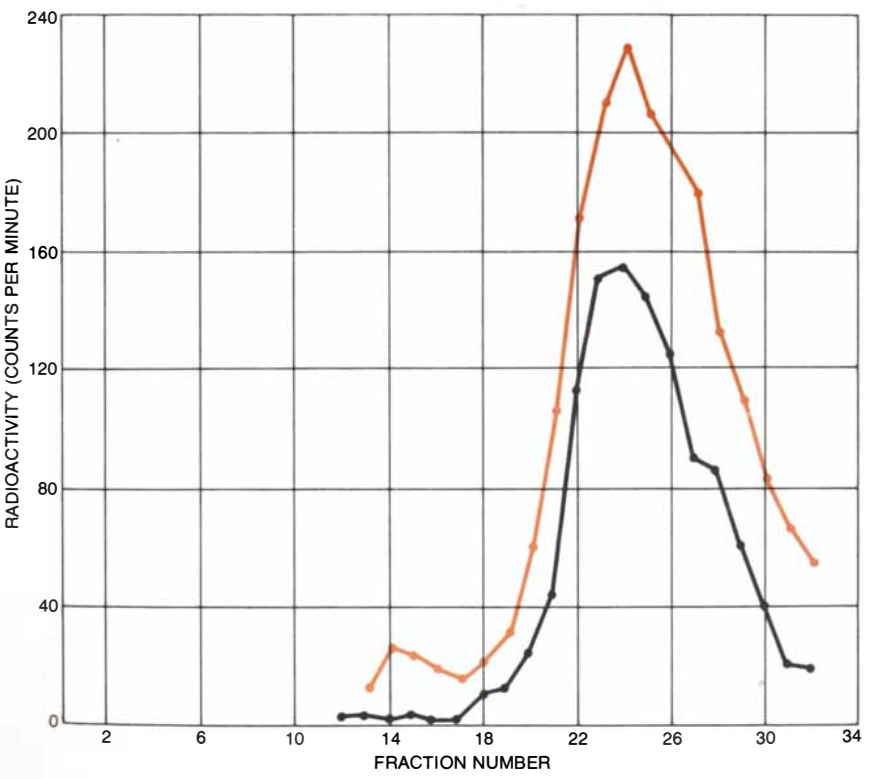


HALF-LEAF EXPERIMENT showed that alpha-galactosides, analogues of the toxin, protect leaves against the toxin. Pieces of leaves were split up the middle. Half of a leaf was placed in a solution of a galactoside (*color*) and half in water. After 24 hours toxin was injected in both halves and the initial symptom of eyespot disease, a transparent area in the leaf, was measured at intervals. Symptom development was inhibited (*right*) in halves of leaves that had taken up alpha-galactosides such as melibiose (*solid colored curve*) or raffinose (*broken colored curve*) but not in halves that had taken up plain water or beta-galactosides such as lactose (*gray curve*).

the spores of the fungus, incubation and evaluation. Steiner and Byther realized that they could cut the process short by using helminthosporoside itself as a selection tool. They produced quantities of the toxin by culturing the fungus on cane-plant extract, placed it in spray cans and applied it as a mist to the young cane plants. Amazingly, within from two to three days after the spraying all the susceptible seedlings either were dead or were displaying strong symptoms of the disease; the unaffected plants could be considered to be resistant to eyespot disease and ready to be tested for other diseases, for sugar yield and for additional qualities. This procedure is now standard practice in Hawaii and is being considered for adoption elsewhere around the world.

In spite of that early practical payoff, the basic question remained: Why was helminthosporoside host-specific? Presumably there had to be a specific site in the susceptible plant with which the toxin molecules interact. If this were the case, then analogues of the toxin (molecules with structural similarities) might interfere with the production of runners by the toxin. I cut susceptible leaves along the central rib and placed half of a leaf in a solution of melibiose or raffinose, both of which have the same alpha-galactosidic bond as helminthosporoside, or of lactose, which is similar but has a beta-galactosidic bond. The other half of the leaf was placed in plain water. After the two leaf halves had taken up their respective liquids for a day I injected each of them with a small amount of the toxin. Then I measured the extent of "water clearing," an increase in leaf transparency that presages the development of a runner and that results from the breakdown of cells and the release of intracellular fluid. The leaf halves that had taken up alpha-galactosidic compounds appeared to be protected from the effects of the toxin. Lactose and other beta-galactosides had no such effect. The results suggested strongly that there was a toxin-binding site in the cells of the leaves and that the site could also bind other alpha-galactosides, which then blocked the molecules of toxin.

Such a site could presumably be demonstrated directly and perhaps located with a radioactively labeled helminthosporoside. I labeled some toxin by culturing the fungus on sugar containing the radioactive isotope carbon 14 and applied the radioactive toxin to the leaves of a resistant clone and a susceptible one. Symptoms developed in the susceptible leaves. Then I pulverized both kinds of leaves, made extracts and put them in a chromatography column filled with a fine wetted Sephadex powder. When such a column is eluted with water, the first fraction that comes off contains large particles, including bits of membrane and proteins, that are not retained by the Sephadex granules; smaller molecules such as sugars (and the toxin) come off later. The first fractions of the extract from the susceptible leaves showed radioactivity; those from the resistant leaves did not [*see illustration on this page*]. Apparently the toxin was being bound by some component of the plant of large molecular weight.



RADIOACTIVE TOXIN was bound by a large-molecular-weight component of extracts of leaves from susceptible plants but not by extracts of resistant leaves. Leaves were exposed to toxin labeled with radioactive carbon and extracted, and the extract was put through a chromatography column. The first fractions to emerge from such a column contain large molecules. The small peak of radioactivity in the curve for the extract from susceptible leaves (*color*) indicates the binding; there is no such peak for resistant leaves (*black curve*). The large peaks represent unbound toxin, which emerges from the column later.

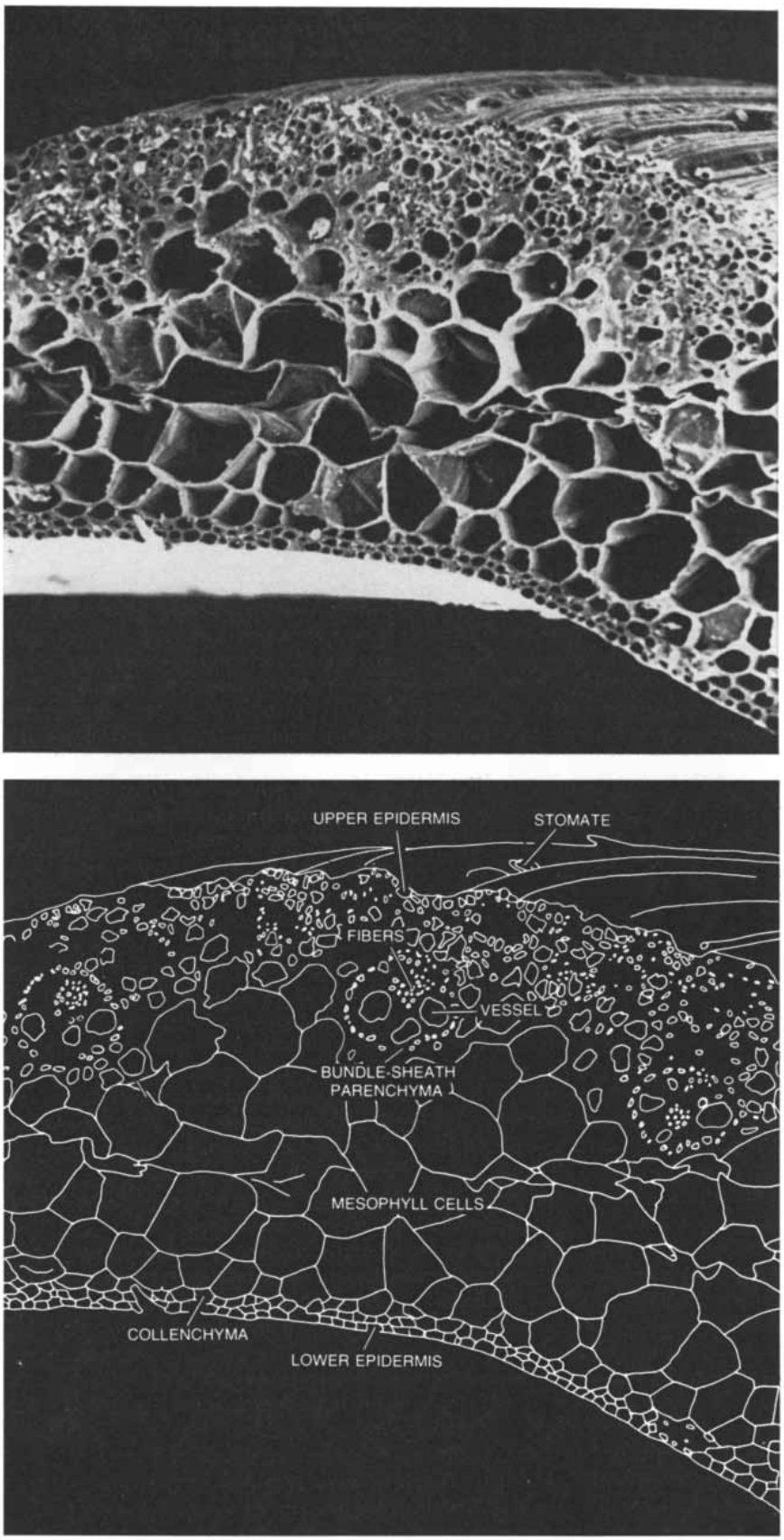
What component? Among the likely possibilities were cellular membranes of some kind. I isolated the membrane fraction of affected leaves by centrifugation and found that the centrifuged pellet had the ability to bind toxin; treating the pellet with Triton, a detergent that solubilizes the lipids and proteins of membranes, transferred the binding activity from the membrane to the detergent solution. That pointed to the membrane as the site of binding. Further tests showed that membrane fractions from clones that were resistant to the toxin (and the fungus itself) failed to bind the radioactive toxin. Membranes from susceptible clones did bind the toxin, and the most susceptible clones bound it most readily. A biochemical variable, the binding of toxin, was thus for the first time related not only to susceptibility to a disease but also to the degree of susceptibility. In addition I found that the binding activity of susceptible membranes was directly inhibited by alpha-galactosides and not by beta-galactosides. The correlation between the earlier demonstration of the effect of the galactosides on symptom production and this effect on binding again indicated that the symptoms of the disease could be attributed to the binding of the toxin.

Was the binding site on the membrane lipids or was it on a protein associated with the membrane? When membrane particles were boiled (which denatures protein), toxin binding was abolished; when they were treated with pronase (an enzyme that digests protein), the binding activity was reduced. That pointed to some membrane protein as the site of binding activity. In order

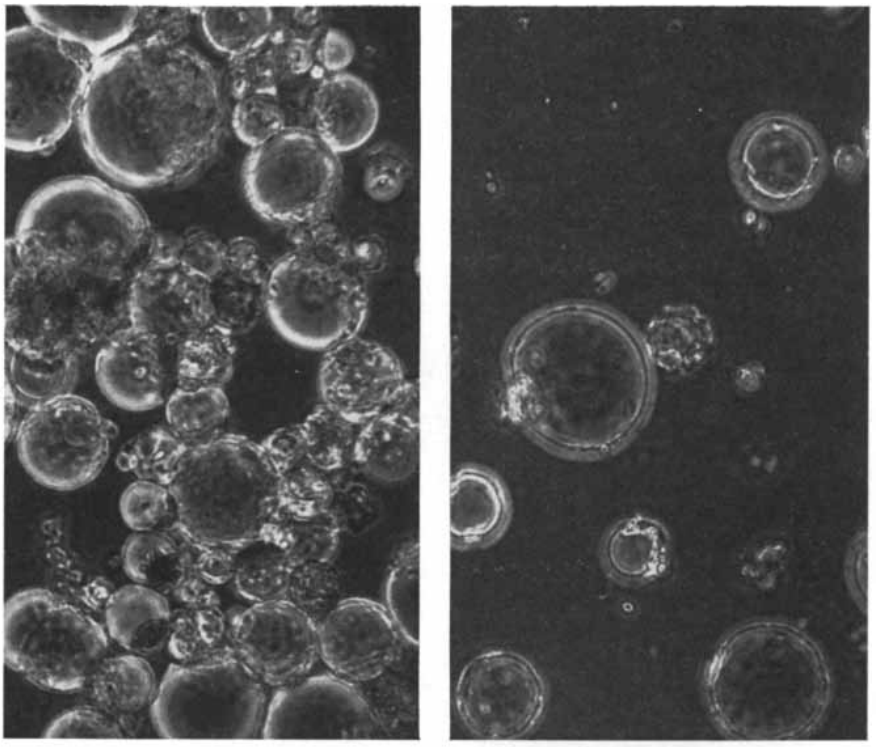
to isolate the binding protein, I next separated the protein fraction from the membranes with a detergent, exposed it to radioactive toxin and passed it through a gel-chromatography column, which separates proteins according to their molecular size. The protein that bound the radioactive toxin was easily detected as it came out of the column.

Gel electrophoresis in the presence of a strong ionic detergent, sodium dodecyl sulfate, indicated that the protein consisted of four subunits, each with a molecular weight of about 12,000, which is to say with about 110 amino acids; the intact protein had a molecular weight of 48,000. Since only one amino acid (glycine) was found to be associated with the amino ends of the protein chains and since only one subunit band could be seen on the gels, we can guess that the four subunits are identical; enough of the protein will have to be made available for full sequencing of the amino acids before that can be definitely established. The technique known as affinity chromatography was utilized by Colleen Hayes and Irwin Goldstein of the University of Michigan to purify quantities of a different protein that binds alpha-galactosides; now Kenneth Hapner in my laboratory is using that procedure to acquire quantities of the toxin-binding protein. Kinetic measurements indicate that the protein has at least two binding sites for helminthosporoside, that one site may bind the toxin more tightly than the other and that the binding of toxin at the first site may serve to facilitate binding at the second site.

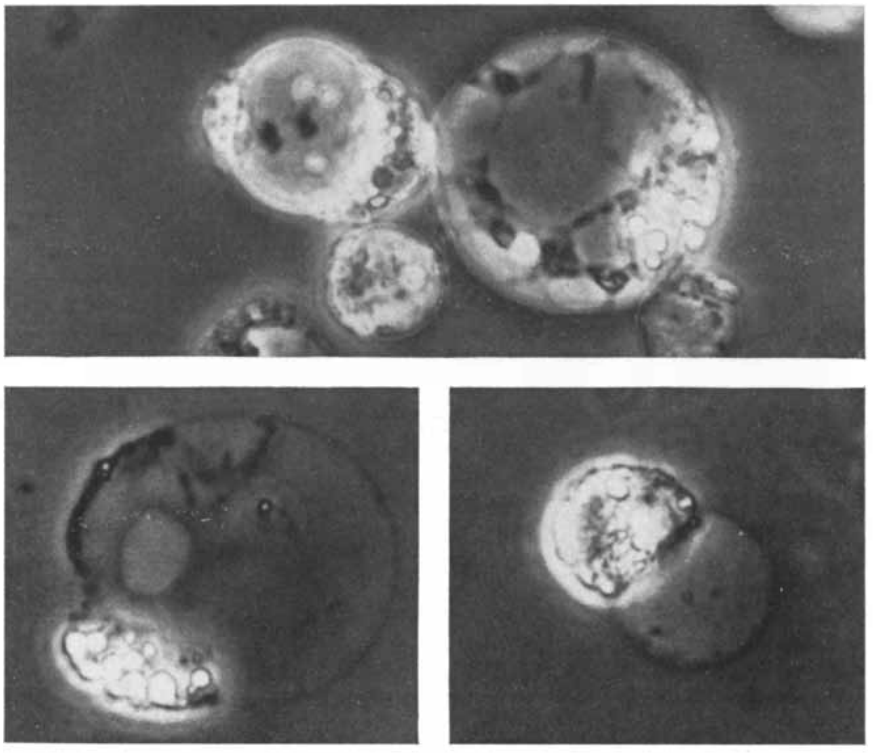
If a binding protein is present in clones that are susceptible to the toxin, what about the clones that are disease-resistant? They apparently contain a similar but nonfunctioning protein. I have isolated a four-subunit protein from a resistant clone that has a molecular weight of 48,000 and that does not bind the toxin. Certain detergent treatments somehow transform this inactive protein, however, so that it begins to bind the toxin. The two proteins, one from susceptible cane and the other from resistant cane, are identical according to standard immunological tests but can be shown to differ by four of the 110 amino acids. Presumably the slight difference in amino acid sequence is enough to alter the shape of the protein and thus account for the lack of toxin-binding activity; the difference may generate a twist or a lobe in the protein molecule that protects the binding sites from the toxin. In essence, then, it appears that the conformation of one protein makes



CROSS SECTION OF CANE LEAF is enlarged 1,800 diameters in a scanning electron micrograph made by Bill Hess of Brigham Young University (*top*); some of the structures of the leaf are named in the diagram (*bottom*). Stomates are porelike openings that allow gas and water exchange. The vascular bundles contain large dead cells, the vessels that transport water through the leaf. Parenchyma, collenchyma and mesophyll cells are living cells that engage in photosynthesis; collenchyma cells, with thick walls, also give structural support.



PROTOPLASTS are cells from which the outer wall has been removed, exposing the outer membrane. Protoplasts from susceptible leaves were incubated with rabbit serum containing antibodies to the toxin-binding protein of the cells and also with normal serum. The protoplasts exposed to antibodies agglutinated (*left*); others did not (*right*). Since agglutination is a surface phenomenon, this indicated that the binding protein is on the outer membrane. Cells are magnified 400 diameters in photomicrographs made by Donald Fritts.

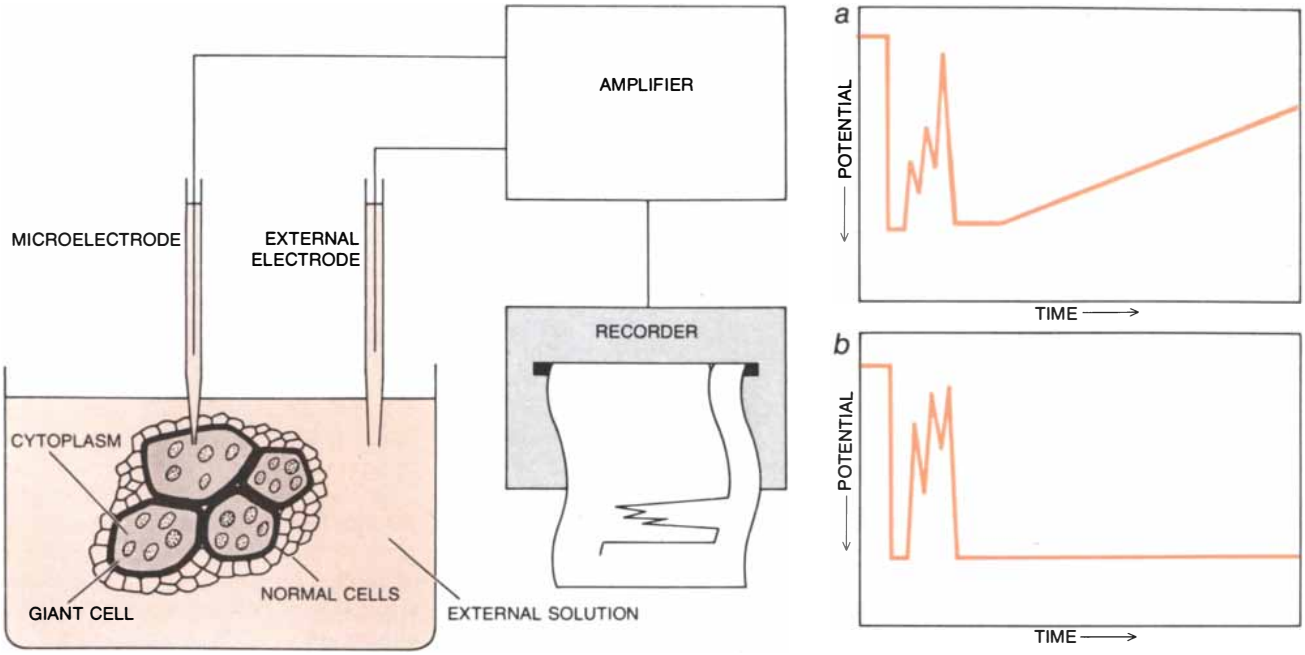


NORMAL PROTOPLASTS (*top*) from susceptible plants quickly undergo changes in size and shape (*bottom*) when they are exposed to the toxin; eventually such toxin-treated cells burst. Those events suggest that the toxin affects the cell membrane's ability to regulate the passage of ions, as a result of which fluid accumulates inside the cell. The protoplasts are enlarged some 900 diameters in these phase-contrast micrographs, also made by Fritts.

a given plant susceptible or resistant to leaf-spot disease. On further investigation we may find that a change of only one amino acid in the binding protein may be enough to render a plant resistant. Recently we have succeeded in making several resistant mutants by irradiating susceptible plants with gamma rays. All these resistant mutants specifically lack toxin-binding activity. Further study will show just how the binding protein has been changed by the radiation.

Having established that the binding protein was associated with the membrane fraction of the cane-leaf cell, we next sought to find out which one of the cell's several membranes was involved. The first clue came from an experiment with animal antibodies. I prepared antibody to helminthosporoside by injecting the toxin into rabbits and then taking blood serum from the rabbits. Leaves from susceptible plants were treated with the serum. When those leaves were subsequently injected with the toxin, they did not develop symptoms; apparently the antibodies had bound to the sites that normally bind toxin, protecting the leaves from the action of the toxin. Rabbit serum without the antibodies had no such effect. The experiment demonstrated for the first time that passive immunity can be induced in a plant by treating it with animal antibodies. It also suggested that the binding protein was located on the plasma membrane, the cell's outer membrane. That is because antibodies are very large and it was unlikely they could penetrate into the cells. It was more likely they were combining with the binding protein right at the surface of the cells. The antibodies could easily move through the cane leaf in the large vessels that transport water and nutrients and pass through the walls of those vessels to reach the adjoining living cells.

Convincing evidence for the localization of the binding protein was obtained by treating susceptible cane-leaf protoplasts, cells from which the outer wall has been removed, with purified rabbit antibodies to the binding protein. Such treatment caused the protoplasts to agglutinate just as red blood cells do when they are treated with the protein phytohemagglutin. Normal rabbit serum did not cause agglutination. Since the antibodies are specific to the binding protein, that protein must be on the membrane surface to interact with them. The cells agglutinate because there are several binding sites for the protein on each antibody molecule; each molecule can



EFFECT OF TOXIN on the cell membrane was demonstrated in an experiment conducted by Anton Novacky, M. G. K. Jones and Victor Dropkin of the University of Missouri. They induced giant cells in a cane root by infecting it with root-knot nematodes; such cells, shown here schematically, are filled with cytoplasm (unlike most mature plant cells), into which a microelectrode can be introduced to measure the difference in the electric potential between the cell and the bath solution outside it. The addition of toxin to the bath caused a drop in the potential across the membrane (*a*); addition of a control solution did not (*b*). The drop in membrane potential presumably reflects the fact that the membrane's ability to regulate the passage of ions across it is interfered with by toxin.

therefore react with two or more protoplasts and link them together.

At this point we had located the toxin-binding protein in the cell membrane and had identified it with susceptibility to leaf-spot disease. What function might such a protein normally perform in the life of the cell? Since it is on the cell surface and since it binds an alpha-galactosidic toxin, I guessed that it might normally act to transport alpha-galactosides through the membrane into the cell. I tested raffinose and found it was indeed taken up by protoplasts from susceptible cane. The toxin-binding protein bound raffinose even more avidly than it did the toxin. Susceptible protoplasts treated with toxin did not take up raffinose; the toxin, having been bound first, had blocked the available sites. In other words, the protein normally binds raffinose and then passes it across the membrane by the process known as active transport. Whereas raffinose is bound and then passed across the membrane, however, the toxin is bound and stays at the surface, which is another indication that its detrimental effect on the cell must be exerted at the outer membrane.

That detrimental effect could not be the blockage of galactosides such as raffinose, however, since the protoplasts of resistant clones, lacking the active binding protein, do not take up raffinose and nevertheless function very well. What vital activity is it, then, that is inhibited by the toxin? Anton Novacky of the University of Missouri and his colleagues looked for an effect on one of the cell membrane's primary functions: its regulation of the passage of ions into and out of the cell. Novacky worked with giant cells that he induced in sugarcane by infesting root tissue with a worm, the root-knot nematode. When he tested such cells with a microelectrode, he found that exposure of the cell to helminthosporoside caused an immediate drop in the electric potential across the membrane [*see illustration above*]. The drop indicated that the toxin interfered with the membrane's ability to regulate the passage of ions. The same thing was suggested when I exposed protoplasts of susceptible cane to the toxin: the protoplasts changed in size and shape as if in response to changes in the concentration of ions, and therefore of the amount of their intracellular fluid. Steiner and Byther actually detected a leakage of charged molecules from tissues treated with the toxin.

All of this indicated pretty clearly that the binding protein must not be functioning alone in determining susceptibility to the disease. It had to be interacting with some system concerned with the cell's ion balance. Now, one important factor in maintaining ion balance is a plasma-membrane enzyme known as potassium-magnesium-ATPase, whose effect is to regulate the cell's uptake of potassium ions. I treated plasma membranes with the toxin and found that the enzyme's activity was stimulated. The same thing was true in intact cells or tissues, with the result that their uptake of potassium was increased. Steiner and Byther noted that heating susceptible leaves in a water bath at 50 degrees Celsius (122 degrees Fahrenheit) rendered them completely resistant to the effects of the toxin; I found that the heat treatment did not affect the binding protein itself but did inactivate the membrane ATPase.

It appears, then, that the binding of toxin by the membrane protein causes the protein to activate the enzyme potassium-magnesium-ATPase. The enzyme's regulation of the movement of potassium ions into the cell is disturbed. The increased concentration of ions causes water to move into the cell through osmosis, which tends to equalize the concentration of solutions on each side of a membrane. Eventually, because of the increased osmotic pressure or the general loss of membrane integrity, the cell bursts.

Just how the toxin-binding protein influences the ATPase is not absolutely clear. The evidence suggests that the

binding of toxin changes the shape of the binding protein and thus affects the enzyme. According to a model proposed by S. J. Singer of the University of California at San Diego, proteins are inserted, somewhat like icebergs in water, deep in the two layers of lipid molecules that constitute the membrane. Information about the change in shape could be transferred from the binding protein to the enzyme either directly or indirectly, by somehow perturbing the lipid layers and affecting the ATPase at a distance [*see illustration below*]. In this case the effect seems to be exerted through the lipid because heating susceptible cane leaves to only 35 degrees C. decreases the effect of the toxin. The heat is not enough to inactivate a protein, but it could so randomize the lipid molecules that they cannot transfer the message that the binding protein has changed its shape. The temperature effect is substantiated by data from the field: Steiner and Byther have recorded a sharp decrease in leaf-spot disease in susceptible clones during the warm months, July and August.

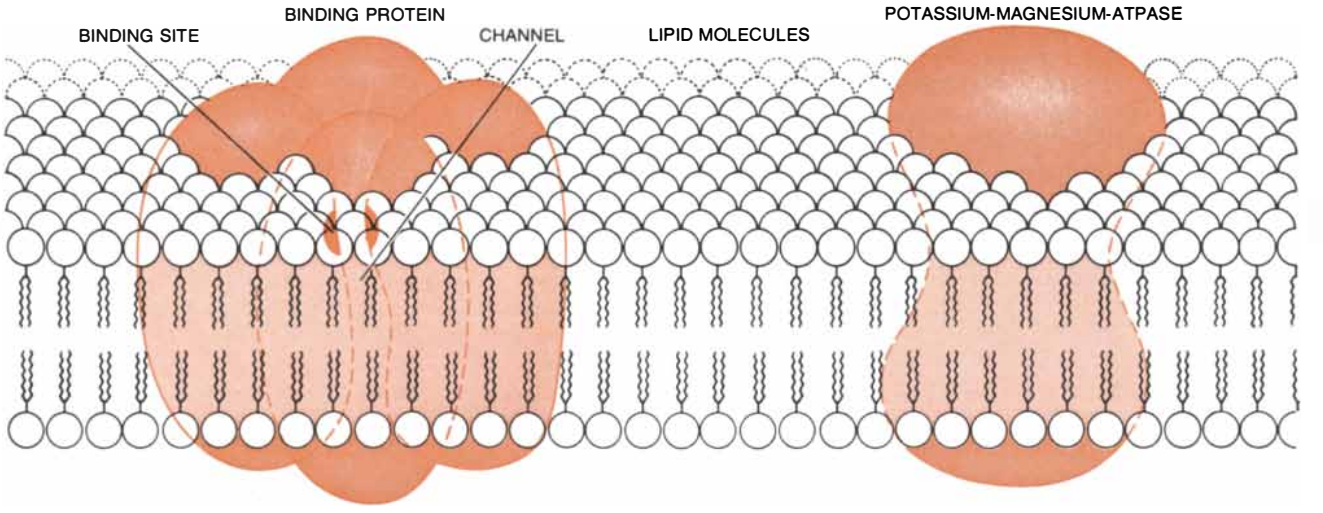
Recently, quite by accident, we discovered that for the fungus *H. sacchari* to maintain its ability to cause disease in culture it needs to be grown on a medium containing an extract of the sugarcane plant. If the fungus is maintained on a synthetic culture medium and transferred several times, it loses its ability to produce the toxin—and also its capacity to cause disease. When it is transferred back to a medium containing sugarcane extract, it again begins to produce the toxin and regains its ability to colonize the cane plant. Frederick Pinkerton in my laboratory has shown that there is a positively charged compound in the cane-plant extract, with a molecular weight of about 1,500, that has the ability to "turn on" the fungus by inducing toxin production; the compound is not present in resistant plants. We have yet to learn the nature of this inducing compound and how prevalent the induction phenomenon is in plant disease.

One can conceive of the evolution of the disease process as a series of moves and countermoves by the pathogen and the host: toxin production by the fungus is countered by the inducer mechanism in the host; the ability to bind to a host protein is countered by the development of a nonbinding analogue protein. Now, in effect, man has compressed evolutionary time by selecting resistant hosts. Possibly the next move will be made by the fungus: a strain could develop that makes a different plant toxin.

Let me summarize the process as we now understand it. A toxin, helminthosporoside, is found in spores of the fungus and is released when they germinate. The toxin is critical to the pathogenicity of the fungus: it makes way for the colonization of susceptible cane. A plant is susceptible only if it has a toxin-binding protein. Toxin is bound to that protein, which is on the plasma membrane. Binding prevents the normal flow of alpha-galactosides across the membrane but that interference is not critical. What does appear to be critical is the activation, through the binding of toxin, of the enzyme potassium-magnesium-ATPase. That activation upsets the ion balance, disturbing the cell's osmolarity, photosynthetic activity and respiration, and the cell dies.

We have begun to look for other pathogens that produce toxins recognized by substances in the host plant. Arthur Karr and Dale Karr in my laboratory have already isolated five host-specific toxins from *H. maydis,* the fungus that causes Southern corn leaf blight. The toxins specifically affect corn plants with the Texas male-sterile cytoplasm, the strains that were hit by the 1970 epidemic. Host-specific toxins have also been shown to be present in some other pathogenic fungi.

In the system that I have described susceptibility or resistance is inborn in a plant, determined by the presence of one or another form of a protein that either recognizes or fails to recognize a toxin. Similar recognition systems must be quite general in other diseases, caused by bacteria as well as by fungi and with the recognition mediated by compounds other than toxins and proteins. There are different kinds of disease resistance in plants, however, notably an induced resistance that is analogous to the antigen-antibody immunological system of animals, including humans. Plants do not produce antibodies but some of them do produce phytoalexins: compounds that are formed in a plant in response to elicitors released by certain pathogens and that proceed to inhibit or even destroy the pathogen. Phytoalexins provide another biochemical basis for disease resistance and are under intensive study in laboratories around the world.



"FLUID MOSAIC" MODEL OF A MEMBRANE suggests how the binding of toxin could affect the passage of ions across the membrane. The membrane is a double layer of lipid molecules into which proteins are inserted something like icebergs in water. The binding protein (*left*) is composed of four subunits arranged to create a transfer channel through the membrane. The binding of toxin, perhaps at two sites (*solid color*), could change the shape of the binding protein. That could perturb the lipid layer, which in turn activates the enzyme potassium-magnesium-ATPase (*right*). Activation of the enzyme would upset the ion balance of the cell.

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Moths, Melanism and Clean Air

Some light species of moths that got dark in 19th-century England are reverting to light forms as air gets cleaner. A complex process of evolution is shaped by migration as well as by visual selection

by J. A. Bishop and Laurence M. Cook

Of more than 700 species of larger moths found throughout the British Isles, the peppered moth (*Biston betularia*) is surely the best-known to students of evolution. Light in color but with small dark markings, as its common name implies, this insect flies by night and rests by day on such surfaces as the lichen-clad bark of trees. There its mottled appearance provides camouflage. At least this is true of the peppered moths found in rural areas of Cornwall, Wales and Scotland. In smoky industrial England, however, some 90 percent of the peppered moths are not mottled but melanic, that is, they are almost coal black; only small numbers of the lighter form are found in the moth population. As H. B. D. Kettlewell demonstrated experimentally in the 1950's, the reason is the birds that are the natural predators of the species kill a high proportion of the moths that are poorly camouflaged. In unpolluted areas the melanic variety is the most conspicuous; in the industrial areas it is the light variety that is least likely to survive. Air pollution is the underlying cause of this evolutionary change, and so the phenomenon is called "industrial melanism" [see "Darwin's Missing Evidence," by H. B. D. Kettlewell; SCIENTIFIC AMERICAN, March, 1959].

The melanic mutation of the peppered moth is not the only example of industrial melanism, nor is the phenomenon confined to urban England. More than 70 other species of night-flying moths in Britain have exchanged light markings for dark ones, and the same is true of moths in industrial areas of continental Europe, Canada and the U.S. Today, as the control of air quality gets more effective, the environmental conditions that have until recently put light-colored moths at a disadvantage are changing, sometimes at a rapid pace. One can predict that as selective predation decreasingly affects the light-colored moths but increasingly affects the dark ones, the evolutionary change should reverse itself. Our studies concern evidence that bears on this prediction. In reviewing the phenomenon of industrial melanism, however, it is prudent to emphasize the unknowns in what may at first seem to be an attractively clear-cut example of evolution in action.

Kettlewell's work is a classic of modern biology, and his experiments and observations have become a standard reference in texts on evolution and population genetics. Such brief accounts, however, often leave the reader unaware of the numerous qualifications Kettlewell expressed in his original papers. The fact is that many aspects of industrial melanism are still far from understood. For example, the process of change in gene frequencies has usually not reached the point where moth populations in polluted areas are made up entirely of melanics even though the forces of natural selection have now been at work for at least a century. Instead the darker and lighter forms coexist in the state known to geneticists as polymorphism.

Industrial melanism is under active study both in Britain and in the U.S. In Britain, in recognition of its bearing on a general understanding of the environment, the work is partly supported by the Natural Environment Research Council. Two problems are of dominant interest to the investigators. The first is the question of why there is a difference in the proportion of melanics found among populations of various moth species that share the same environment. The second is the cause (or causes) of continuing polymorphism. For example, our own studies have examined the role of the migration of moths in the maintenance of polymorphism. In collaboration with P. Harper of the National Medical School of Wales and J. Muggleton and R. R. Askew of the University of Manchester we have established the present pattern of frequency of the light and dark forms in populations of moths that inhabit two contrasting environments. The area we studied consisted of a region of intense urbanization and an adjacent but unpolluted rural region.

Historically the northwest of England was one of the earliest centers of the Industrial Revolution. One factor contributing to its development was the abundance of water from the rivers rising in the Pennines, a chain of mountains that extends for some 120 miles from the vicinity of Newcastle in the north to below Sheffield in the south. The mountain chain, with some crests that rise above 2,000 feet, is generally little more than 40 miles inland from the west coast of Britain and is the first high land encountered by the moisture-laden clouds that move eastward from the Atlantic. Both the rain-fed streams and the humid atmosphere were important assets in the spinning and weaving of yarn (wool at first but later cotton). The water was used as a source of power and also in the manufacturing processes; moreover, the humidity reduced the breakage of yarn.

Mill towns developed along the Pennine foothills: Bolton, Bury, Rochdale, Oldham, Ashton-under-Lyne, Stockport and many smaller centers. Manchester became not only a manufacturing city but also a distributing center and a hub of commerce. Liverpool, some 30 miles to the west, was the nearest seaport. Between the end of the 18th century, when industrial development began, and the middle of the 19th century the use of waterpower was gradually supplanted by steam. Coal, which was abundant in the region, was the fuel for the boilers.

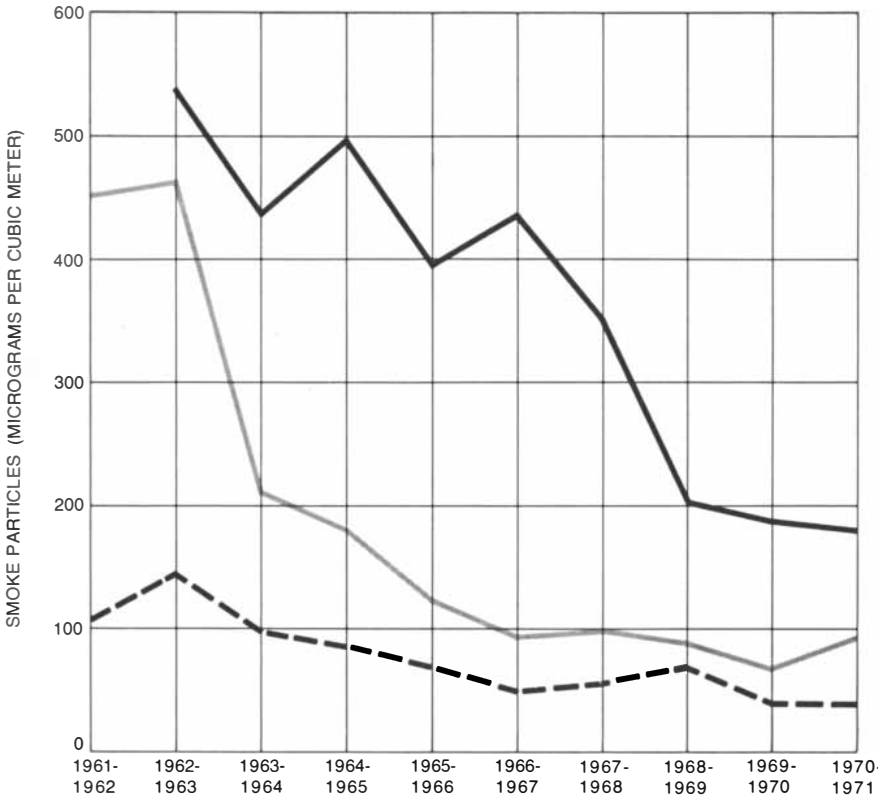
It was also the fuel for household hearths, and the population was on the increase.

The inhabitants of Manchester numbered about 10,000 early in the 18th century. By the beginning of the 19th century the population of the city was 70,000; in 1850 it was 300,000. Before 1900 the population had risen to more than half a million. The novelist Elizabeth Gaskell, a local resident, witnessed much of the change. In one of her books, published in 1855, she describes the impressions of a family approaching Manchester for the first time. They were traveling by rail. "Quick they were whirled over long, straight, hopeless streets of regularly built houses, all small and of brick. Here and there a great oblong, many-windowed factory stood up, like a hen among her chickens, puffing out black 'unparliamentary' smoke, and sufficiently accounting for the cloud which Margaret had taken to foretell rain."

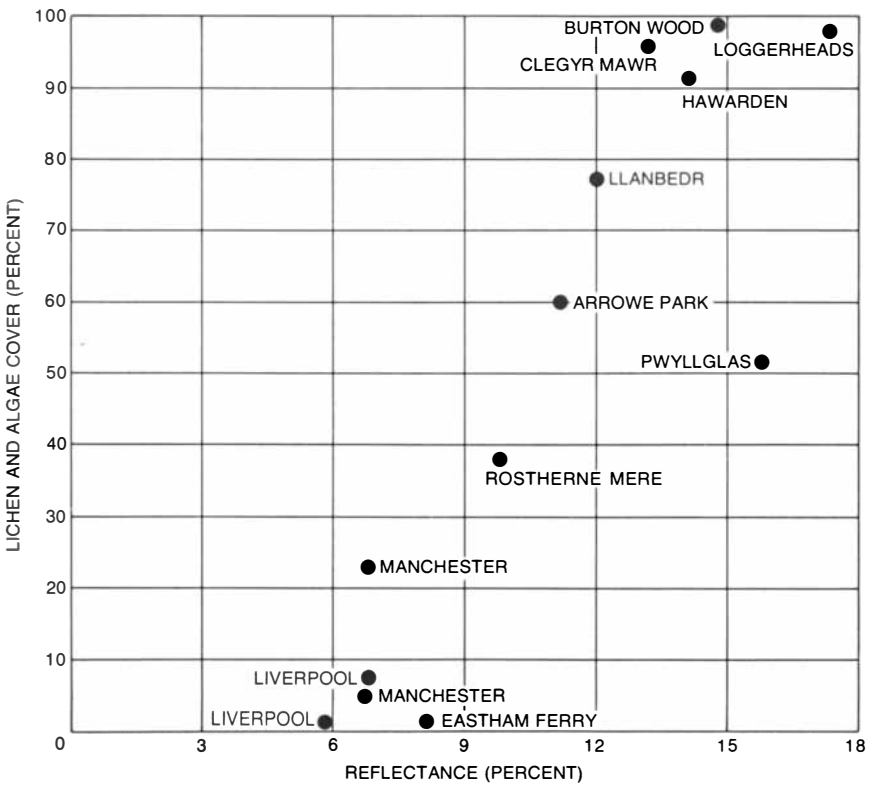
In a humid region subject to temperature inversions the daily release of great quantities of combustion products from homes and factories created an environment conducive to the rise of industrial melanism in several species of insects and other arthropods. Dark mutants appeared not only among moths other than the peppered moth but also among ladybird beetles and even spiders. Just as more than one factor contributed to the rise of industrialization, so the evolution of various industrial melanics cannot be attributed to the effects of coal smoke alone. As numerous studies have suggested, the effect of other pollutants was involved, acting either directly on the organisms that gave rise to mutants or indirectly on other organisms, such as algae and lichens. In addition the distribution of melanics has been shown to be strongly influenced by topographic and meteorological variations.

The time of the initial onset of industrial melanism is tantalizingly difficult

TWO PEPPERED MOTHS rest on the dark bark of an oak tree near Liverpool (*top*); the melanic, or black, form is better camouflaged than the typical light form. Until recently most trees near English industrial cities were like this oak. On a nearby beech tree that is more readily colonized by algae and the lichen *Lecanora conizaeoides* now that air quality is improving, the two forms of the moth are equally conspicuous (*middle*). On the light-colored, lichened bark of an oak tree in rural Wales the typical light peppered moth is almost invisible (*bottom*).



SMOKE POLLUTION has been reduced in English industrial cities by clean-air policies and redevelopment. The curves show the mean deposition of smoke particles during the winter in Salford, an industrial city near Manchester (*black curve*), in the Manchester suburb Withington (*gray curve*) and in Oxford, a city with modern industry (*broken curve*).



TREE TRUNKS ARE LIGHTER the more they are covered with lichens and algae. The cover increases with distance from industry. Here the reflectance of oak-tree trunks (as a percent of the reflectance of a standard white pigment) is plotted against the percent of the trunk, a meter and a half from the ground, that is covered with lichens and algae. Oaks are less favorable to the growth of such plants than some other species, such as beech.

to pin down. The first person in the area who is known to have captured a dark-colored peppered moth was an active lepidopterist, R. S. Edleston, who obtained a specimen in 1849. Edleston lived about a mile from the center of Manchester in the 1840's, and since he was an avid collector it seems safe to assume that the melanic mutants were rare in his day or else he would have captured more than one. In 1875 melanic peppered moths were still rare enough to merit frequent mention in the "readers' queries" section of the periodical *Entomologist*. J. Chappell, another collector, noted that melanic peppered moths had increased in proportion during his lifetime, so that by 1886 they were far commoner than nonmelanic moths.

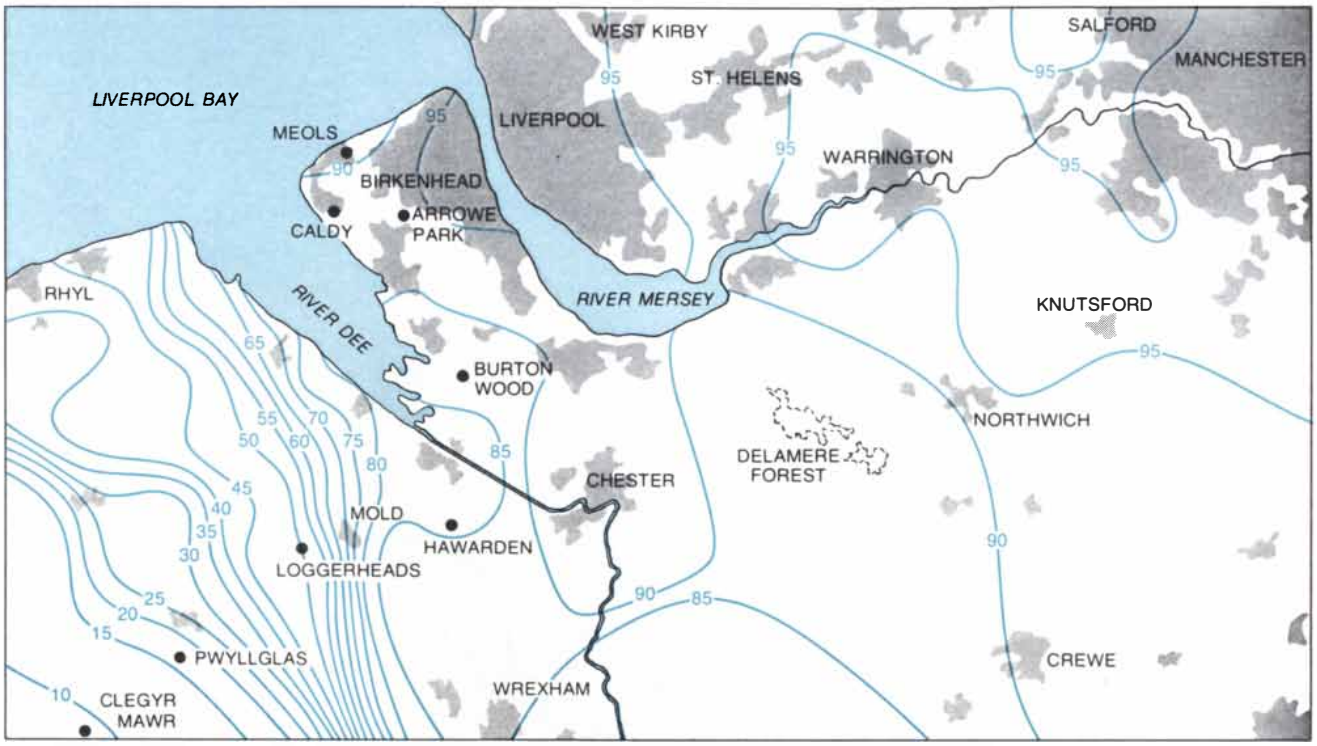
In the same period the effect of air pollution on the lichens that colonized the bark of trees, beeches in particular, was recorded. In a description of the flora of Manchester published in 1859 it was noted that the quantity of lichens "had been much lessened of late years." By piecing together such scraps of information one can build up a picture of the change that was taking place. Evidently a rather short interval—the years between 1850 and 1890—was involved. The interval coincides precisely with the most rapid increase in the human population and the attendant rise in the amount of household coal consumed.

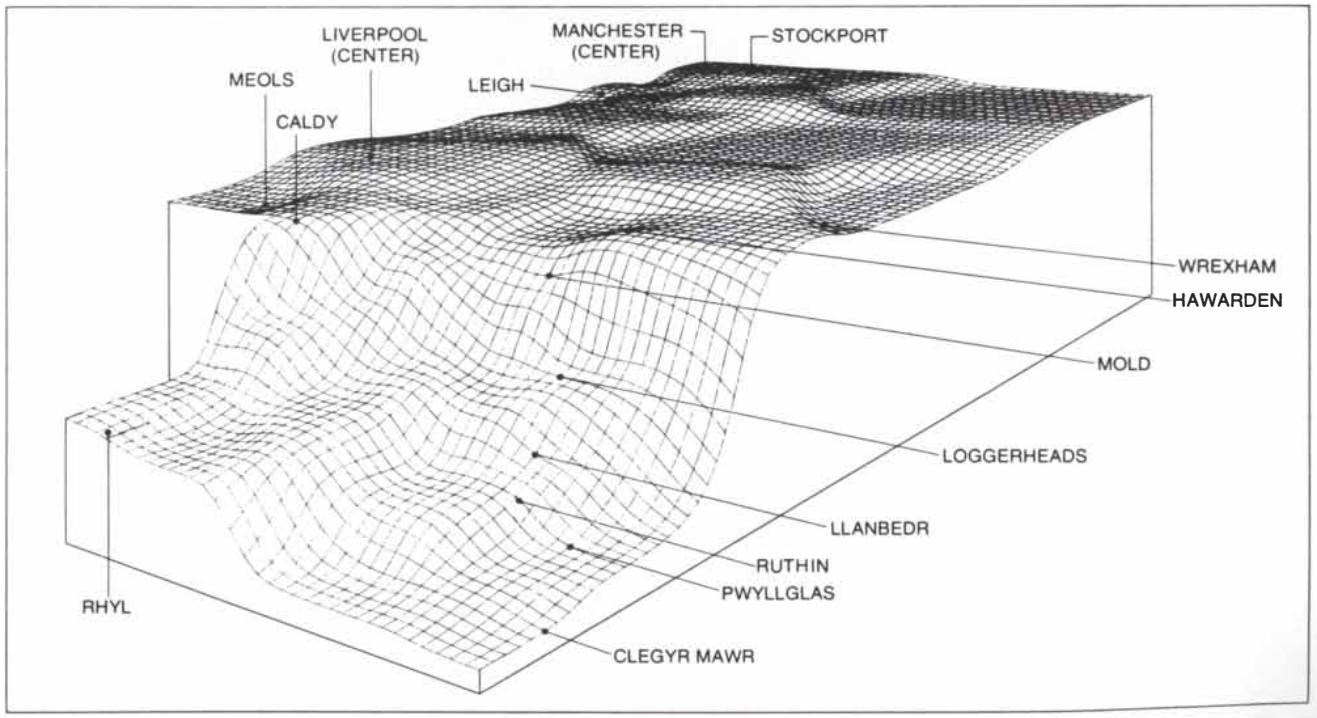
The effect of atmospheric pollution on human health had not gone unnoticed. By 1844 there was already legislation to control the smoke emitted by industrial furnaces in Manchester. It was not entirely effective; hence the "unparliamentary" blackness of the smoke described by Mrs. Gaskell. In 1866 the Medical Officer of Health in Manchester declared that the city's citizens were among the most unhealthy in Britain and related their condition to the state of the atmosphere. Only some 80 years later, following World War II, was anything significant done to improve the situation; before then commercial considerations had prevailed. Today the improvement in the quality of the air makes it possible to see vistas of Pennine scenery from Manchester that have been virtually invisible for more than a century.

The biological effects have also been noticeable. In particular there has been an increase in the quantities of algae and lichens growing on tree trunks in both Manchester and Liverpool. Whereas previously all the trees in the vicinity of the cities were uniformly blackened, the color of some of their surfaces has

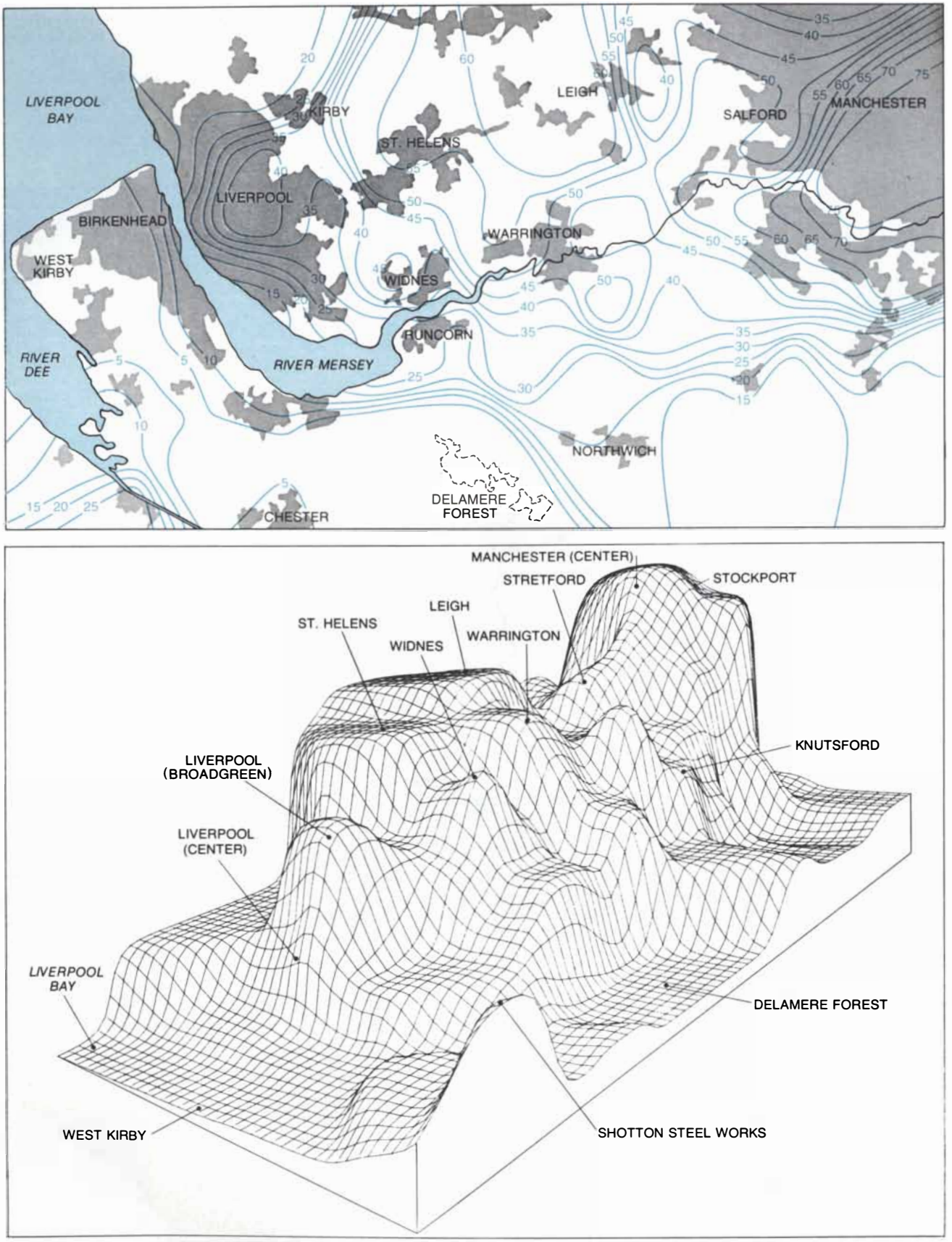
changed. English oaks, trees that are inhospitable to algae and lichens, remain dark, but the bark of the beech trees, some years earlier almost as blackened as the oaks, has become green as colonies of algae and lichens reappear. There is nonetheless a very long way to go before the region is restored to its preindustrial state.

The condition of tree trunks as resting sites for moths has been studied by E. R. Creed, J. G. Duckett and D. R. Lees of the University of Wales. With their methods we have recorded a striking increase in light reflectance and extent of colonization by pollution-sensitive lichens along a 30-mile corridor extending from industrial northwestern England into rural northern Wales [*see bottom illustration on opposite page*]. In this region of sharp transition the pro-





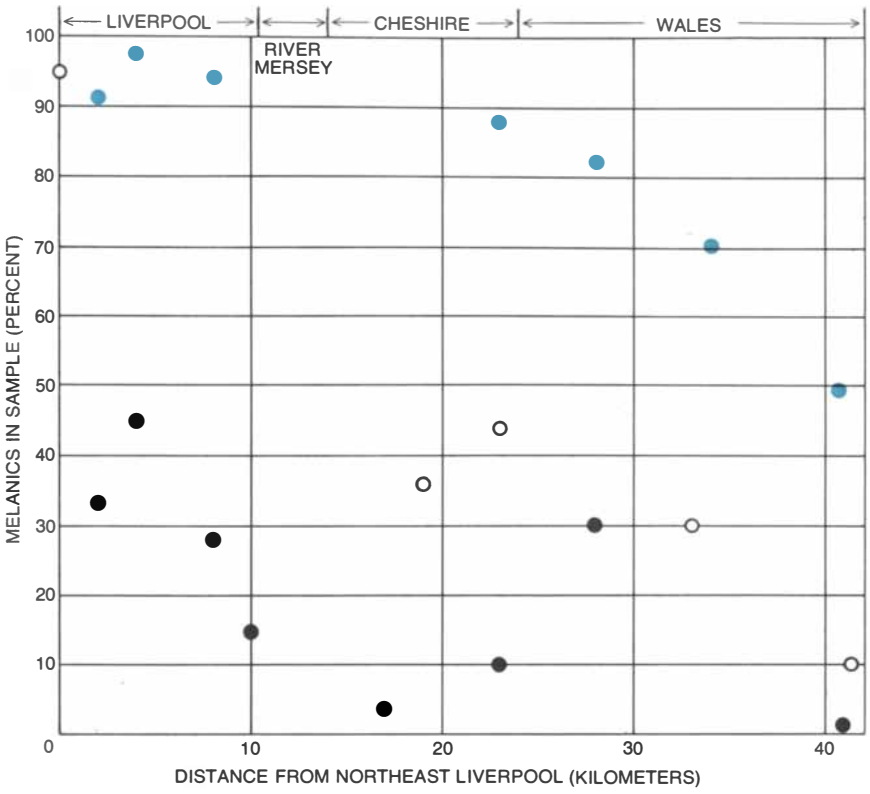
DISTRIBUTION OF MELANIC PEPPERED MOTHS in northwestern England and adjacent areas of Wales is shown on a contour map (*top*) and on a perspective diagram (*bottom*), both drawn by computer and based on samples of moths from more than 100 sites. The contours give the frequency of the melanic form as a percent of the total sample. The contours are converted into elevations in the lower diagram; the hills are areas where the melanic form is common. The surface is viewed from the southwest, from rural Wales. The frequency of the melanic form falls gradually as one moves away from cities, with a major decline evident in Wales.



MELANIC SCALLOPED HAZEL MOTHS are mapped here in the same way that melanic peppered moths were mapped on the preceding page. The area covered is more restricted but again the perspective diagram is seen from the southwest. There are striking differences between these data and those for the peppered moth. The frequency of scalloped hazel moth melanics falls sharply south of Manchester and more gradually west of the city. There is more variation (*hills and valleys*) in frequency, coinciding with industrial or rural environments. Melanic peppered moths remain at high frequency throughout the area covered by these diagrams.

portion of melanic moths in the local moth population is influenced both by natural selection on the spot and by the migration of moths from other areas where the effect of natural selection is not the same; a moth emerging from its cocoon in one area will often die in another area where the pollution level is quite different.

The corridor leading to Wales was first studied in this context by C. A. Clarke and P. M. Sheppard of the University of Liverpool; the peppered moth was the object of their study. We have investigated two other species of moth that also have populations made up of light and dark forms. Much of our work has been done within the corridor, but we also extended the study area as far east as the Pennines. The two species are the scalloped hazel moth (*Gonodontis bidentata*) and the pale brindled beauty moth (*Phigalia pilosaria*). Our initial objective was to determine the pattern of distribution of melanic moths in the region between Manchester and northern Wales, in the hope that the survey would provide a yardstick for measuring the reversal of the earlier evolutionary change.



FREQUENCY OF MELANIC FORM is different in various species, as indicated by a comparison of the illustrations on the preceding two pages and as plotted here. In each species the proportion of melanic moths decreases with distance from Liverpool (*left*), but the frequency is generally higher for the peppered moth (*colored dots*) than for the scalloped hazel moth (*black dots*); data for the pale brindled beauty (*open circles*) fall in between.

We sampled the moth populations at more than 100 trap sites, luring the moths with mercury-vapor lamps or with females (which broadcast sex-attractant pheromones). The numbers of light-colored and dark-colored moths that were trapped were our raw data: the counts were weighted in terms of sample size and were converted by computer into contour maps and perspective views showing the proportion of melanic moths throughout the region [*see illustrations on page 93 and on opposite page*].

The graphic printouts showed that melanic moths were most numerous in populations sampled in urban areas where air pollution was the greatest. Away from towns and cities, particularly toward the southwest, the number of melanics fell rapidly. In the case of the scalloped hazel moth the drop in the number of melanics was most dramatic due south of Manchester. The gradients were just what one would have predicted on the basis of Kettlewell's studies.

Our data show a striking feature that is less readily understood: within the same areas there are obvious and major differences between the ratio of melanics found in each of the three species of moth. The proportion of melanics in a population of scalloped hazel moths is invariably lower than the comparable figure for a population of peppered moths. Where the data are available the proportion of melanics in populations of pale brindled beauty moths is intermediate [*see illustration above*]. The reason for these differences is only partly understood. Evidently they result from an interaction of some kind between, on the one hand, the expression of the gene for melanism and, on the other, the environment and unidentified aspects of species behavior and ecology.

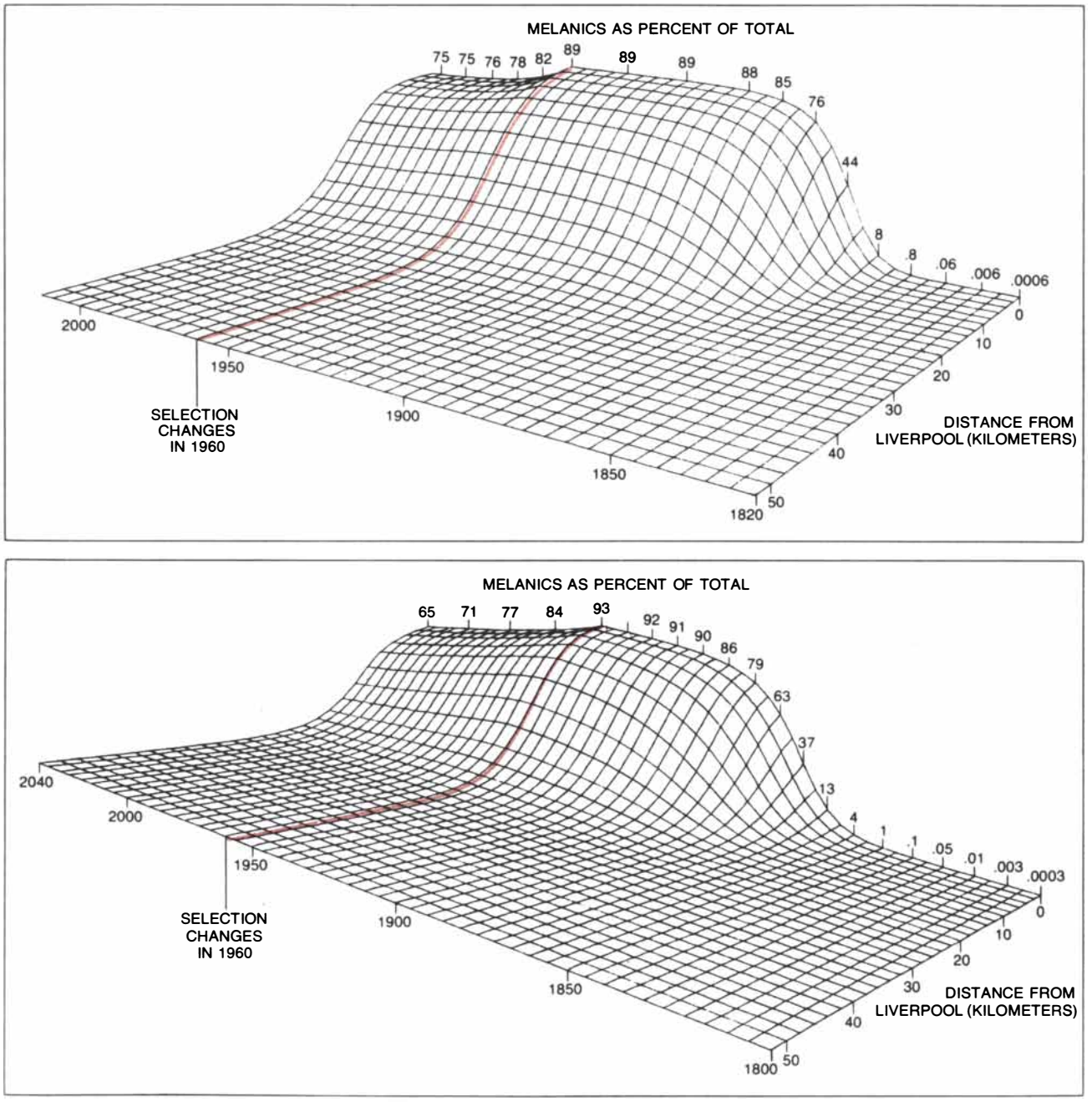
Consider first the expression of the genes for melanism. Genes, of course, are carried on chromosomes. Since chromosomes come in pairs, each gene is represented twice: once on one chromosome and once, at the same position, on the other. In the three species of moth we are studying, the genes that determine melanism are dominant, so that the presence of one gene for the trait will mask the expression of the recessive gene that determines the typical, nonmelanic form. As a result there are two genetically distinct types of melanic moth. One is a heterozygote, with one melanic gene and one typical gene (Cc or cC). The other is a homozygote, with two melanic genes (CC).

A possible explanation for the differences in the numbers of melanics in the three moth species is that the heterozygotes are "fitter," that is, they give rise to more surviving offspring, than either the dominant homozygote (CC) or the recessive homozygote (cc). This postulated superiority in fitness would not, of course, be evident in the dark coloring of the moths; in industrial areas the melanic homozygotes have the same visual advantage as the melanic heterozygotes. It would be some nonvisual disadvantage that reduces the fitness of the melanic homozygote compared with the heterozygote. Under these circumstances the differences in the number of melanics found in comparable populations of the three species would reflect a similarity in the melanics' visual advantage but a difference between homozygote and heterozygote with respect to nonvisual advantages.

The perspective displays of our data show variations between the moth species in their degree of local differentiation. For example, the "hills" and "valleys" in the display of the scalloped hazel moth are much more marked than those in the display of the peppered moth. This difference is readily explained as a consequence of the difference in the two species' population

structures. In some areas scalloped-hazel populations are extraordinarily dense: as many as 50,000 to 100,000 moths per square kilometer per night. The corresponding figure for the peppered moth is as little as 10 per square kilometer.

The difference in density of population has one obvious consequence. A peppered moth is likely to have to travel a great deal farther to encounter a mate than a scalloped hazel moth. In capture-recapture experiments we released marked peppered moths in a parkland area of the Wirral peninsula; our traps were set at an even density at distances up to five kilometers from the release point. A significant proportion of the 1,433 moths we released flew one kilometer or farther before they were recaptured. Scalloped hazel moths, however, seldom flew more than 150 meters. Thus the scalloped hazels do not disperse their genes as far as the peppered moths. This gives rise to a much greater local differentiation of populations, thereby giving the scalloped-hazel display its rugged appearance. The rate of peppered-moth gene dispersal is greater, and so the three-dimensional display for this species is correspondingly smoother.



COMPUTER MODELS show how the proportion of melanic peppered moths may have developed, as a result of the interplay of natural selection and movement, over time and with distance from Liverpool. In the top diagram it is assumed that the melanic heterozygote has a 10 percent nonvisual selective advantage over the melanic homozygote. In the diagram at the bottom no heterozygous advantage is postulated. In both models it is assumed that the frequency of the melanic moths in Liverpool was about 1 percent in 1850 and that there has been no visual selective advantage for either the typical or the melanic form since 1960. The frequency of melanic moths increases more rapidly when the heterozygous advantage is assumed, but the values that are finally attained in 1960 are similar. When heterozygotes are at advantage, a new stable equilibrium is reached (at 75 percent) after environment changes.

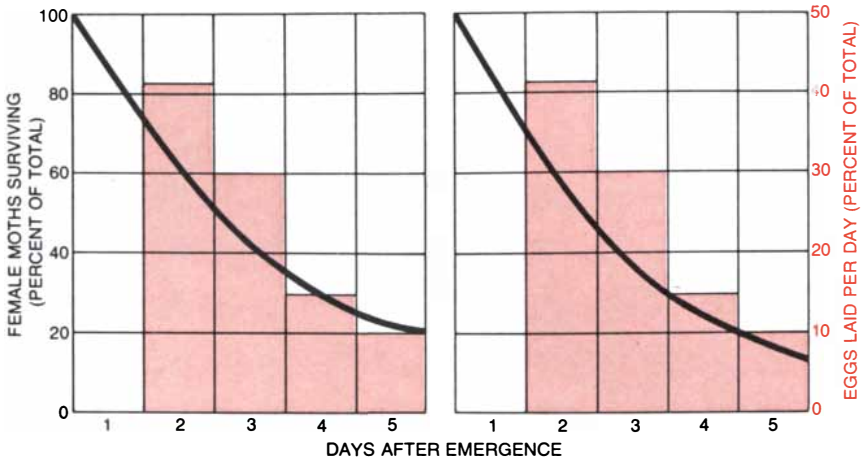
As a further example of the greater homogeneity of populations in moths that range widely we cite the yellow underwing moth (*Triphaena pronuba*). C. E. M. Dale of the University of Manchester has investigated the mobility of this species, and he has found that it migrates considerably farther than the peppered moth. The yellow underwing moth is a polymorphic species, although none of its forms can be regarded as being an industrial melanic. It is significant that the proportion of the moth's various forms in local populations is almost invariant: the average difference in frequency between populations sampled in southern England and Scotland is less than 5 percent.

A third striking feature of the graphic displays of our data is the gradient with respect to melanism in peppered-moth populations as one moves away from Liverpool toward northern Wales. To assess the part that natural selection played in this phenomenon we undertook an experiment along lines first followed by Clarke and Sheppard. Natural selection is measured by assessing the comparative ability of two or more organisms that differ genetically to produce offspring in a given environment. In effect, will one live and breed longer than another? To make such an assessment one must compare each organism's "life table," that is, the probability that an individual will survive to a particular age, along with its age-specific birth rate, that is, the number of offspring produced by the females in each age category.

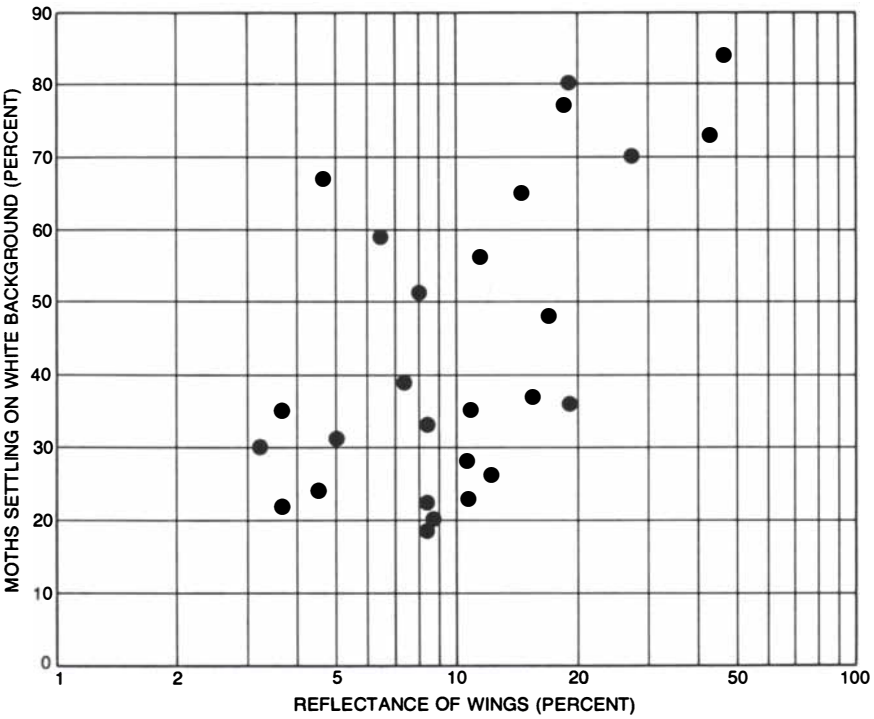
Our experimental procedure was to kill peppered moths, fix them in lifelike positions and glue them to trees chosen at random in each of seven areas of woodland between Liverpool and northern Wales. Equal numbers of melanic and nonmelanic moths were set out. After 24 hours of exposure the number and kind of moths that had been eaten by birds were noted and another series of moths was set out on a different group of trees. At the same time we estimated the number of eggs deposited by female moths of different ages.

Analysis of our figures showed a steady increase in the selective advantage enjoyed by nonmelanic moths, compared with melanic ones, as the distance from Liverpool increased. The estimated selective values correlated well with the change in the appearance of tree trunks that we had measured earlier.

Working with these natural-selection data and our information on moth migration, we constructed a computer model of how the observed gradient might have developed from its inception, assuming that the frequency of melanic moths in Manchester and Liverpool in 1850 was about 1 percent [*see illustration on opposite page*]. The computer model has not been a complete success: the synthetic gradient is considerably more displaced toward industrial Lancashire than the gradient observed in nature. The discrepancy may indicate that we are not correctly assessing the true nature of the resting sites of living moths when we are conducting experiments with dead ones. Alternatively, the assumption that natural selec-



SELECTIVE ADVANTAGE of one or the other form was determined by comparing the day-by-day survival rate of female moths (*black curves and scale at left*) with the proportion of the total number of eggs laid per day (*colored bars and scale at right*). These data from a polluted locality near Liverpool showed that the melanic female (*left*) had a greater chance of surviving to reproduce in that environment than the typical female did (*right*). Away from Liverpool the situation was reversed: the typical form had a selective advantage.



MOTHS TEND TO REST on backgrounds they resemble. Moths of 27 different species were provided with a surface containing equal areas of black and white. Here the proportion of each species that rested on the white surface is plotted against the average reflectance of its fore wings (as a percent of the reflectance of a standard white pigment). There is an obvious relation between lightness of wing color and preference for a white surface. The data were collected by Margaret Boardman, a student at the University of Manchester.

tion is entirely due to selective predation by birds may be mistaken. For example, in nature melanic moths remain common in areas where theoretically the birds should have exterminated them. Some factor may be counterbalancing the melanics' disadvantage, perhaps acting during the larval or pupal stages that make up most of the moths' life history. Complexities of this kind still remain to be investigated.

Is there any evidence that a reversal in frequency of industrial melanics has in fact begun? Changes in gene frequency progress slowly when the number of individuals possessing the favored mutation is low; hence we should not expect an immediate substantial response to the quite recent improvements in the quality of the air. Nevertheless, small but significant changes have already been observed. The first was noted by Clarke and Sheppard at a locality on the Wirral peninsula where they sample the moth populations each year. Between 1961 and 1964, following the introduction of local "smokeless" zones, they found that the frequency of nonmelanic peppered moths increased from 5.2 percent to 8.9. By 1974 the proportion had risen to 10.5 percent. In a less systematic investigation in Manchester we have found that, whereas there were no nonmelanic peppered moths in samples taken during the late 1950's and early 1960's, they now represent about 2.5 percent of the samples. Finally, Creed has reported an increase in Birmingham beginning in 1962 in the frequency of nonmelanic forms of the ladybird beetle (*Adalia bipunctata*), a species distasteful to birds that for some unknown reason also includes melanic mutants. It is therefore probably fair to conclude that the reversal of industrial melanism is now under way.

The factor generally accepted as being responsible for the maintenance of polymorphism in industrial melanics is that a balance is achieved through the advantage of heterozygous animals. Some alternative possibilities nonetheless seem worth considering. For example, suppose that in some localities a polymorphic species of moth rests on tree bark on which colonies of lichens are distributed in patches. Suppose further that the individual moths settle and move onto the background where they are least conspicuous. Under those circumstances the melanics would have an advantage over the nonmelanics on bare bark, whereas the reverse would be true on patches of lichen. Provided that there was competition for resting sites, such a

situation would maintain polymorphism in the species without any need to postulate that the heterozygote has an advantage over the homozygote.

When the frequency of one form or another diverged from the equilibrium level, the individual moths present in excess numbers would be forced to take up positions where they were conspicuous. Thus exposed to predation, they would tend to be eliminated, and so equilibrium would be restored. A mechanism of this kind could be at work among the populations of scalloped hazel moths, which are found in dense colonies and do not fly far.

A similar possibility may apply to the peppered moth. Sufficient migration between polluted and unpolluted localities may take place to maintain polymorphism in populations at both extremes. The evidence suggests this possibility; peppered moths do migrate between areas where the degree of pollution and selective predation differs widely. For example, the proportional changes observed in the region including northwestern Cheshire and southwestern Lancashire could be attributed to this mechanism without invoking the heterozygotes' advantage.

An unexplained aspect of melanic polymorphism is the difference in gene frequency seen in the three moth species we have studied. It is, of course, possible that visual selection is of similar magnitude in all three species and that, as we have suggested, it is balanced by different degrees of nonvisual selection against homozygotes. Yet we know that moths vary greatly in their preferred resting sites [*see bottom illustration on page 97*]. Similarly the range of sites with a good match to the moths' wing patterns also varies. Therefore at least in theory the observed differences in equilibrium frequencies among the three species can also be accounted for by density-dependent selection working at varied resting sites.

These last comments are frankly speculative. If we are to fully understand industrial melanism, the nonvisual differences between melanic and nonmelanic moths must be studied more intensively. Such studies may well prove that the heterozygotes' advantage is established over a wide range of environmental conditions and is present in most or all polymorphic species. Nevertheless, the data now in hand are equally explicable by a system of density-dependent selection. It is clear that in future theoretical studies of the peppered moth the species' high migration rate and low population density cannot be ignored.

THE COPROLITES OF MAN

Archaeologists have unearthed fossil human feces that range in age from a few hundred to 300,000 years. Analysis of their contents is yielding information on prehistoric diet, environment and behavior

by Vaughn M. Bryant, Jr., and Glenna Williams-Dean

The human fossil record is short and scant, but it does offer a source of information about behavior that is not available to those who study the fossils of, say, dinosaurs. Where conditions favor the preservation of organic matter archaeologists frequently uncover desiccated human feces in or near prehistoric camps and dwellings. Objects of this kind, known to paleontologists as coprolites, are not uncommon among the remains of animals older than man; in fact, some sedimentary rocks consist largely of the fecal pellets of certain marine animals. These ancient coprolites, however, have become petrified, which makes it virtually impossible to analyze their original organic contents. Such analysis can now be routinely undertaken with human coprolites, thanks to laboratory techniques developed in the past decade. Analysis of coprolites ranging in age from the middle Paleolithic period to late prehistoric times is providing scholars with remarkably specific evidence on the diets and seasonal activities of early hunters and farmers in both the Old World and the New.

The excavator in the field may be unable to distinguish between the coprolites of man and those of other animals, but laboratory analysis as it is practiced today almost always yields a correct identification. The key step in the procedure, pioneered in the 1960's by the late Eric O. Callen of Macdonald College in Canada, is the immersion of the specimen in a dilute solution of trisodium phosphate. In the Anthropological Research Laboratories of Texas A&M University, where we have done most of our own work, we immerse the specimen for a minimum of 72 hours. If the specimen originated with an omnivorous or carnivorous mammal, the fluid usually remains translucent; if it is colored at all, the color is a pale brown. If the specimen originated with a herbivorous mammal, the fluid is translucent and sometimes yellowish. If the specimen is of human origin, the fluid is opaque and dark brown or black. Only one mammal other than man, the raccoonlike coatimundi, is known to leave feces that give rise to a similar chemical reaction.

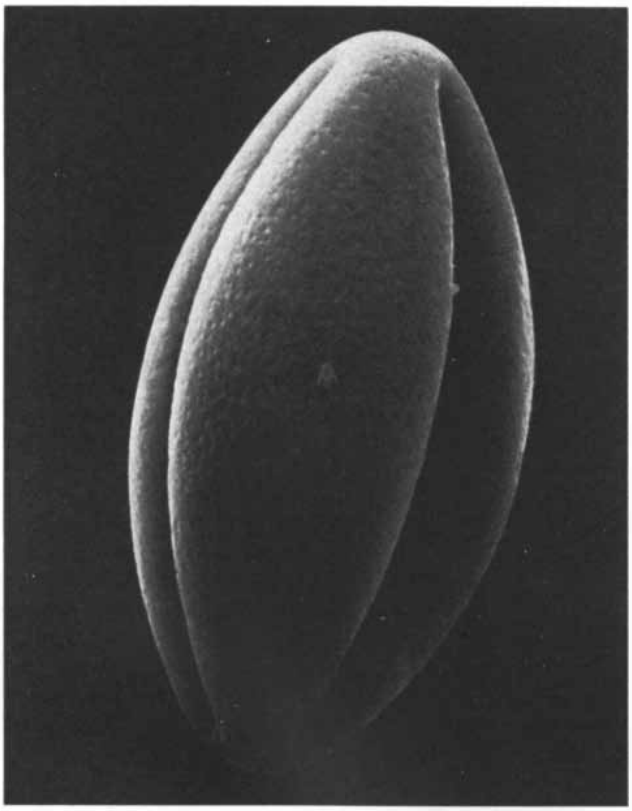
If the results of the reaction are not conclusive, further steps are almost certain to dispel doubt. The sample is passed through a 20-mesh brass screen, which passes particles smaller than 850 microns, and then through a 100-mesh screen, which passes particles smaller than 150 microns. At both stages the retained material is gently washed with distilled water so that any fine particles, such as plant pollen, that still adhere to the larger debris can also pass through the mesh. The solid residues trapped on both screens are dried and prepared for examination under the microscope. The liquid fraction is centrifuged to collect pollen grains, plant crystals and any other small objects it contains.

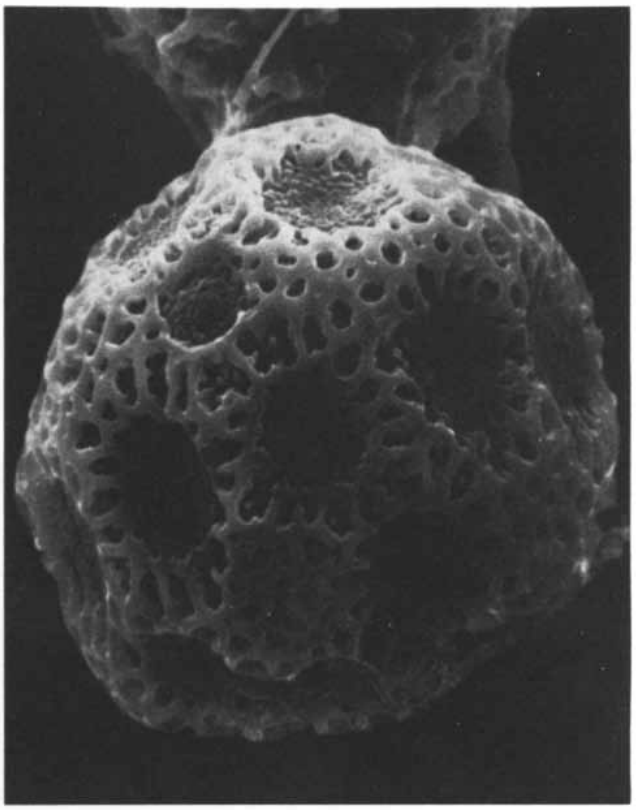
Since the human diet characteristically consists of both plant and animal material, and since human beings have for at least half a million years processed their food by fire, the solid residues retrieved by screening include materials from a wide variety of sources. Along with bits of charcoal picked up in the course of cooking there may be plant fibers, cracked or milled seeds, hairs and fragments of bone, nutshell, eggshell, mollusk shell, feathers and the hard parts of insects. A few of these materials may be present in nonhuman coprolites, but when they are found in great variety, the specimen is almost certainly human. Moreover, if the specimen's pollen content is taken into account, the possibility of confusion between a human source and a nonhuman one can be still further reduced.

In principle it is possible to glean from such material information not only about the dietary preferences of groups and individuals but also about an individual's state of health (as indicated by the presence or absence of parasites), about techniques of food preparation, about the seasons of the year when a site was inhabited and about contemporary environmental conditions. In practice most of the information concerns dietary preferences and seasonal activities. For example, pollen analysis reveals that some 2,800 years ago the Archaic Indians of southwestern Texas collected and consumed the flowers of a number of desert and semidesert plants. Whether the flowers were sucked or chewed for the nectar they contained, were brewed into tea or were put into salads is more difficult to determine; perhaps they were consumed in all three ways.

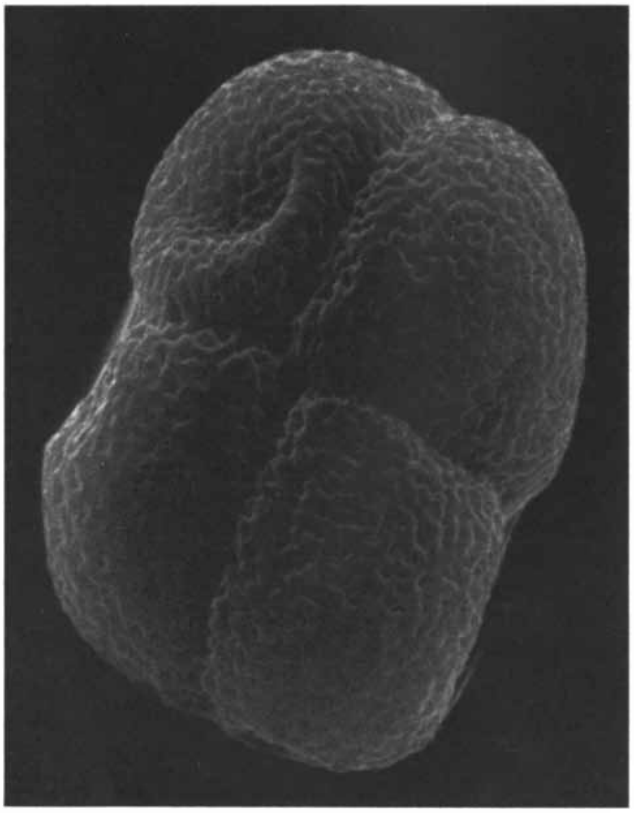
Seeds have a hard test, or outer coat, that resists digestion. A test or even a fragment of one usually has a characteristic shape or surface pattern that makes it possible to identify the plant family, and perhaps the genus and species. An example of seed-fragment analysis that illuminated ancient food-preparation techniques is Callen's study of coprolites from Tehuacán, a site in Mexico that embraces some 12,000 years of New World prehistory. Some of the fragments of millet tests Callen recovered showed evidence of crushing, indicating that the grain had been prepared by pounding. Other fragments showed evidence of splitting, indicating that the grain had been prepared not by pounding but by being rolled back and forth on a stone *metate*.

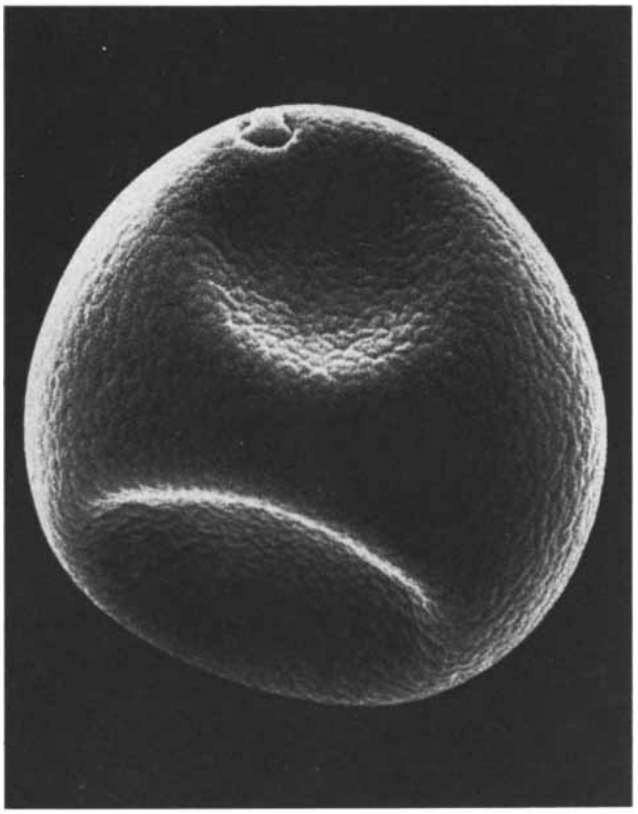
We ourselves gathered interesting information on techniques of food preparation in a study of coprolites from a rock-shelter in southwestern Texas. Fragments of cactus-seed tests in speci-



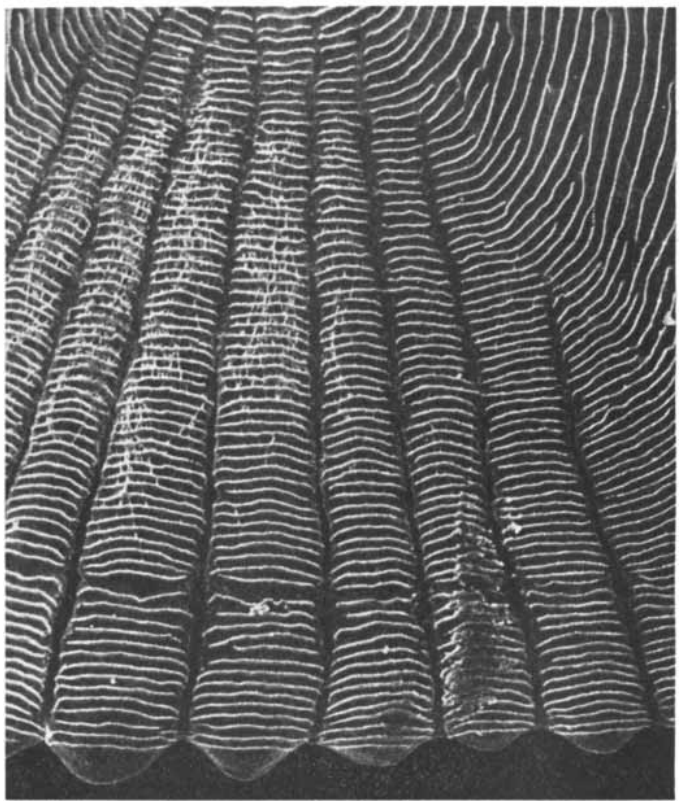


GRAINS OF POLLEN from mesquite (*left*) and prickly-pear cactus (*right*) are representative of insect-borne pollens found in ancient coprolites. These scanning electron micrographs, made in the electron-microscope center at Texas A&M University, are respectively enlarged 3,100 and 1,350 diameters. Both grains are modern; they are from the authors' collection of specimens for comparison.

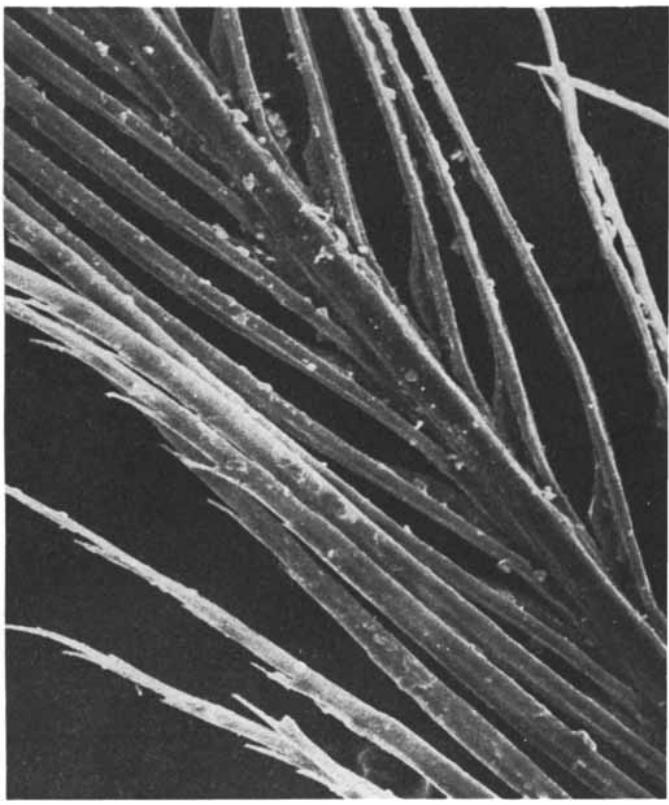




WINDBORNE POLLENS are represented here by a four-grained cluster of cattail pollen (*left*) and one grain of a wild sorghum, Johnson grass (*right*). They are respectively enlarged 4,500 and 2,250 diameters in these scanning electron micrographs. Windborne pollens are broadcast seasonally, and anyone who prepares food or drinks water during that season is likely to swallow a few grains.



FISH SCALES, like the scales of reptiles, make up a class of animal remains that pass through the alimentary canal unaltered. This sunfish scale, bearing a pattern of growth rings, is enlarged 175 diameters.



FEATHERS are also little changed by the digestive process; the pattern of their barbules often identifies the species of bird. This specimen is a chicken feather, enlarged 550 diameters.

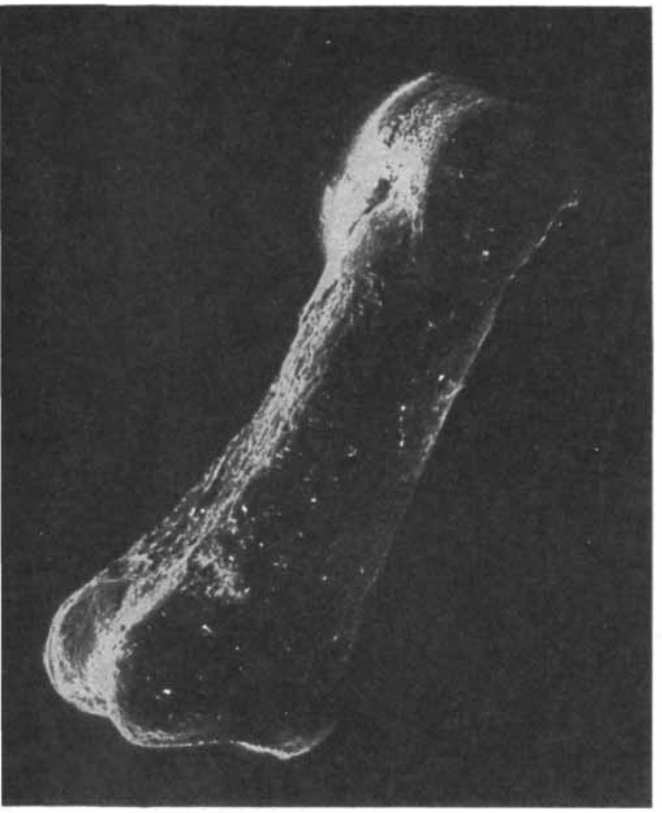
mens from five of the eight strata at the site showed that the cactus seeds had been prepared for eating by either pounding or grinding. The seed tests of other plants, particularly millet and goosefoot, were charred, indicating that the seeds had not been milled but roasted. Many coprolite seed tests are unbroken; when a seed is not itself valued as a food, it may still be ingested whole when the fruit of a plant is eaten. As a result it has been possible to demonstrate that the diet of prehistoric hunters and farmers at a number of sites in the New World included such food items as chili peppers, grapes, tomatoes, guavas, blackberries and squashes.

A subtler form of dietary evidence, usually confined to regions where the ground water is rich in dissolved minerals, is the phytolith, or plant crystal. Unlike animals, plants cannot excrete the inorganic substances in their water supply. The calcium and silicon that are taken up along with ground water are deposited in the plant tissue in crystalline form, most often as salts of calcium and anhydrides of silica. The form of a particular crystal is not usually associated with any one plant species. Nonetheless, we have found, in the course of examining the phytoliths in plants of the same family or genus that grow in southwestern Texas, certain crystals that have similar forms. For example, the crystals of calcium oxalate that appear in four species of the prickly-pear cactus (*Opuntia*) are quite similar in appearance. Furthermore, one phytolith is species-specific. It is a rhomboidal crystal that is found only in the tissue of one species of agave, *Agave lecheguilla* [*see illustration on page 106*]. Identification of these crystals has enabled us to demonstrate that several individuals among the succession of Archaic Indians who visited the rock-shelter in southwestern Texas had eaten prickly-pear cactus and agave, even though the coprolites in which the crystals were found did not contain identifiable fibers, seeds or pollen from the plants.

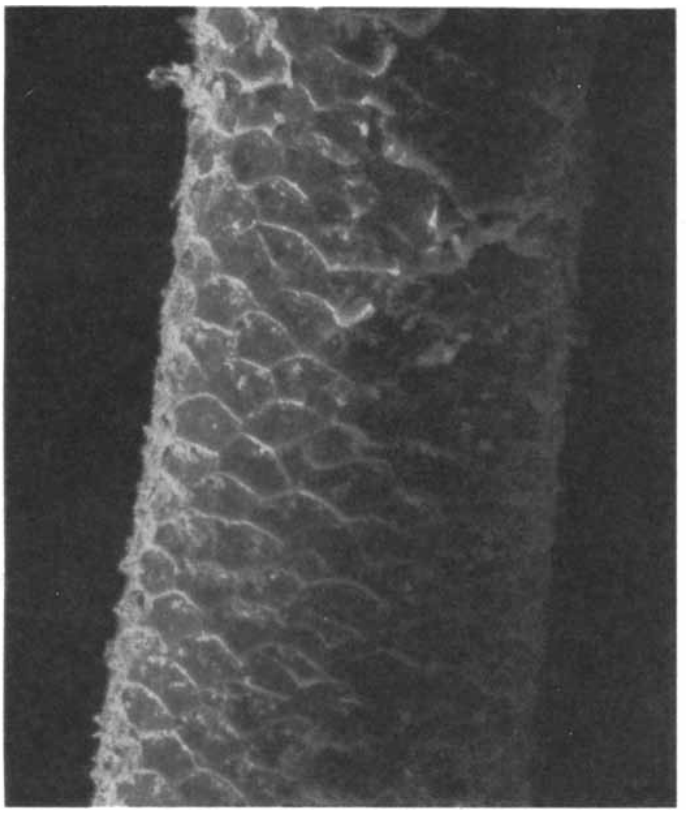
Information is of course provided by animal material as well as plant material. For example, at one site in Nevada, Lovelock Cave, Lewis K. Napton and O. A. Brunetti of the University of California at Berkeley were able to identify the various species of waterfowl that the occupants had eaten from an investigation of the fragments of feathers they found in coprolites. The local diet had included the heron, the grebe, the mud hen and the goose. In our own analysis of materials from the Texas rock-shelter we have recognized various animal remains, including fragments of grasshoppers and other insects, and the bones of small mammals, reptiles and fishes [*see illustration on page 107*].

When the prey is large, for example deer or bison, butchering and cooking practices are likely to minimize the chance that bones or bone fragments will be ingested. Almost inevitably, however, a few hairs will adhere to the meat and will be swallowed. We have recognized hair from one small mammal, the field mouse, in some rock-shelter coprolites, and we have even recovered such seemingly perishable items of animal material as insect larvae.

Still another kind of animal material makes its way through the alimentary tract largely unaltered: the scales of fishes and reptiles. The two kinds of scale can be told apart without great difficulty. Fish scales show a pattern of concentric growth rings and are generally rounded. Reptile scales have no growth rings and are often pointed at one end. Under ideal circumstances, and with an adequate reference collection for purposes of comparison, more can be learned than simply whether a



SMALL BONES, if not too fragmented by chewing, are often identifiable. This limb bone of a small rodent, enlarged 45 diameters, is from a coprolite found at a rock-shelter in Texas.



ANIMAL HAIR, like scales and feathers, resists digestion. This hair, from the coat of a white-tailed deer, shows a scale pattern that is characteristic of ruminants. The specimen is seen enlarged 1,100 diameters.

scale represents a fish or a reptile. Napton and another Berkeley colleague, Robert F. Heizer, were able to identify three different species of fish eaten by the occupants of Lovelock Cave.

Evidence of parasitic infestation appears occasionally in the course of coprolite analysis. Specimens between 3,000 and 5,000 years old from a Peruvian cave site, Huaca Prieta, were shown by Callen and T. W. M. Cameron to contain tapeworm eggs. Specimens from a 10,000-year-old stratum at Danger Cave in Utah were found by Gary F. Fry of Youngstown State University and Edwin Englert, Jr., of the University of Utah to contain the eggs of another intestinal parasite, the thorny-headed worm. Coprolites from Mesa Verde in Colorado contained pinworm eggs. As for the ticks, mites, lice and fleas that infest human body hair, ethnographic evidence regarding human grooming behavior is enough to dispel any surprise that their remains are also found in coprolites. Callen has identified ticks in specimens from one Tehuacán stratum that dates back some 6,000 years. Specimens from Mesa Verde and from Salts Cave in Kentucky contain mites, and those from the Utah cave site contain lice and louse eggs.

It is only in recent decades that archaeologists have come to appreciate how much information can be provided by pollen analysis. As botanists are well aware, the exine, or outer wall, of the pollen grain has a remarkable chemical stability, and so buried pollen grains are virtually indestructible. Moreover, the morphology of the exine is genetically determined, so that the form of a pollen grain will often indicate the plant species that gave rise to it, or at the least the genus or family. Putting aside the information that conventional pollen analysis can give the archaeologist, pollen grains that have been accidentally or purposely ingested are still another class of objects that pass through the alimentary tract virtually unaltered. Under the microscope pollen can be as informative about prehistoric diet as any other kind of plant material. The species the pollen represents can indicate the season of the year when a site was occupied and even give a general picture of the environment at the time.

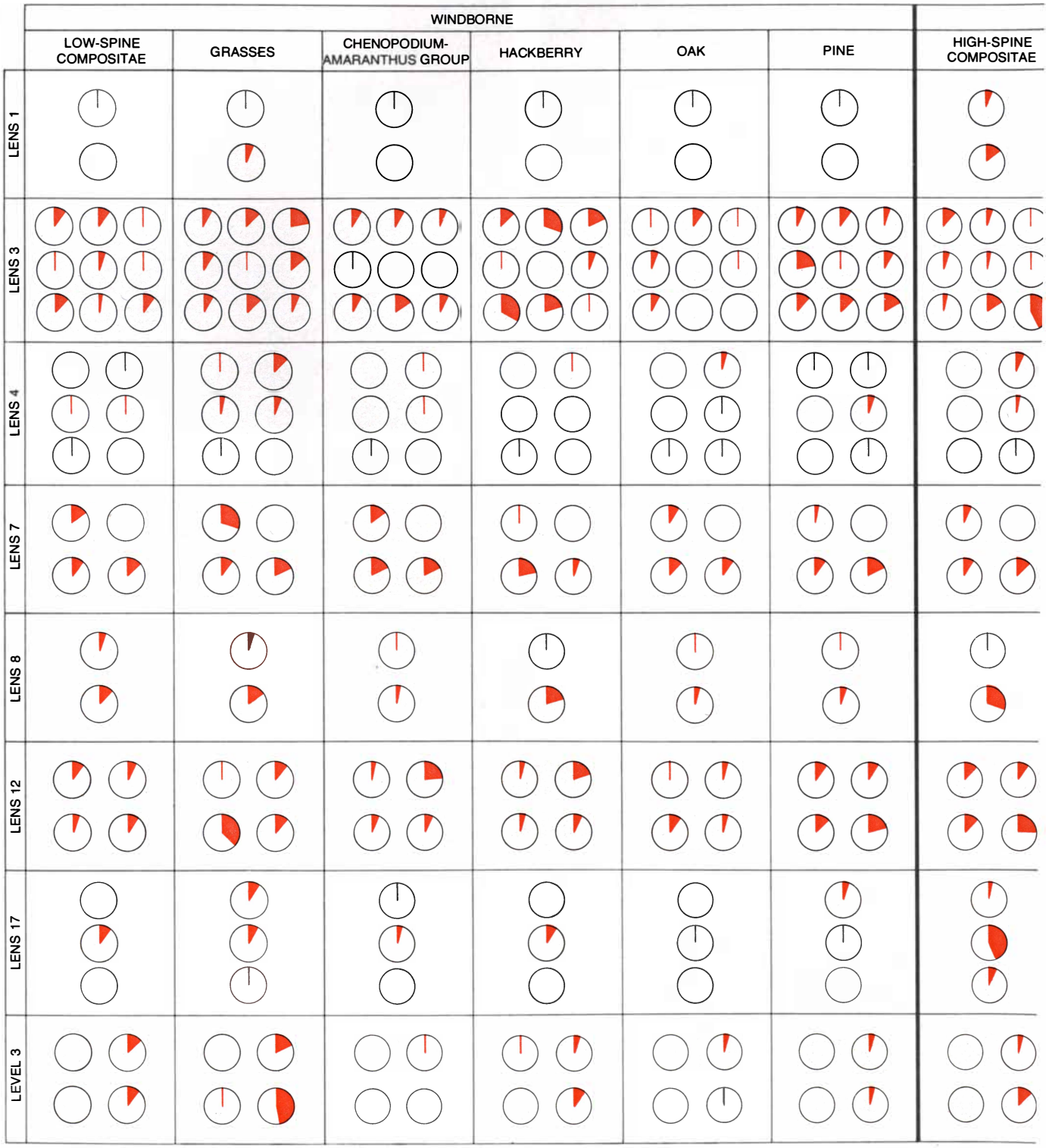
Let us describe what the identification of pollens and other plant materials has revealed about the activities of the people who lived in the Texas rock-shelter we have mentioned. The coprolites found at the site are the result of intermittent human occupation over a period of some 1,300 years, from 500 B.C. to A.D. 800. A total of 43 specimens were recovered from the various occupation levels; all but nine contained pollen. One of the pollen analyst's first tasks is to separate the grains into three classes: those grains that the wind carries from flower to flower, those that are transported by animals (most of them insects) and those that come from plants that are self-pollinating. (Certain aquatic plants release their pollen under water, but these grains generally lack an exine and are rarely preserved; they do not play a role here.)

Windborne pollens are released in vast quantities. As an example, the spruce forests of central and southern Sweden are estimated to release 75,000 tons of pollen per year. One anther of a wind-pollinated plant can produce as many as 70,000 grains of pollen and rarely produces fewer than 10,000. In insect-pollinated plants the production is smaller, about 1,000 grains per anther; in self-pollinating plants it can be fewer than 100 grains per anther.

The six principal windborne pollens found in the specimens from the Texas rock-shelter belonged to three plant gen-

era and to three broader groups of plants; the morphology of the latter three kinds of pollen did not allow identification of the species or genus that produced them. Depending on the season, a more or less steady "rain" of all six pollens fell on the site. Some grains were probably ingested because they had fallen on articles of food; others may have accumulated in the drinking water or may even have been inhaled and then swallowed.

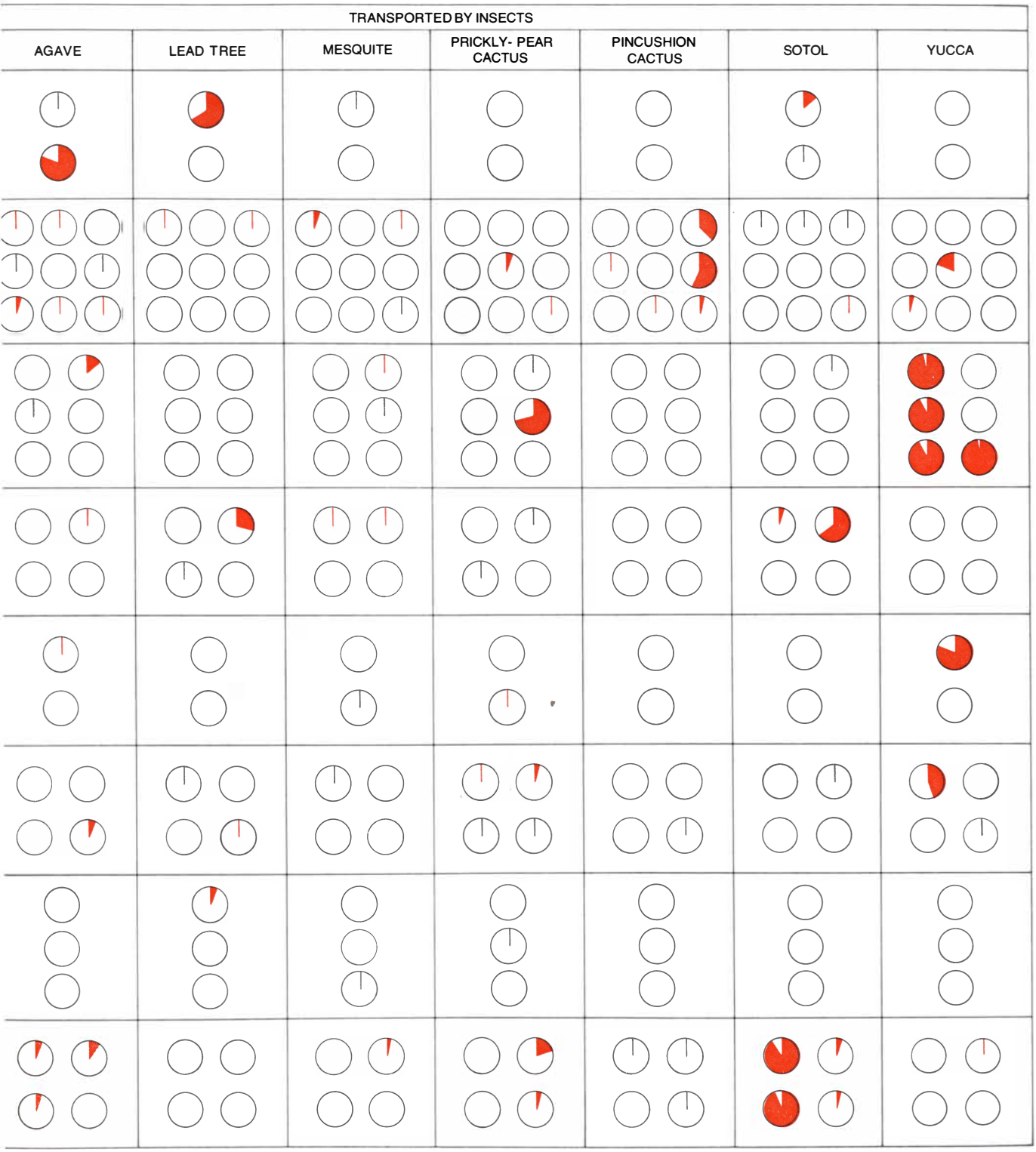
The three plant genera that contributed to the pollen were hackberry (*Celtis*), oak (*Quercus*) and pine (*Pinus*). Both hackberry (the species *C. laevigata* and *C. reticulata*) and oak (the shin oak, *Q. pungens*) still grow in the comparatively well-watered bottomland near the site. The nearest pines known, however, are isolated stands of pinyon (*P. cem-*



PRINCIPAL POLLENS found in 34 of the coprolites unearthed at a rock-shelter in southwestern Texas came from plants belonging to six groups that broadcast windborne pollens (*left*) and to eight groups with insect-transported pollens (*right*). In many specimens no pollen grains or only trace amounts were present. The presence of large amounts of pollen in other specimens, however, indicates

broides) found some 80 miles to the east.

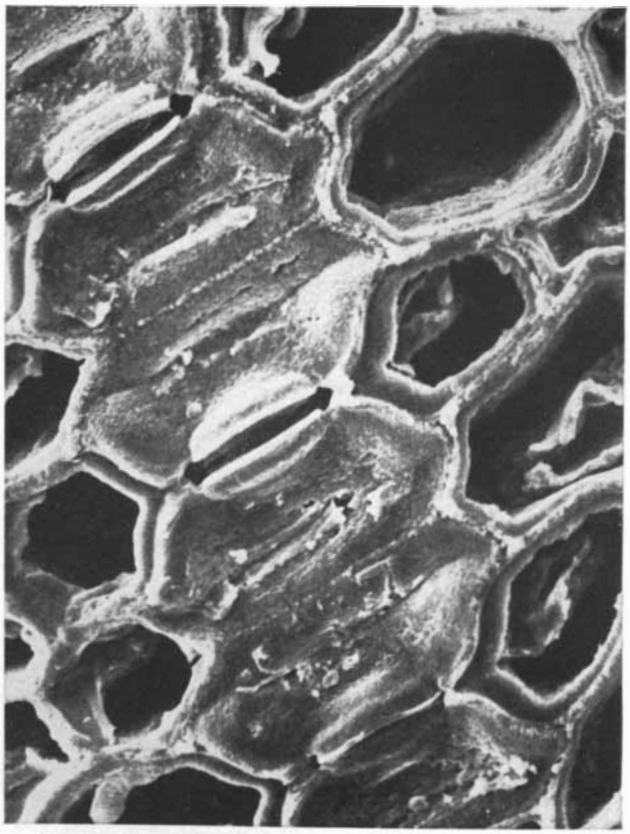
The plants from two of the three less well-defined groups that contributed to the rain of pollen included members of the large family of composite-flowered plants (the Compositae) and members of the equally large family of seed-bearing grasses (the Gramineae). The third group consists of a constellation of plants well known to botanists in the southwestern U.S. It is called the Cheno-Am group because the formal names of its two principal constituents are the Chenopodiaceae (the goosefoot family) and the genus *Amaranthus* (pigweed). The pollens produced by the many species in the two groups of plants are almost impossible to tell apart. Much the same is true of the many species of Compositae, except that the exines of the windborne composite pollens have short spines



that the Archaic Indians who periodically visited the site ingested several kinds of flowers, either sucking or chewing them for their nectar, brewing them into tea or eating them in salads. In only one instance was a windborne pollen present in a specimen in association with evidence that the plant yielding the pollen was used as food; the ingestion of these pollens was largely accidental.

SEEDS, frequently found in coprolites, may identify the kind of plant that bore them. This quinoa seed is enlarged 70 diameters.

FIBERS make up another class of plant materials with forms indicative of origins. This is a cotton fiber, enlarged 6,000 diameters.



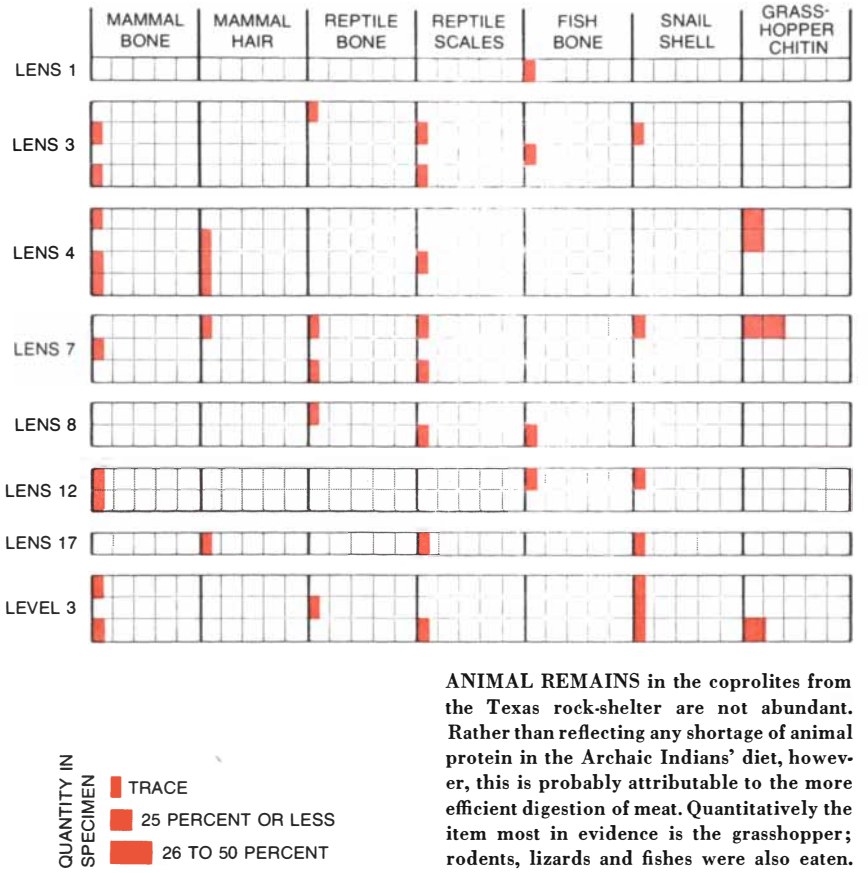
STOMATES on leaf surfaces also make identification possible. This agave leaf fragment, from a coprolite, is enlarged 800 diameters.

PLANT CRYSTALS can reveal details of diet. Enlarged 3,000 diameters is a crystal (*long rod*) present only in *Agave lecheguilla.*

whereas the exines of the animal-transported pollens have long ones.

The amount of windborne pollen in the rock-shelter coprolites ranged from none or mere trace amounts to as much as 48 percent of the pollen present. With one exception there is no evidence that the ingestion of any of the windborne pollen was related to diet. The exception is represented by the specimen that contained 48 percent windborne pollen. The pollen was of Cheno-Am origin, and many goosefoot seeds were also present in the specimen. The goosefoot has a long flowering season, so that pollen from late blossoms might easily have mixed with early-maturing seeds when the seeds were being collected for food.

Analysis of the windborne pollens at the rock-shelter provides the basis for one generalization about the local environment during the period from about 500 B.C. to A.D. 800. At least trace amounts of all six windborne pollens were present in one specimen or more from each of the eight strata at the site. Although pine is missing from the vicinity of the site today, with that one exception it appears that the plants of the present were also the plants of the past. The windborne pollen data do not, however, tell us anything about the relative numbers of plants of each kind during the 1,300-year interval. It is even possible that pines did not grow near the rock-shelter and that the pine pollen found there was wafted in from distant stands of pinyon.



ANIMAL REMAINS in the coprolites from the Texas rock-shelter are not abundant. Rather than reflecting any shortage of animal protein in the Archaic Indians' diet, however, this is probably attributable to the more efficient digestion of meat. Quantitatively the item most in evidence is the grasshopper; rodents, lizards and fishes were also eaten.

Eight genera or larger groups of plants that bear insect-transported pollen also contributed plant materials to the contents of the rock-shelter coprolites. Among them were representatives of the Compositae that are characterized by long-spined pollen grains, but the balance of the flora was typical of arid and semiarid environments. One recognizable species was the desert agave *A. lecheguilla*. The other six pollens define genera only: the lead tree (*Leucaena*), the mesquite (*Prosopis*), the prickly-pear cactus (*Opuntia*), the pincushion cactus (*Mammillaria*), the yucca-like sotol (*Dasylirion*) and a showy genus of the lily family, the yucca itself (*Yucca*).

Evidence that the blossoms of the agave, the sotol and the yucca were sucked or chewed for their nectar, brewed into tea or eaten in salads is overwhelming. One specimen or more from the seven lens-shaped upper strata in the rock-shelter contained at least trace amounts of agave pollen; in Lens 1 the proportion of agave pollen in one specimen reached 81 percent [*see illustration on pages 104 and 105*]. Sotol pollen was found in at least one specimen from all but two strata. In the earliest deposit at the site the proportion of sotol pollen in two specimens exceeded 90 percent. Five of the eight strata yielded specimens that contained yucca pollen; in Lens 3 and Lens 8 the proportion was greater than 80 percent, and in Lens 4 the proportion in four of the six specimens exceeded 90 percent.

Cactus flowers appear to have been less popular. Pollen from pincushion-cactus blooms was found only in specimens from three strata. Lens 3 contained the maximum concentration: 57 percent. Prickly-pear flowers were somewhat more highly valued; only Lens 1 lacked any trace of their pollen. Nevertheless, only Lens 4 (with a specimen content of 71 percent) and the earliest deposit (with a content of 20 percent) show evidence of significant consumption of this cactus flower. When one considers that the two cacti grow in similar habitats and bloom in the same season, it is puzzling to find that only four specimens contained both pollens in trace amounts or more. The scanty evidence for the simultaneous consumption of the two flowers may reflect some unknown dietary preference or may simply be due to the limited size of the coprolite collection.

In addition to the goosefoot seeds associated with the Cheno-Am pollen the collection contained many other macroscopic plant materials. The inhabitants of the rock-shelter ate not only the flowers but also the leaves of several monocotyledonous plants such as yucca, sotol and agave. They also ingested flowers from the lead tree and the mesquite. As one of us (Bryant) knows from personal experience, mesquite flowers are quite bitter when they are eaten raw. Perhaps the blossoms were boiled to make tea or were allowed to ferment to render them more palatable. Some specimens were found to contain tree bark in considerable quantities; what treatment, if any, made bark an acceptable item of diet is not known. Perhaps its use was medicinal.

The amount of animal protein eaten by the inhabitants of the shelter, except for that in grasshoppers, may have been quite limited [*see illustration above*]. Among the fragments of animal material identified in our analysis are the bones of fishes the size of minnows, the scales of small reptiles (probably lizards) and the shells of land snails.

The evidence of the plant materials bearing on the seasons when the rock-

shelter was occupied included some variables. In Lens 1, near the surface, the limited number of coprolite specimens at first raised doubts about the adequacy of the sample. Nonetheless, the 81 percent proportion of agave pollen in one of the two specimens and the 66 percent proportion of lead-tree pollen in the other suggest that the shelter was tenanted in late spring and early summer. The flowers of those plants bloom at that time of the year. Occupation in late spring and early summer is also suggested by the quantities of cactus and yucca pollen and of wild-onion bulbs in the two specimens. The content of windborne pollen similarly supports this conclusion; hackberry and pine are both spring-pollinating plants.

With two exceptions much the same kind of late-spring and early-summer residence seems to hold true for the other strata at the site. Lens 8 contained only two specimens; the lack of plant material in one of the two makes any judgment about the season of occupation impossible. In Lens 12, although the data for pollen other than the windborne varieties are skimpy, many of the other plant materials in the specimens, such as cactus fiber and yucca fiber, could have been collected and ingested at any time of the year. Because cactus fruits ripen late in summer and because prickly-pear seeds are present in several specimens from Lens 12, it seems reasonable to assume that at the time this deposit was formed the site was occupied in middle and late summer. All in all the coprolite evidence indicates that the Texas rock-shelter was visited annually during the warmer months by a nomadic population of primitive hunters and gatherers.

The most ancient coprolites recovered at the shelter were less than 3,000 years old. What might one learn from specimens of much greater antiquity? Before Callen's untimely death he examined four supposedly human specimens from the Neanderthal site of Lazaret in France. The context of the discovery of the Lazaret specimens suggests that they were between 50,000 and 70,000 years old. Callen found on immersing the specimens that all four of them failed to

PLANT MATERIALS other than pollens in the rock-shelter coprolites indicate a consistent reliance on the prickly-pear cactus as a foodstuff. Some seeds of the cactus were found intact, implying that the fruit of the plant was consumed. Others were cracked and charred, indicating that the Archaic Indians had first milled and then cooked them. Some of the ingested plants are not identifiable from their fibers, but the fibers from other specimens are recognizable as coming from monocotyledonous plants. Yucca, sotol and agave are monocots.

color the solution. In two of them he could identify fragments of bone, hairs and bits of charcoal. This evidence for the use of fire in the preparation of meat convinced him that at least these two specimens were probably of human origin. He did not find plant materials in any of the specimens.

Recently in our laboratory we began work on a large sample of much older material: some 500 supposedly human coprolites from a French Mediterranean site, Terra Amata. The specimens were made available to us by the excavator, Henry de Lumley [see "A Paleolithic Camp at Nice," by Henry de Lumley; SCIENTIFIC AMERICAN, May, 1969]. Apart from coprolites no human remains were found at the site, but the kinds of stone tools that were uncovered imply that the residents of this seaside camp probably represented the species *Homo erectus*, the precursor of modern man. De Lumley believes that the strata unearthed at Terra Amata may be as much as 300,000 years old. Whereas Callen found his much younger Neanderthal specimens were chemically unreactive when they were immersed, some of the Terra Amata specimens have faintly colored the solutions in our laboratory.

Much work remains to be done with de Lumley's specimens. Nonetheless, preliminary analysis has identified grains of sand, which are almost inevitably ingested at the seashore, flecks of charcoal, which indicate the use of fire in the preparation of food, and fragments of mollusk shell, which point to one food resource that may have been exploited by the inhabitants. So far we have found no bone and no plant remains, even though analyses of other Terra Amata specimens, undertaken some years ago in the laboratory at the University of Aix-Marseilles, showed the presence of several windborne pollens and the insect-transported pollen of the broom plant (*Genista*).

The potential of analyses such as these for giving the archaeologist both a detailed inventory of preferred foodstuffs in a variety of prehistoric contexts and a relatively precise indication of the time of the year when transient sites were occupied has gained increasing recognition. Today our laboratory regularly receives for analysis specimens that have been unearthed by investigators in all parts of the world. As the work continues perhaps we can provide other glimpses of prehistoric human behavior as unexpected as our discovery that the Archaic Indians of southwestern Texas were, at least in a dietary sense, "flower people."

MATHEMATICAL GAMES

The curious magic of anamorphic art

by Martin Gardner

Anamorphic art is a term unfamiliar to most people; indeed, it is unfamiliar to most artists. From the Greek *ana* (again) and *morphē* (form), it refers to realistic art so monstrously distorted by a projective transformation that it is difficult to recognize. The distortion can be "formed again" by viewing it on a slant or as a reflection in a suitable mirror. The mirror, called an anamorphoscope, is usually a polished cylinder or cone. The appearance of the undistorted reflection is so magical and surprising that few people seeing it for the first time fail to exclaim in wonder.

At this point the reader may want to pause to make the best cylindrical anamorphoscope he can in order to view some of the anamorphic art reproduced here and on the cover. For the best results the cylinder should have a base that fits the circle in the picture. Acceptable results, however, can be obtained with a cylinder that has a larger or a smaller base. A small juice or soup can with the label removed and the residual glue on the can washed off may do the trick. A transparent cylindrical bottle with a cylinder of black paper inserted into it works fairly well. Chromium-plated tubing, available in some hardware stores for plumbing fixtures, is even better. Aluminum foil is not smooth and stiff enough, but silvered Mylar paper, taped around a cylinder of the right size, makes an excellent anamorphoscope. The reader is urged to get several square feet of this material (it is sold in art-supply and hobby stores), not only for cylindrical viewing but also because it can be used, as will be explained, to make a conical anamorphoscope for viewing the bottom illustration on page 113.

It was in the early Renaissance that European painters, who were just beginning to master perspective, became fascinated by the simplest kind of anamorphic art: stretched pictures that are seen correctly when viewed on a slant. The first known examples are in Leonardo da Vinci's notebooks; this is not surprising because Leonardo was one of the earliest contributors to the geometry of perspective. Surfaces viewed on a slant are, of course, anamorphically distorted even though we are usually not aware of it. A door seen from a certain angle is a trapezoid, but our brain, conditioned by experience, perceives it as a tilted rectangle. When people who are not used to television see a television screen from the side, the images appear to be too skinny. The rest of us have learned to correct for this bias so well that squeezed images on television seem normal. When the Renaissance painters discovered how to transform flat shapes to give a depth illusion to the canvas, they discovered simultaneously how to do it in reverse. A picture stretched according to the same rules of perspective becomes a grotesque form.

Hans Holbein's painting *The Ambassadors* (1533) contains a famous example of anamorphic art [*see illustration on page 112*]. You can see the stretched shape at the bottom of the painting normally by closing one eye and slanting the page away from you, with the lower left corner of the page pointing toward your open eye and about six inches from it. Another way to see the skull is to place the edge of a flat mirror about three inches from the lower left corner and look into the mirror with both eyes while tipping it until the skull appears normal. Holbein's painting was probably intended to hang near the top of a stairway so that people going up would be startled by the skull.

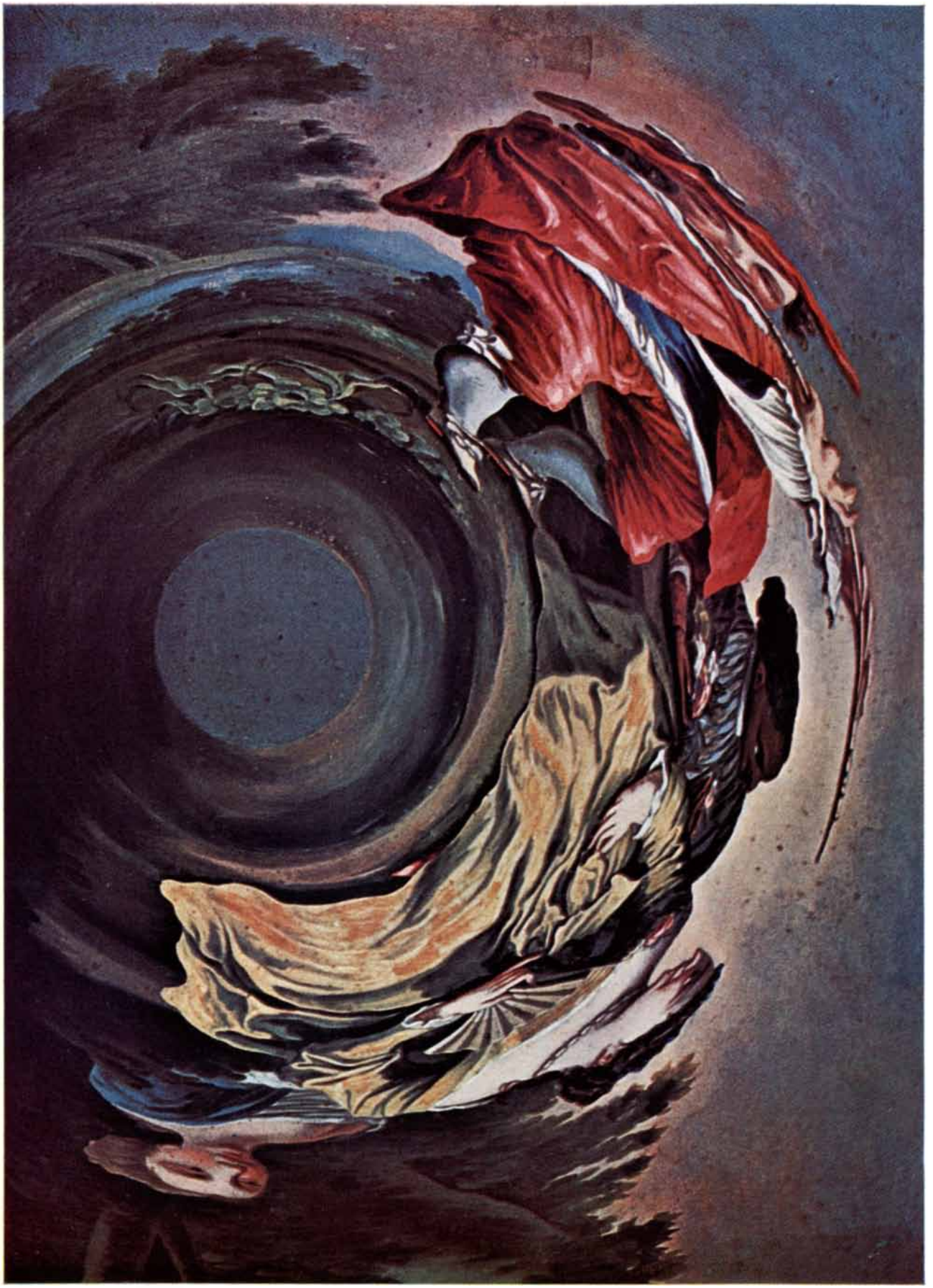
Another slant picture is an old newspaper puzzle by Sam Loyd [*see illustration on page 116*]. It has a concealed portrait of the mature George Washington. Can you find it? (A second puzzle consists in dividing the square Washington pie into six square pieces, not necessarily the same size.) Slant pictures of this kind occasionally appear in children's books and on advertising premiums. Sometimes printing is stretched out so that it can be read only by slanting the page.

The geometric technique for drawing slant pictures was explained in detail in the first major treatise on anamorphic art: ***La Perspective Curieuse,*** by Jean François Niceron (Paris, 1638). The picture is first ruled into square cells. The matrix is stretched to a trapezoid, then the artist copies the picture by filling in the trapezoidal cells, stretching the contents of each cell as accurately as he can to match its corresponding cell on the original picture. The finer the matrix, the more accurate the copy.

The exact shape of the trapezoidal matrix depends on the position of the eye when it sees the shape as a normal square. The full three-dimensional structure is complex, but it turns out that there is a simple way to construct the trapezoid, given the desired position of the eye. Consider a square of side 8 ruled into 64 square-inch cells. We want to distort it so that it will appear normal when the eye is 25 units from the midpoint of the picture's top edge and seven units above the plane [*see bottom illustration on page 114*]. The construction is as follows. XY is the square's width. FB, on the perpendicular bisector of XY, is 25 units. BE, perpendicular to FB, is seven units. Draw XB, YB and YE. This determines CD, the trapezoid's bottom edge. Other lines from B and E to the unit marks on XY determine the lines to XY that complete the 64 trapezoidal cells. Neither E nor B indicates the eye's position. The eye is seven units above the horizontal plane of the paper. A perpendicular dropped from the eye to the plane intersects FB at point G. The construction assumes that G is at least eight units from F.

Another way to draw the picture is to close one eye, view the paper on a bias and then draw the picture so that it looks normal. This is better than trying to do it with a mirror, because in the mirror your hand moves along one coordinate in a direction opposite to the way it moves on the actual sheet, and your reflexes find that hard to manage. A simple photographic method of making slant pictures is to project the picture (with an enlarger or a slide projector) onto enlarger paper so that the light strikes the paper at the angle intended for viewing.

Although there is no evidence that the ancient Greeks played with anamorphic pictures, they sometimes deformed the columns of temples to correct the distortion perceived by someone near the front of the building. For similar reasons Renaissance painters occasionally deformed



With a Tender Little Song, *a cylindrical anamorphic painting from the Tannenbaum Collection*

murals so that viewers looking up at them would see them with less distortion. Slant pictures were sometimes concealed in paintings or stretched along the side of a long corridor to be viewed from an entrance or an exit. Another popular practice was to put slant pictures inside boxes with a peephole at one end for viewing the picture at the proper angle.

Anamorphic paintings for cylindrical and conical mirrors were fashionable toys in both Europe and the Orient during the 17th and 18th centuries. They were usually done by anonymous artists and were sold with handsomely made anamorphoscopes. Occasionally the pictures carried messages of political protest; at times they were pornographic or scatological. Several examples of erotic anamorphic pictures appear in *Chinese Erotic Art,* by Michel Beurdeley et al. (Charles E. Tuttle Co., 1969). This early anamorphic art is now a collector's item. In December, 1973, a set of 10 oil paintings, for both cylinders and cones, from 18th-century France was sold at a Sotheby Parke Bernet auction in New York for $10,800, which is a bargain in view of today's prices. Herbert Tannenbaum, a New York art dealer, had found the set in 1939 in a curiosity shop in Amsterdam and had bought them without even knowing what they were.

Excellent collections of European anamorphic art are in the Philadelphia Museum of Art, the Milwaukee Art Center and many European museums. An unusual display of anamorphic originals is featured in an exhibit called *By Design:*

The Ambassadors, ***a slant anamorphic painting by Hans Holbein***

Curious Deceptions in Art and Play, which opens January 19 at the Exhibit Center in Xerox Square in downtown Rochester, N.Y. Assembled by Lillian Silver and sponsored by Xerox, the exhibit will continue through April 20. Readers in the area should not miss it. There will be pictures by Maurits C. Escher and by leading "op" artists, topological sculpture by Max Bill, exhibits of magic squares, tangrams, geometric vanishes, optical illusions, upside-down pictures, hexaflexagons and many other constructions in the area where art and mathematical play intersect.

To make a conical anamorphoscope cut a circular disk of the proper size from silvered Mylar, cut a radius, overlap the cut edges and then glue or tape the overlapping edges in place. For the illustration at the right designed for conical viewing the radius of the disk that makes a cone of the right proportions is 1¼ inches. Adjust the overlap until the base of the cone fits the inner circle on the picture. Place the cone on this circle and view directly from above with one eye. The restored picture is small and circular, completely within the circumference of the cone. If you press on the apex of the cone with a fingertip or a paper clip, it will make the cone more rigid and produce a better picture. For ideal results you need a solid conical mirror made with great accuracy.

As with slant pictures, there are three ways to deform a picture for cylindrical or conical viewing. The geometric procedures, reproduced from the Niceron treatise cited above, are shown in the illustrations on page 115. The methods for an exact construction of the distorted matrix are complicated; interested readers can do no better than to consult the Niceron book for details. (If there are better explanations in a more recent book, I do not know about it.)

Note how the conical reflection literally turns a picture inside out. Point *A*, at the center of the picture in the bottom illustration on page 115, becomes the circumference of the distorted drawing and the original circumference becomes the inner circle of the distortion.

When Salvador Dali made a set of erotic anamorphic paintings (prints were sold in Switzerland with a cylindrical anamorphoscope), he simply looked into the cylinder while he painted on the surface under it. That is not easy because in the mirror your hand motion is reversed. You see what you are doing right side up, but your hand must paint the picture upside down.

One can make crude anamorphic pho-

Cylindrical anamorphic photograph by Alan Fontaine

Venus and Adonis, ***a conical anamorphic painting. Photograph © Arnold Newman***

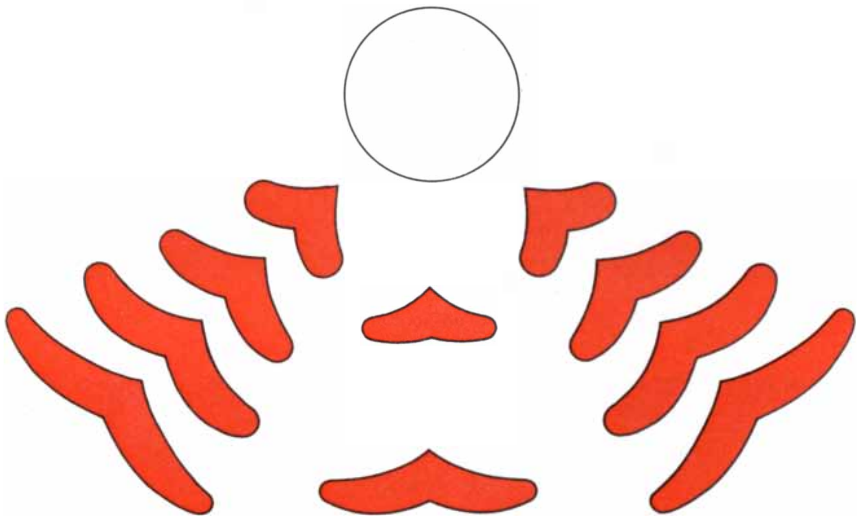
tographic prints by wrapping a negative halfway around a transparent cylinder and sending slanting light through the cylinder from a point source outside and behind the cylinder to project the picture onto enlarging paper under the cylinder. More accurate prints are made by projecting the picture onto the side of an accurately made cylindrical mirror so that it reflects to the enlarging paper. One should use an enlarger or a 35-millimeter slide projector with a diaphragm at the lens and stop down the lens until the image is sharp on the easel. All light from the enlarger that does not fall directly on the cylinder should be blocked off by black cardboard with a rectangular hole. Conical prints are made in similar fashion. The mirror cone should be large (about six inches in diameter). The picture is projected straight down on top of the cone through a circular hole in black cardboard to block off extraneous light.

The term anamorphic is used by photographers for any lens that stretches or compresses an image along one coordinate, as well as for the deformed images it produces. In 1953 Twentieth Century–Fox introduced the wide screen with its motion picture *The Robe*. Anamorphic lenses squeezed the wide image onto standard 35-mm. film, then anamorphic lenses in the projector stretched the image back to fit the wide screen. Most motion pictures today are taken and projected with sophisticated anamorphic lens systems. Similar systems adapt wide-screen motion pictures to videotape.

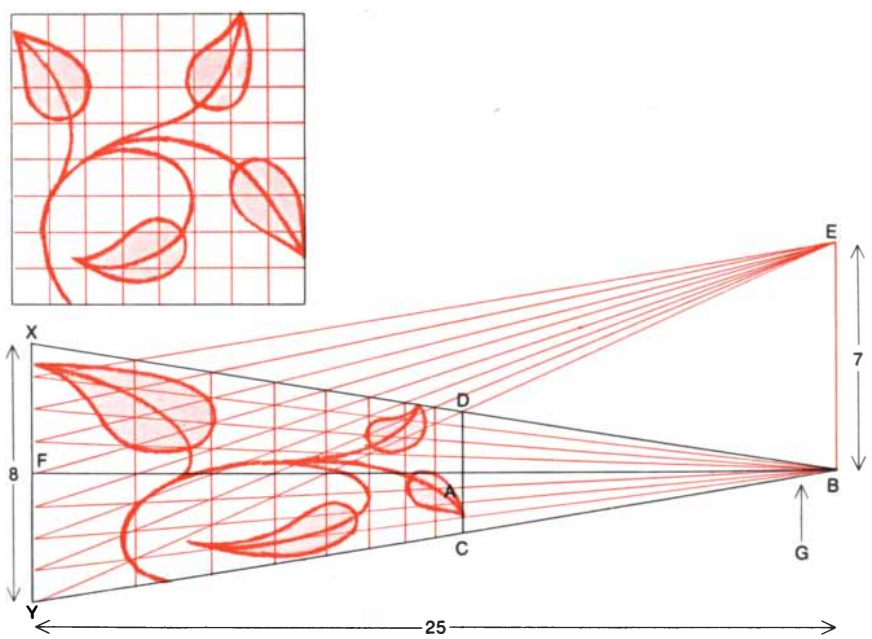
Psychologists who study perception have experimented with three-dimensional anamorphic models of chairs, tables and other objects. The deformed models appear to be normal when seen from a certain angle. The Ames room is a radically distorted room that seems to be normal when viewed through a hole in the wall. A person in the room appears to grow or shrink when he moves from one part of the room to another [see "Experiments in Perception," by W. H. Ittelson and F. P. Kilpatrick; SCIENTIFIC AMERICAN, August, 1951]. Seventeenth-century architects did not discover the Ames room, but they did play games with false perspective. The most startling example, which can still be seen in the Palazzo Spada in Rome, is an anamorphic arcade designed by Francesco Borromini about 1638. You seem to be looking down a long corridor at a large statue beyond the exit. Actually the deformed corridor is only 28 feet long and the statue is three feet high. The illusion was created by making the entrance 19 feet high and 10 feet wide and the exit only eight feet high and three and a third feet wide (a trick, by the way, long familiar to designers of equipment for stage magicians).

There are many other forms of flat anamorphic art: pictures to be reflected in spheres, pictures in properly placed *n*-sided pyramids and other polyhedrons and pictures to be seen through various kinds of distorting lenses. The wavy mirrors in fun houses produce anamorphic images. What is a good caricature if not a complex set of anamorphic distortions that our mind sees as more like the person than he is himself? And there are extreme ways to transform a picture and restore it again (a hologram, for instance, or the broadcasting of a television image), but the term anamorphic is best confined to coordinate transformations, particularly of the three types we have considered. Map makers do not use the term anamorphic, but the many ways in which the earth's surface is projected on the plane—cylindrically, conically and otherwise—are coordinate transformations closely related to anamorphic art.

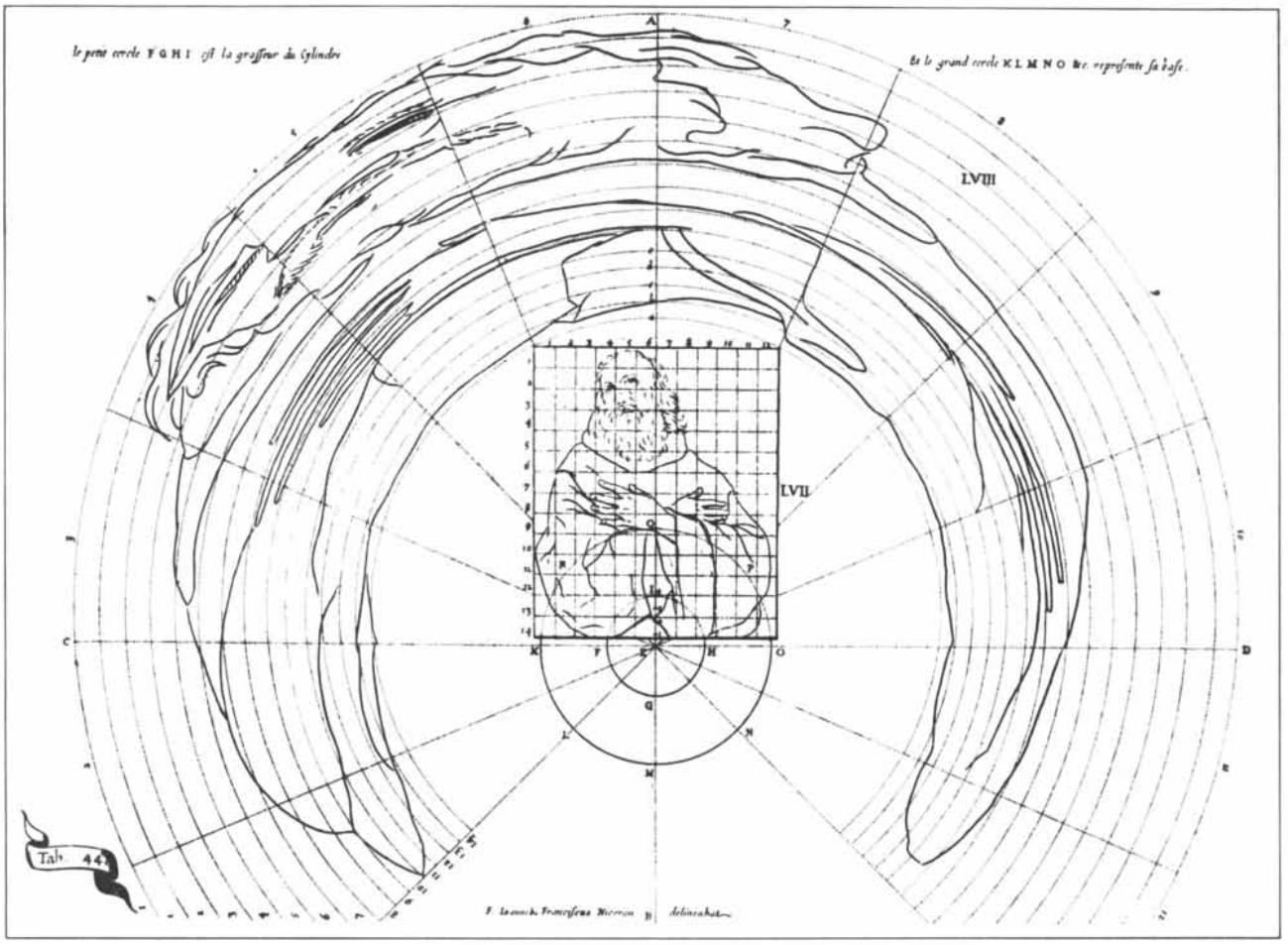
Botanists apply the word anamorphic to radical changes that certain plants undergo when they are grown in different environments. Zoologists have used the term for the evolutionary modifica-



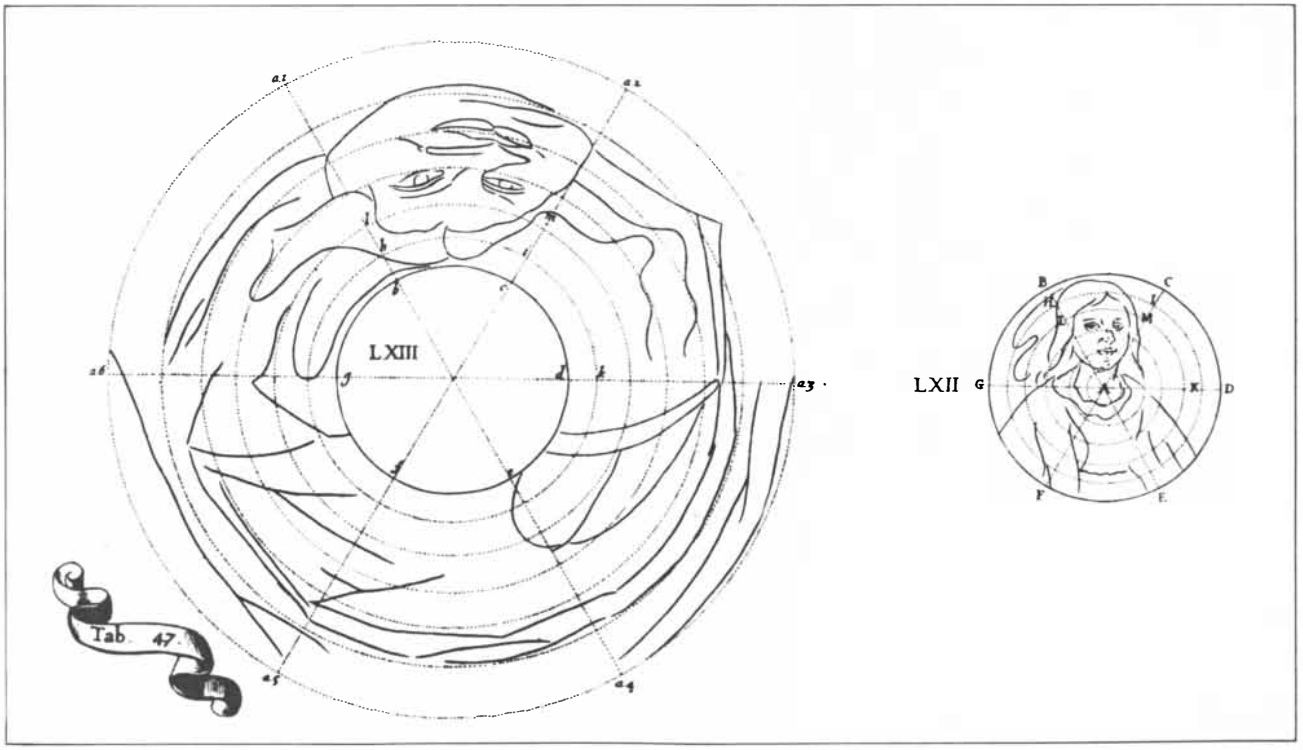
Cylindrical anamorphic picture



Geometric method of making slant anamorphic pictures



Jean François Niceron's method of drawing cylindrical anamorphic pictures



Niceron's method of drawing conical anamorphic pictures

tions of animal forms. D'Arcy Wentworth Thompson's classic work *On Growth and Form* has a chapter filled with diagrams showing animal species that differ from one another by anamorphic distortions so much like the types discussed here that if you view, say, one species of fish on a slant or in a cylindrical mirror, it becomes identical with another species. Similarly, a profile of the human skull, mildly anamorphosed, becomes the skull of a chimpanzee or a baboon.

The ability of our visual system to correct anamorphic distortion suggests that vision is concerned more with topologically invariant properties than with Euclidean ones. The visual system not only utilizes the upside-down images on the two retinas in such a way as to provide a right-side-up impression of a three-dimensional world but also corrects for anamorphic distortion by irregular lenses and corneas. A person with marked astigmatism, fitted for the first time with glasses, perceives the world as being deformed because his brain is still correcting for the old distortions. It may take weeks before he sees the world normally again. Experiments have been conducted in which the subject wears special glasses that produce extreme topological transformations. After a few weeks and headaches the world begins to look normal once again. When the glasses are removed, the world looks distorted, although fortunately only for a short time.

Hamlet advised some actors to hold the mirror up to nature. Is the mirror of a great play, novel, painting or motion picture a distorting mirror or is it a magic anamorphoscope that gives pleasing form to an ugly, shapeless world? Are philosophical systems and religions, even the views of crazy little cults, anamorphic distortions of truth or are they too anamorphoscopes designed to give meaning to a meaningless reality? "It was to correct their anamorphosis of the Deity," wrote Thomas Jefferson, "that Jesus preached."

To the outsider a system of beliefs appears to twist truth like a grotesque anamorphic painting. To the insider, who sees the world in the specially shaped mirror of his perceptual system, everything appears to be normal. Is there a metaphysical system that reflects truth like a flat, untipped mirror? Alas, every true believer is convinced his own anamorphoscope is precisely that.

Letters are still arriving with pentagonal tangrams that are not among the 18 listed last September. Although there is still no formal proof, it seems likely there are just 53 pentagons, of which 22 are "snug" and 31 are "loose." Åke Lindgren of Uppsala in Sweden and Allan L. Sluizer of Northbrook, Ill., are the only readers who so far have found all 53. Daniel Frohardt and the team of Paul Heckbert and Veit Elsen found 52. Many readers found 51 and 50. Several correspondents pointed out that the cyclic number for the first snug pentagon should have been 72111, not 72211.

Mike Gunderloy, Christopher Hamkins and Donald Hayes each proved that games of snuggle up and snuggle down could go the maximum of 15 moves. No one did better on the farm problem than my solution of 10½ square units.

A Sam Loyd puzzle with a hidden anamorphic picture

The Ascent of Man

On Tuesday, January 7, Bronowski's *The Ascent of Man* comes to American television. This enthusiastic survey of human history and accomplishment will be presented in a 13-week series meant to intrigue, illuminate, and delight. It will provide a surpassing television experience for those viewers who seek the exceptional. We cordially invite you to tune in.

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THE AMATEUR SCIENTIST

A high school student builds a recording spectrophotometer

Conducted by C. L. Stong

The identity and even the behavior of many substances can be determined by measuring their color with a recording spectrophotometer. The instrument is essential for the precise determination of color because the human perception of color is partly subjective. The instrument measures only the spectral character of the light reflected or transmitted by the specimen. An example of the subjective factor is that a sheet of paper the observer believes to be white is perceived as white whether it is viewed in sunlight, in the red rays of the setting sun or in the light of a yellow flame. Conversely, a fabric of unknown color may appear greenish when it is examined indoors under an incandescent lamp but appear distinctly blue in the light of the northern sky.

The recording spectrophotometer floods a specimen with the constituent colors of the spectrum sequentially, measures with a photocell the amount of light at each hue that the specimen transmits or reflects and with an automatic pen recorder plots a graph of the measured intensity of the light with respect to its wavelength. The graph fully describes the constituent hues that in sum constitute the color. The price of commercial instruments ranges from several hundred to several thousand dollars depending on their resolution, that is, the discreteness with which they plot differences in hue. An instrument that is adequate for many experiments by amateurs and that fully demonstrates the principles of the recording spectrophotometer has been improvised at a cost of about $50 by a Canadian high school student, Sean Johnston (4447 Venables Street, Burnaby, British Columbia, V5C 3A5). He describes his instrument as follows:

"Having built several spectroscopes, I decided last year to make a spectrophotometer that resembled the one described in 'The Amateur Scientist' several years ago. In it rays of light from an incandescent lamp that diverge from a slit are made parallel by a lens, dispersed into their constituent hues by a prism or a diffraction grating and finally made to converge through a second slit one color at a time, depending on the angle of the prism or the grating with respect to the axis of the optical train. Such a device is known as a monochromator. It can separate any color of light from a mixture of colors. If the dispersing element is rotated through an angle of sufficient magnitude, all hues can be made to appear sequentially at the output slit. A photocell on which this output is incident can be wired to generate a voltage that varies in proportion to the intensity of each hue.

"The addition of the photocell light meter converts the monochromator into a spectrophotometer [see "The Amateur Scientist," SCIENTIFIC AMERICAN, May, 1968]. To reduce the cost of materials I substituted a diffraction grating of the reflection type for the prism that served in the instrument described above. I also replaced the vacuum tubes of the photometer with solid-state devices. The reflection grating (No. 50,201) was purchased from the Edmund Scientific Co. (300 Edscorp Building, Barrington, N.J. 08007). The cost of the project was subsequently increased significantly when I added an automatic pen recorder, thus converting the instrument into a recording spectrophotometer. The motor that drives the recording pen was also obtained from the Edmund Scientific Co. (No. 71,702).

"The available literature indicated that the best spectrophotometers split the light from a single source into two parts, a principal beam and a reference beam. Both beams proceed through the monochromator portion of the instrument, in which the light is dispersed into its constituent colors. The color of each beam can be independently altered, however, before the light is dispersed. For example, one might arrange for the principal beam to be intercepted by a chemical solution and the reference beam to be intercepted by the solvent. A photometer can be designed that in effect subtracts the colors of the reference beam from those of the principal beam. The output of a photometer so designed would represent the true colors of the solute.

"Two general schemes have been devised for making the subtraction. One is known as the 'double beam in time' and the other as the 'double beam in space.' In the first scheme the principal beam and the reference beam as they emerge from the monochromator are directed sequentially onto a photocell by an oscillating mirror or an equivalent device. The photocell accordingly generates an alternating current that is amplified to run an electric motor, which operates the recording pen.

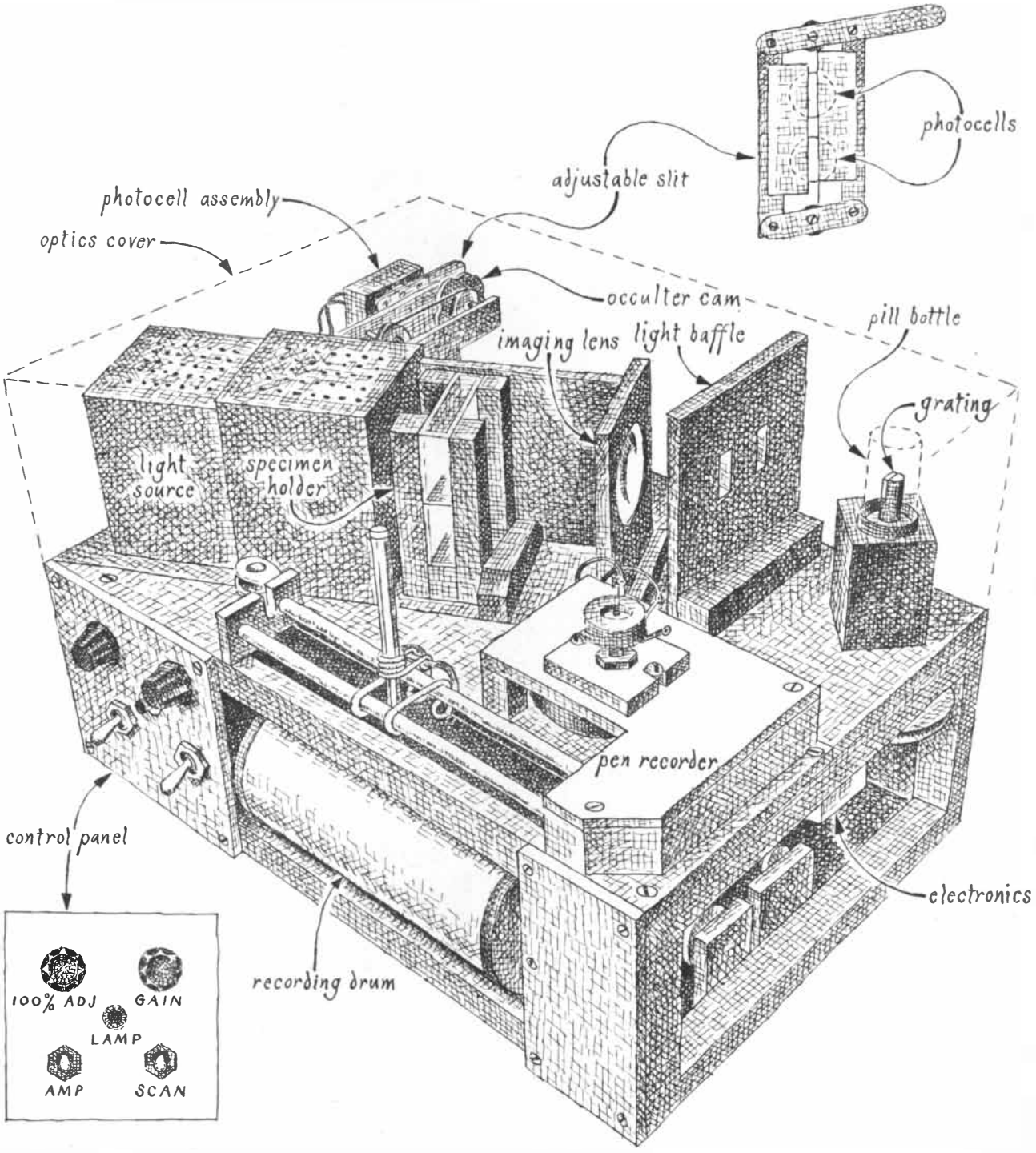
"The direction in which the motor runs is determined by the phase of the alternating current; therefore it is determined indirectly by the relative amplitude of the beams. Simultaneously the motor moves an 'optical comb,' or mask, to intercept the reference beam to a certain degree. The interception adjusts the reference beam to an intensity that matches the intensity of the principal beam. The scheme, which is also known as an 'optical-null a.c. servomechanism,' simultaneously and automatically moves the recording pen to the corresponding null position of the graph. The system is highly stable, primarily because alternating-current amplifiers are inherently more stable than direct-current ones.

"Notwithstanding this desirable feature, I resorted to the second scheme, involving the double beam in space, because the instrument is far simpler and cheaper to build. In this arrangement the dispersed color of each beam is incident on a companion photocell. I substituted inexpensive cadmium sulfide photocells for the photomultiplier tubes found in commercial instruments.

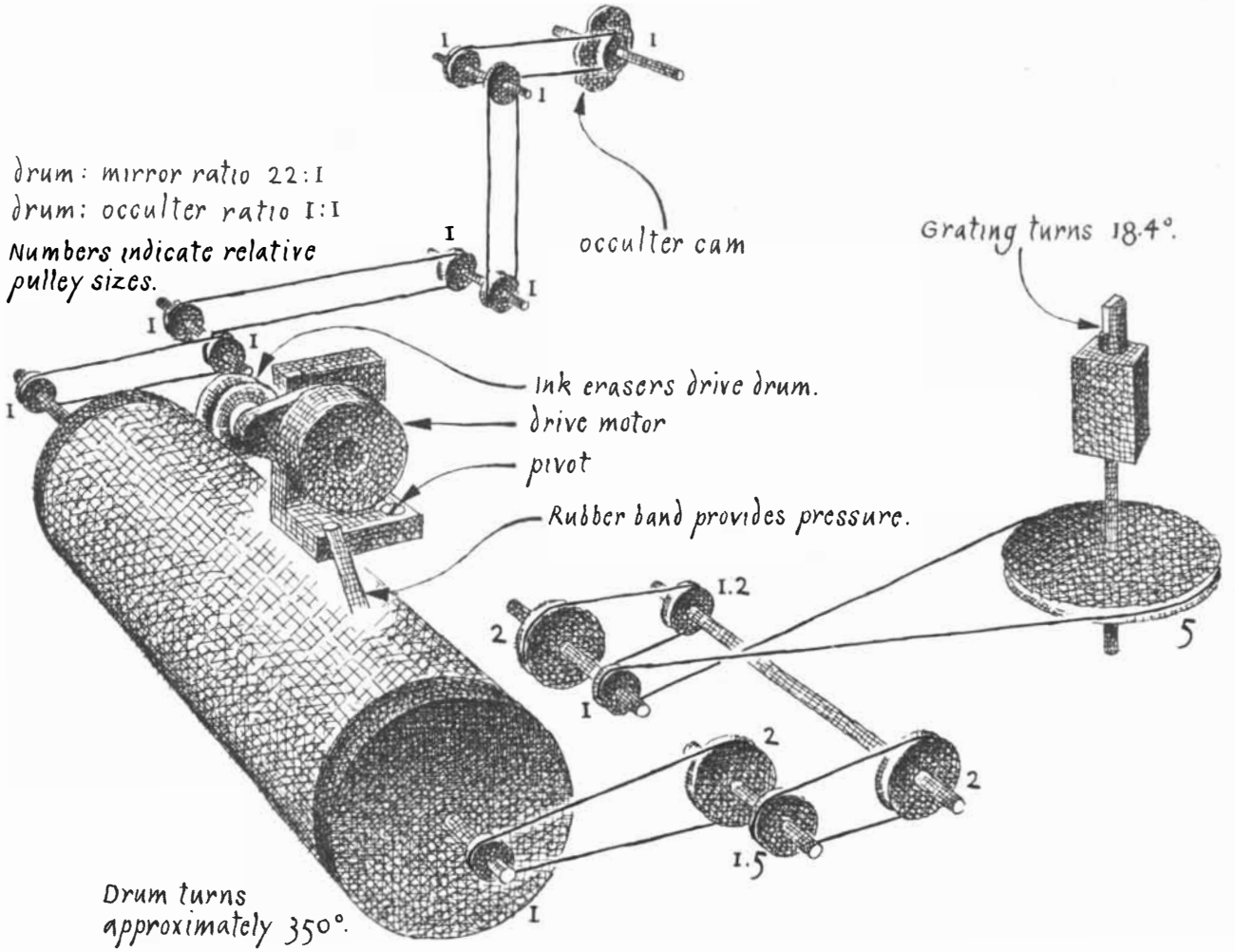
"To subtract the output of the refer-

ence beam from that of the principal beam I connected the photocells in series to function as adjacent arms in the circuit of a Wheatstone bridge, which has four arms. The other two adjacent arms are two variable resistors [*see upper illustration on page 121*]. The resistance of the photocells varies inversely with the incident illumination. When the incident illumination is equal on both cells, the resistances of the cells are equal. If the variable resistors are then adjusted to be equal, the bridge is balanced and no potential difference exists between the junction of the resistors and the junction of the photocells even though the circuit contains a three-volt battery.

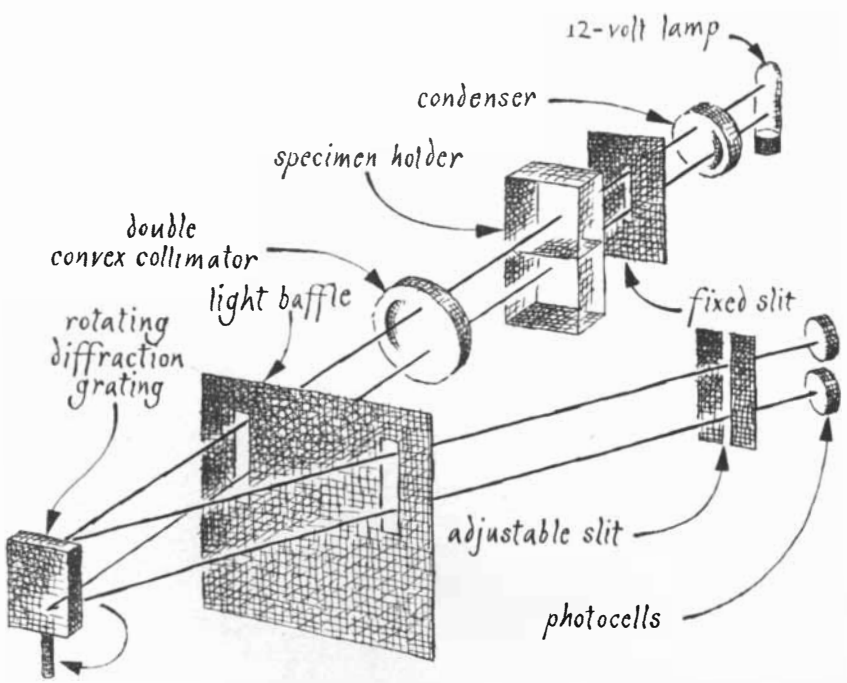
"If the intensity of either light beam varies, however, a proportionate potential appears across the now unbalanced bridge and hence across the input terminals of the amplifier. The amplified potential operates the direct-current motor. The shaft of the motor assembly rotates the movable contact of one of the variable resistors in the Wheatstone bridge in the direction required to balance the circuit, thus reducing the input potential of the amplifier to zero. Simultaneously the motor moves a recording



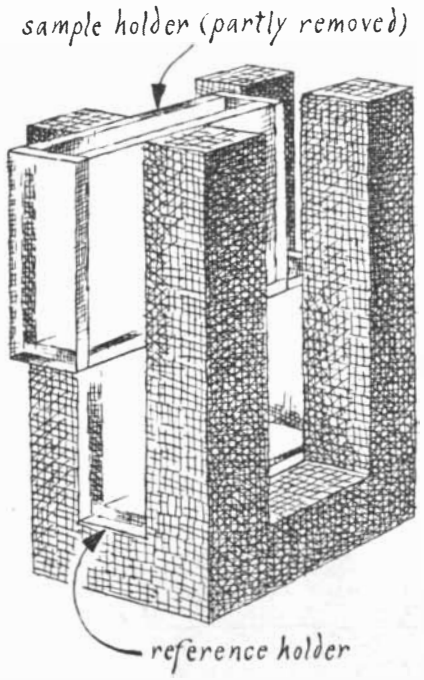
Sean Johnston's recording spectrophotometer



Arrangement for propelling the drum



The optical train



The specimen holder

pen through a distance that corresponds to the algebraic sum of the light intensity of the two beams.

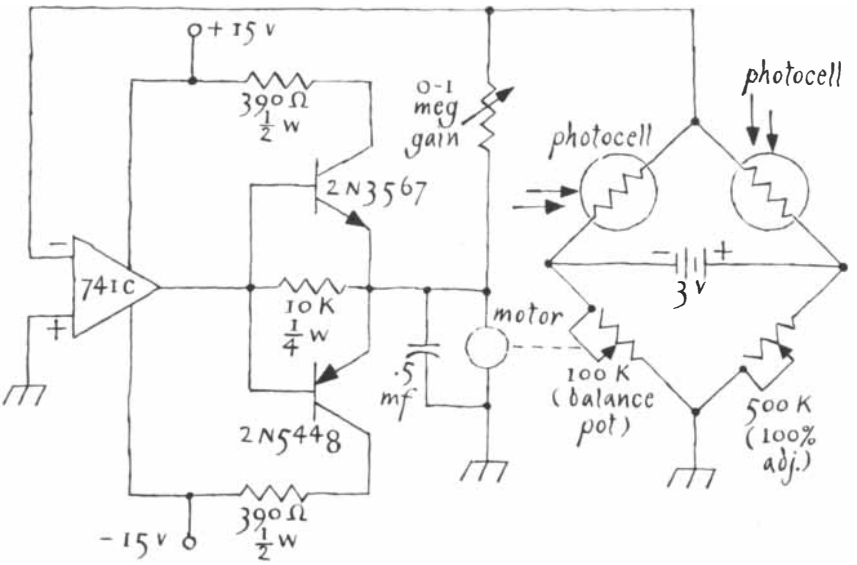
"The recorder consists of a felt-tipped pen that moves in a straight line parallel to the axis of a rotating drum around which the graph paper is wrapped. A graph is made by rotating the drum through 350 angular degrees. A system of pulleys and belts that is coupled to the drum simultaneously and synchronously rotates the diffraction grating through an angle sufficient to scan the visible spectrum from violet (400 nanometers) to dark red (750 nanometers) [*see top illustration on opposite page*].

"A second system of pulleys and belts similarly rotates an opaque cam called an occulter. The cam partly intercepts the reference beam as required to compensate for deficiencies in the system, with the result that a graph indicating 100 percent transmission of all colors, as with a water-white specimen, approximates a straight line. The contour of the cam is being determined experimentally and filed by hand. I am still working to improve it.

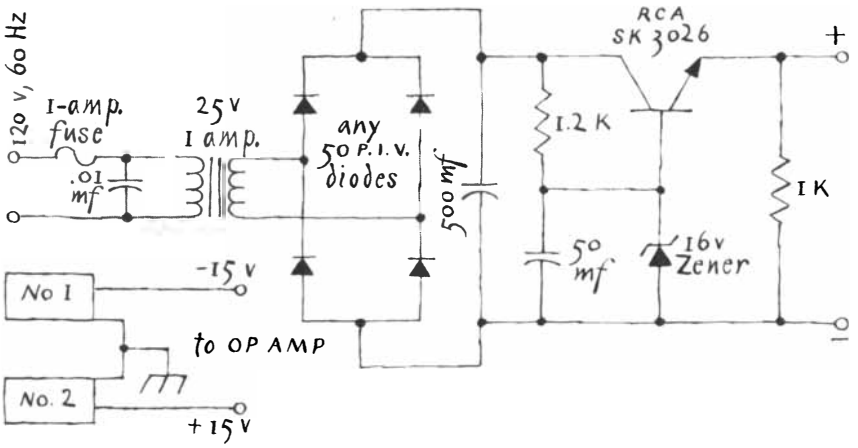
"The drum consists of two soup cans fastened end to end with epoxy cement and adhesive tape. The assembly is covered by a length of rubber inner tube that is secured at the ends with broad rubber bands. The drum is rotated through frictional contact with a pair of typewriter erasers of the disk type that are fastened with epoxy cement to the shaft of a synchronous motor, which turns at one revolution per minute. Motors of this kind are common in electric clocks.

"The motor is fastened to a supporting bracket by a single screw on which it can pivot in the vertical plane. Firm contact between the rotating typewriter erasers and the rubber band at one end of the drum is maintained both by gravity and by the tension of a pair of rubber bands stretched between the motor and the base. The pulleys of the drive system came mostly from a Meccano set. The belts are of catgut.

"The specimen is scanned by the full spectrum during approximately one revolution of the drum. Thus the apparatus generates a graph that depicts the spectral response of specimens consisting of an unchanging mixture of colors, such as colored glass or gelatin filters. By disconnecting the belt that couples the drum to the diffraction grating, graphs can be made by plotting changes in the intensity of a selected color against time. This effect is frequently associated with chemical reactions. The angle of the



Electronic circuit of the instrument



Circuitry of the power supply

diffraction grating can be set by hand to expose such specimens to any desired hue. When changes in the intensity of the transmitted hue are plotted against the rate at which the drum rotates, they measure the speed of the chemical reaction.

"The most difficult but most interesting part of the apparatus to develop was the pen mechanism. As I have mentioned, the electric power for operating the motor that moves the pen is the amplified potential that appears across the Wheatstone bridge. The signal appears whenever the bridge is out of balance in response to variations in the intensity of the light that falls on the photocells. The amplitude of the signal varies in proportion to the net intensity of the light beams.

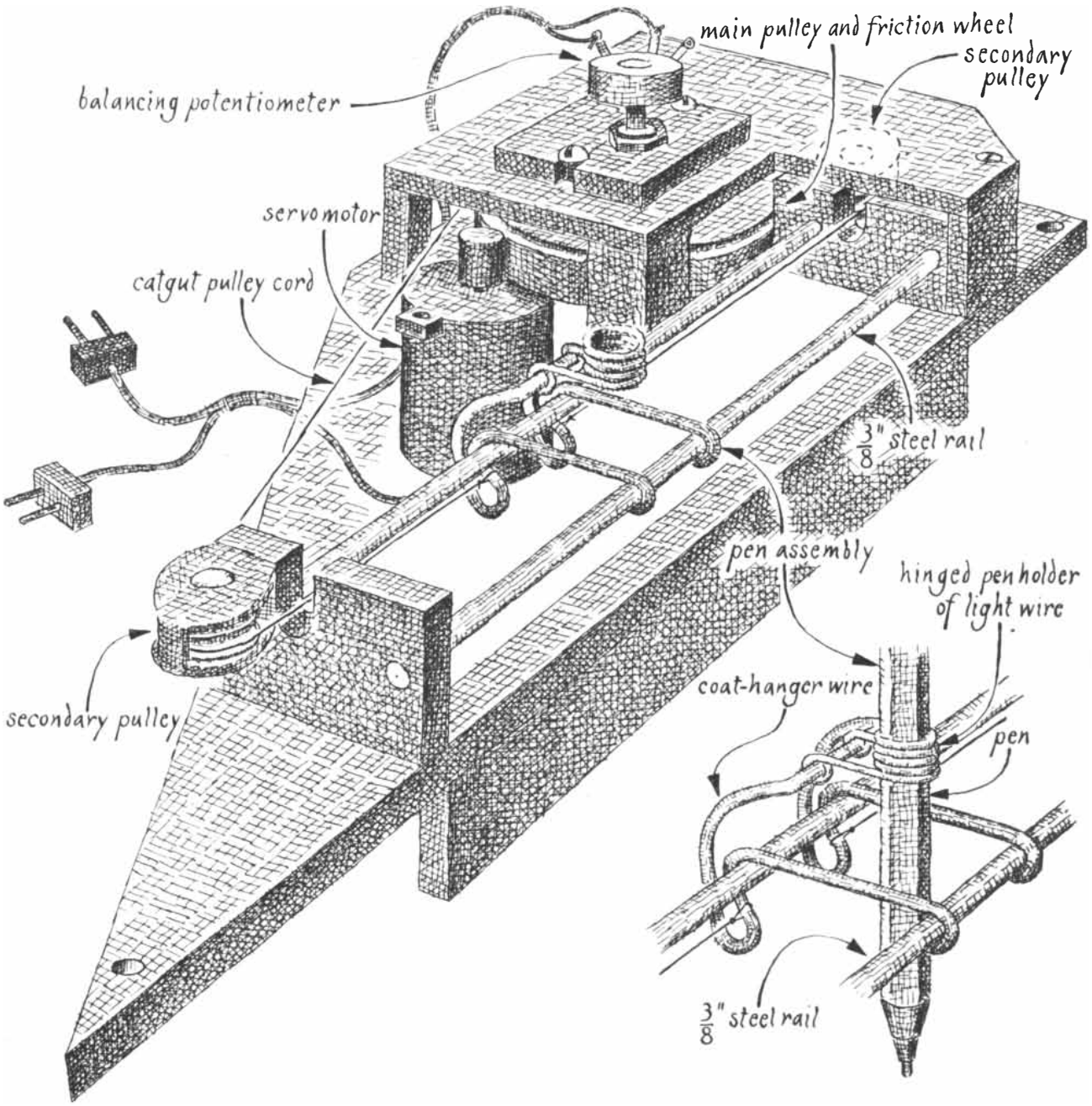
"There is a minimum level below which the motor that moves the pen will not respond. Moreover, when balance is restored to the bridge by the operation of the balancing resistor that is coupled mechanically to the motor, the pen does not stop instantly at the point of balance. Inertia causes the mechanism to overshoot.

"For these reasons the graph of a smoothly increasing signal can appear as a series of stairsteps. When the signal current increases to the minimum required to start the motor, the pen moves upward abruptly. Because of the momentum it continues to move upward

briefly after balance is restored. The movement of the pen then stops but the transverse motion of the paper, which is carried by the rotating drum, continues. The result is a graph in the form of a step instead of a smooth line. The solution is to minimize the mass of the moving parts, to minimize friction and to amplify the signal appropriately. By these stratagems the size of the steps can be reduced to the point at which they merge into a continuous line.

"Almost any small, reversible direct-current motor can be installed to operate the pen. The Edmund No. 71,702 motor that I selected includes a built-in set of reduction gears that turn the output shaft 60 revolutions per minute when the motor is connected to a source of .011 ampere at a potential of three volts. With this power input the motor develops a torque of eight inch-ounces. I increase the force at the pen severalfold by additional speed reduction.

"The shaft of the motor carries a rubber friction roller that I made by pushing a twist drill through a rubber eraser. Turning the assembly at high speed with an electric hand drill, I held a piece of sandpaper against the eraser until the rubber was eroded to a smooth cylinder. The rubber was cemented to the shaft. It presses against the rim of a four-inch plywood disk that is locked on the shaft of a conventional potentiometer. A four-inch pulley is also locked on the shaft. The potentiometer, the motor, the rails and two secondary pulleys are mounted on an independent framework of quarter-inch plywood [*see illustration below*]. The rails guide a sliding carriage made of coat-hanger wire. The carriage supports a helical coil of smaller wire that is free to swing in one vertical plane. The helix makes a snug fit with the felt-



Details of the pen servomotor

tipped pen. Its freedom in the vertical plane enables the pen to follow irregularities in the surface of the paper.

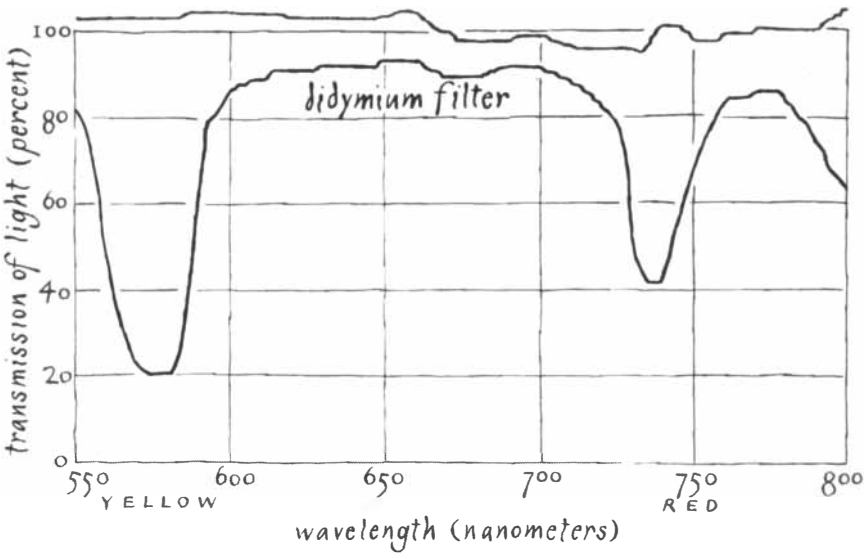
"The secondary pulleys were bought at a local hardware store. Half of the block in which each pulley was mounted was cut off with a hacksaw and discarded. The cut face of each block was cemented to the plywood frame with epoxy. One end of the catgut cord that transmits power was tied to the carriage. The other end was then threaded over the pulley at the outer end of the carriage rails, around the motor-driven pulley, around the pulley at the inner end of the rails and then returned to the carriage, to which it was tied. The rails are three-eighth-inch iron rods of the kind sold for hanging window drapes.

"The two power supplies for the amplifiers represent the costliest part of the construction, particularly the step-down transformers that reduce 120 volts to 25 volts. I happened to have materials on hand for making the entire instrument except the electronic components. They cost approximately $40. Doubtless the cost could have been cut in half if I had taken the time to search the surplus market.

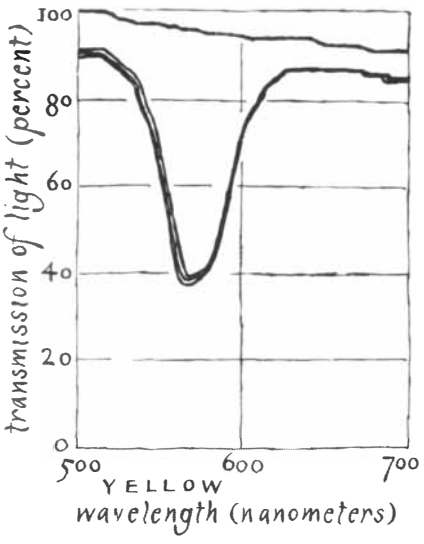
"The usual precautions should be observed when the electronic components are assembled. For example, in bending the leads of a solid-state component always grasp them close to the devices to avoid cracking the seals. In making solder joints connect an alligator clip to the leads or grasp them with long-nose pliers to obtain a heat sink. The 2N3567 and 2N5448 transistors or equivalent devices should be provided with heat sinks, which can be of the snap-on type. Incidentally, any transistors can be substituted in this application provided that they are rated at a beta of 40 to 100, a power dissipation of at least .3 watt and a collector-to-base potential of at least 40 volts.

"The optical system consists of a 12-volt incandescent lamp of the kind used in spotlights, a condensing lens for collimating the rays that diverge from the lamp, a pair of fixed entrance slits, a companion pair of specimen holders, a focusing lens, an aperture, a rotatable diffraction grating of the reflecting type, an exit aperture, an adjustable pair of exit slits and a cadmium sulfide photocell for each of the two beams [*see illustration at bottom left on page 120*]. Specimens are inserted into the light beams at an arbitrary point between the entrance slit and the focusing lens.

"The supporting fixture consists of a plywood frame into which cuvettes are



Transmission graph of didymium filter

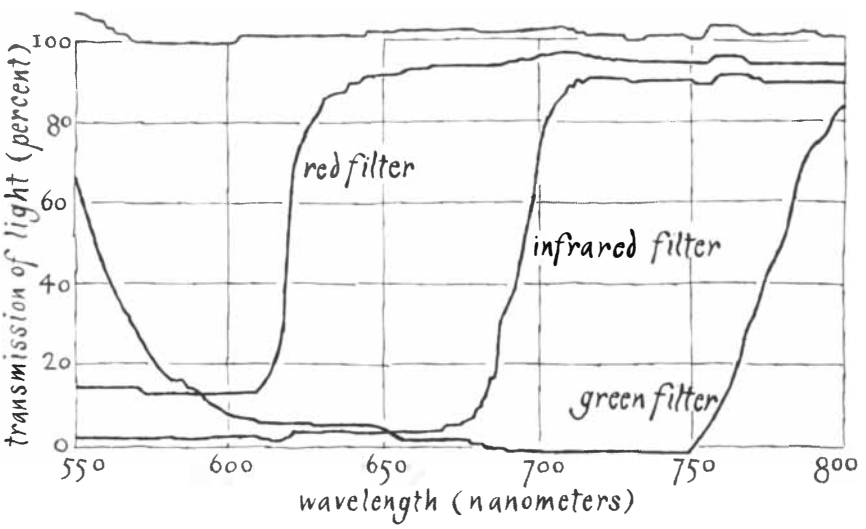


Three graphs of didymium superposed

slid. (A cuvette is a clear, rectangular container of glass or plastic for holding solutions.) In my arrangement the specimen solution is placed in the upper cuvette for interception by the principal beam; the reference solvent is placed in the lower cuvette. Cuvettes can be made by cementing or waxing together appropriately sized rectangles of clear, flat glass of the optical grade used for projector slides. This scheme applies only if the experimenter excludes test solutions that would react with the cement or the glass. I also made a set of small frames that fit the supporting fixture to hold glass or plastic light filters.

"Cadmium sulfide photocells are designed for maximum sensitivity to a specific color. For example, the Clairex Type CL-702 is most responsive to the blue end of the spectrum and is suitable for use with fluorescent light. The sensitivity of the Clairex Type CL-705 is maximum at 550 nanometers and closely matches the spectral response of the human eye. This type is commonly employed for light measurements and is suitable for use with incandescent lamps. The response of the Type CL-703 peaks at 735 nanometers in the deep red portion of the spectrum. It can be used with either incandescent or neon lamps. Types that peak at intermediate wavelengths are also available from mail-order distributors that specialize in electronic supplies, such as Allied Electronics Corp. (2400 West Washington Boulevard, Chicago, Ill. 60612).

"The interception of the reference beam by the occulting cam tends to increase the output of the amplifier just as though the intensity of the principal beam had been increased. In effect the occulting cam acts as a 'phantom specimen' of negative transmittance. Normally the adjustable resistor of the Wheatstone bridge is operated to shift the recording pen to a position on the graph that the experimenter arbitrarily selects as the point of 100 percent transmission. If the instrument were perfect, and if the specimen were completely clear, the resulting graph would be a straight line at the 100-percent-transmission level. The instrument is far from perfect. For this reason the uncorrected graph of 100 percent transmission is an irregularly undulating curve that extends above and below the 100-percent-transmission line [*see illustration at left above*]. By altering the contour of the occulting cam experimentally, however, I have succeeded in limiting the excursion to less than 3 percent. By continuing to alter the shape of the cam I hope to reduce the error to less than .5 percent.



Graphs of three types of filter

"The less than perfect response of the instrument can be traced to a number of obvious sources. For example, the monochromator could be improved by adding a telescope lens between the diffraction grating and the exit slit. The spectral response of the cadmium sulfide photocells is far from linear. Of greatest importance, however, is the relatively low quality of the diffraction grating, particularly with respect to resolution. The stock from which the grating is made was originally developed to split light into its constituent hues for a system of color photography that was later abandoned. I hope to replace the material

eventually with a diffraction grating of instrument quality, such as the Edmund No. 41,028.

"Most supports of the optical elements were made from plywood either a quarter or an eighth of an inch thick. The grating support is a block of wood that measures 2 × 1½ × 1½ inches. The grating is fragile. To protect it I included the inverted lid of a plastic pill bottle as part of the mounting assembly. When the grating is not in use, I snap the pill bottle over it.

"For convenience in testing the apparatus during construction and in subsequent maintenance I made each functional element as a removable subassembly. Parts made in this way include the recording drum, the servomotor, the optical train and the electronics system. A panel on the front of the instrument includes on-off switches for the lamp, the drum motor and the electronic system and knobs for adjusting one variable resistor of the Wheatstone bridge and the gain of the amplifier. This latter control is rarely used because I operate the system at maximum gain.

"To begin operating the instrument I attach one edge of a sheet of blank paper to the drum with adhesive tape, rotate the drum by hand to wrap the paper snugly and fasten the remaining edge with another strip of tape. I then switch on the electronic system, including the lamp. Before inserting specimens in the cuvettes I set the diffraction grating by hand so that blue light (450 nanometers) falls on the photocells.

"The adjustable resistor of the Wheatstone bridge is then operated to the point where the pen carriage moves close to the left edge of the graph paper. I insert the pen in the carriage. The drum motor is switched on. The pen traces the 100-percent-transmission line at the top of the graph.

"After one full revolution the drum is stopped, the grating is returned to its initial position and specimens are inserted. The drum is again operated to record the graph. The first of the accompanying graphs [*top left on opposite page*] depicts the characteristic opaqueness of a didymium filter to yellow light. The second graph was made by resetting the diffraction grating three times and recording three traces of the didymium filter on a single sheet of paper to demonstrate the repeatability, or precision, of the instrument. The remaining set of graphs was made by sequentially recording the transmission characteristics of a red, an infrared and a green filter on a single sheet of paper."

BOOKS

A kit that re-creates the ancient astrolabe; other aids for the navigator and stargazer

by Philip Morrison

THE ASTROLABE, by Roderick S. Webster, author and mathematician, and Paul R. MacAlister and Flolydia M. Etting, designers. Paul MacAlister and Associates, Box 157, Lake Bluff, Ill. ($18). STAR FINDER AND IDENTIFIER. Weems & Plath, Inc. Annapolis, Md. ($15). WHITNEY'S STAR FINDER: A FIELD GUIDE TO THE HEAVENS, by Charles A. Whitney. Alfred A. Knopf ($4.95). ASTRONOMICAL CALENDAR 1975, by Guy Ottewell. Department of Physics, Furman University, Greenville, S.C. ($4.95). Geoffrey Chaucer owned an astrolabe and wrote a "lucid essay" on its use, intended for his 10-year-old "Sone, Litell Lowys." (The essay is still helpful, says Roderick Webster, the computer of the first instrument listed above.) Galileo three centuries later had an astrolabe too, like every traveler and learned man throughout the Renaissance. It was Islamic science, working on Alexandrian principles at least as old as the sixth century and perhaps going back to Hipparchus himself, that developed the instrument and transmitted it to all Europe from Muslim Spain. The device is essentially a flat projection of the celestial sphere marked with the stars and the path of the sun, arranged to turn on its pole over another projection of the heavens as seen from the horizon to the zenith by an observer at some fixed latitude. The ability to turn the sky disk to the right orientation makes it possible to model the true appearance of the sky at any time and conversely to determine the time of night from the measured angle above the horizon of any plotted star (or of the sun by day). The Greek name means "star-taker"; the star's altitude was taken by the use of a sighting device on the reverse of the disk while the instrument hung freely from the hand by a loose ring. The face served as an analogue computer and of course was specially elaborated for astrological computations. (It was not easily used at sea.)

Art and science were joined in these devices. A couple of thousand of them are now preserved in museums and private collections, deservedly for their elegance as fine metalwork. About the oldest we have goes back to the 10th century in Cordova; the artificers of Lahore in the Punjab still made beauties in the 18th century. (The officials of some conservative mosques regularly used the astrolabe up until this century.) In Islam it has long been an attribute of status to possess an astrolabe; some late Indian ones are unworkable, having degenerated to mere showpieces in a time of clocks and tables.

Anyone interested in the scientific thought of the past may well covet an astrolabe; no deeper material association with the tradition of early science can be found. A few genuine old instruments reach the market, where they can be bought today for the price of a fine automobile, but the kit offered by the Chicago design firm of MacAlister is a welcome assuagement to the antiquarian of more modest means. A delightful astrolabe hangs before this writer now, inscribed in English, gleaming like any polished and engraved brass treasure of the museums, at a little distance even Renaissance in feeling and form. Actually it is made of cardboard covered with metal foil, with the scales printed and the shapes die-cut in advance, and was assembled from flat sheets in a couple of hours. A thoughtful assembly of the device (excellent directions are given) is a good road to understanding its principles. What results is handsome and serviceable, although the inevitable warping of the cardboard and the play at the axes limit accuracy to about a degree of arc. (The gluing job is not simple enough for a complete novice; seek the help of a dexterous and experienced friend, or practice first with a couple of other cardboard constructions so that you do not spoil your astrolabe.) The pierced disk that bears the star pointers is attractive even though cardboard does not admit the delicacy of design that was open to the best workers in brass. The positions are those for A.D. 1975 and are useful for 50 or 75 more years of slow precession. All the traditional parts are here: the computing and the sighting pointers and the plates for four latitudes, very properly stored within the "mother," the eight-inch main base. Plenty of auxiliary scales are provided, but it is impractical to plot the planets on the foil surface with ink and then to erase them, as Copernicus liked to do. (Small markers of pressure-sensitive tape are suggested.)

The serious use of the astrolabe has not ended, and the new star finder designed on the Rude and Collins principle (their instrument was once U.S. Navy issue) is a modern version of the astrolabe. The stereographic projection of the stars now appears printed in black on a sturdy white plastic disk that can take pencil marks. Modernity is cosmopolitan; whereas all astrolabes of the past were made for northern use, this instrument has two faces with more than one sky hemisphere on each. The mock-brass astrolabe plots no star south of Antares, but this one includes stars south to Carina and the Southern Cross. In all, 57 stars are plotted, the ones whose positions are tabulated in the *Nautical Almanac*. In the same global style horizon disks and their accompanying sky grids are furnished for every 10 degrees of latitude from 5 to 85, north and south. Printed in blue line on transparent plastic disks, one of these horizons is chosen and placed over the star disk. The classical astrolabe reversed the scheme. Lacking any durable, workable transparent material, the classical designers cunningly pierced out most of their sky disk, leaving only a tracery of pointers to bear the star positions. Since the horizon grids had to be multiple and were even harder to make as cutouts, they became solid baseplates. The unique star map, the *rete*, or net, of the old astrolabe, was superposed. This austere finder has no extra circles, not even the ecliptic. It is intended as an aid to the ship's navigator. Less than familiar with the constellations over the entire sky, he must, at the ship's peril, be able to recognize which stars he has used for a position fix. Even if he knows the sky well, a night when

only a few stars gleam transiently through shifting holes in the cloud cover is a trial. This device enables him to prepare an accurate sky map for safe recognition of any single bright star, given a rough geographic position and a good clock. The instrument is neat and well made, more stable and several times more accurate than the cardboard astrolabe of the same size, although it is far less evocative. The instructions are laconic formulas that occupy less than a page. They are adequate only for the experienced, but the device itself is satisfying.

The "locator wheel" of Charles Whitney is an example of an astrolabe reduced to rudimentary simplicity for casual stargazers. The sky map is here, now with constellation diagrams printed on a small white paper disk. The transparent plastic overlay bears a rather crudely outlined horizon curve for about 45 degrees north latitude. Setting the date and the time then displays the stars visible in the sky; rough measurements of the hours of sunset and sunrise can be made because the sun's path is also plotted among the stars. This form of planisphere has long been familiar to amateurs of the sky, and the present realization is inexpensive and intelligent. It comes as an enclosure in an excellent small book meant for beginners. The text begins where the beginner is and does not omit explaining the north polar direction, the look of planets and of airplanes and where to find the moon. It is limited to objects "visible to most campers or... to those who merely wish to step outside for a few minutes with a... pair of binoculars." It is a fully useful work at a level not always honestly achieved, and its tables for sky events until 1977—planets, moon phases, meteor showers—will help even experienced watchers through that year.

We come at last to a Copernican document. It is plain that geocentrism works perfectly well for the look of the sky. This fully packed calendar, latest among a number of useful annual publications for sky watchers, is explicitly Copernican. It is no instrument but a printed series of maps. Its entries, two pages for each month, display with the usual list of events a scale map of the solar system on Copernican principles. Drawn on the map are the planetary orbits, including the earth's, and the arcs traversed that month by each planet. Using the constellation directions as a background, the reader can see at once which way the planets lie in the sky. It would work for Martian amateurs too. (With each month there is also an astrolabe-like sky projection with stars and constellation forms mapped in white on black.) There is plenty of other information: finder charts of the outer planets against the star background, graphical sunrise and sunset times, even double-star orbits for the telescopic amateur. The calendar aims to suit a wide span of users and does so well, but it is perhaps best for the more knowing. One delightful account tells how and on which twilight evenings to take up the ancient sport of trying to find the slenderest crescent moon.

SUPERSHIP, by Noël Mostert. Alfred A. Knopf ($8.95). At this moment a steady parade of tankers, gravid with crude oil, stretches from the Persian Gulf across the lonely Indian Ocean, through the granite shallows of the Strait of Malacca, on to Japan. The ships are spaced 100 miles apart all along the route. A similar procession is continually returning, ballasted with seawater, to reload. These are huge ships; designated Very Large Crude Carriers, they are each rated at upward of 200,000 tons. They stop nowhere en route. They rarely dock save for repair; they turn around in a day or so, loading and discharging their liquid cargo via pipeline at islands of steel set in water 100 feet deep 10 miles offshore. Crewmen serve a long time aboard, and at the end of their wearying terms they are replaced by launch or helicopter while the supership sails on. Rotterdam or the Niger delta may be the destination as well as Japan; so far no such ship can be seen in American waters.

Size is the economic key. The biggest VLCC has only one crew and one engine room. Seawater buoys up the load, so that the weight of steel increases much less rapidly than the volume of cargo. The age of the VLCC dawned only 25 years ago, pioneered by the Kure naval dockyard under the impetus of a Texas oilman, Daniel K. Ludwig. Now the big ships are prefabricated all over the world: the huge sections are welded together and lifted by crane into a dry dock for the final welding into a ship. Japan still builds about half of the tonnage. The extraordinary rise of these ships has been hasty, their workmanship often negligent, their peculiarities enigmatic (three have exploded, perhaps while water was being sprayed to clean their dark, cathedral-size tanks) and their management marginal. The most conscientious and best-trained officers can barely handle a ship 1,000 feet long and 90 feet deep, crewed by two dozen men, the outlandish hull powered by a single high-pressure steam boiler, yet automated and utterly dependent on unfailing electrical power. Routine orders pass along the vast empty deck over walkie-talkies to sailors bicycling to their tasks. These ships are not built to last. In a scant decade acres of plates corrode and weaken, the steam-raising system begins to break down, and the ship finds itself a "trader of low degree" before the newer and larger design to come.

The big oil companies own and care for a third of the tonnage, but they save capital and allow for shifts in the market through the free use of chartering. Two-thirds of the superships thus belong to a handful of very wealthy men: independent tycoons, Greek, Hong Kong, Norwegian, American and Indian, who succeeded first in some "speculation with secondhand ships" when charter prices skyrocketed and now have enlarged their names and their fleets. Their ships are built with loan money; the risky charter market obeys the cool, quick hand of the well-heeled and consummate dealer. It was the 1960's, after the first closing of Suez by the 1956 war, that nurtured this hasty evolution, its structural-design computations and novel financial devices.

This book is the knowing narrative of a professional writer, a man who lives in Tangier and follows ships as they stream past his eye through Gibraltar. He plays out two themes, sharply and sensitively, against the background. One tale is his cruise to the Gulf and back aboard one showpiece VLCC of the famous P & O line, a modern chronicle of seamen and the sea viewed in a loving day-by-day rendering, with a deeper running comment on the historic change each day displays. Once it was the deck officers who alone held command: all power was from the canvas set by hand. Then came the engineers, indispensable but touchily subordinate. Only a decade back electrical work was a petty officer's task—changing fuses, perhaps. Now the electronics officer shares indispensability: the engine room, like the radar sets, is automated and computer-linked. A captain who demands letter-perfect performance, a proud Goanese stewards' department, one officer's young wife aboard in bright red velvet, a power loss leaving the great ship dead in the water—so runs the narrative of a long voyage suspended between old and new.

The gigantic gale waves rising off the Durban coast threaten the supership as they must have frightened Portuguese caravel masters long ago. Indeed, the tanker's chance-filled, marginal and lengthy voyages remind us of the days of sail, but now on a giant ship filled with

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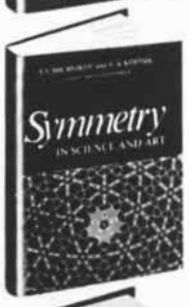

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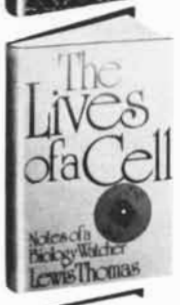

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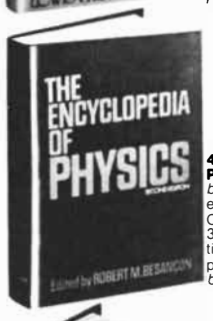

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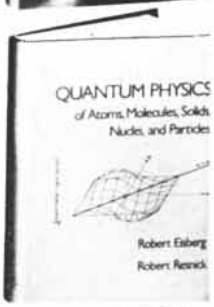

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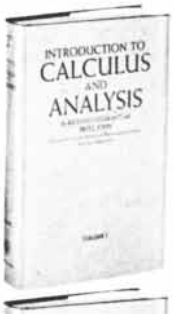

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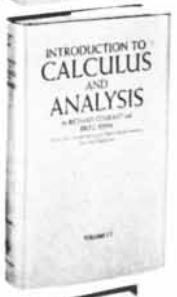

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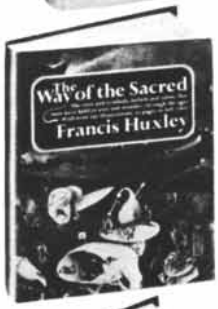

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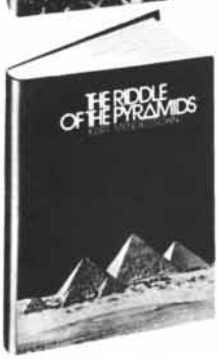

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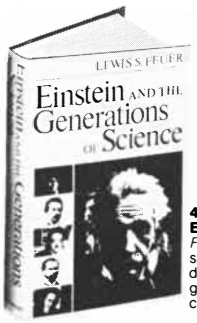

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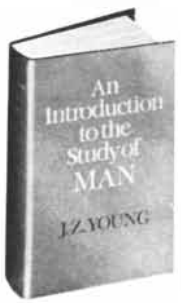

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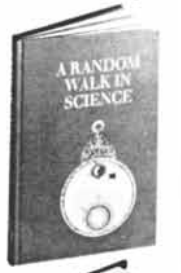

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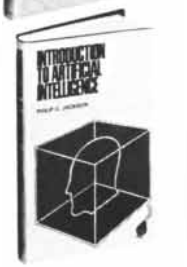

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strange fumes and seawater, too big to roll, condemned like the Flying Dutchman to remain at sea forever. The offshore mists of the steaming Persian Gulf still look like those of Bantry Bay, except at night when the gas flares on the seaward rigs enflame the sky.

Mostert's second theme is greed. "As ships get bigger and more technical and difficult to handle, and as they... set afloat upon the waters quantities without precedent of dangerous and damaging substance, they are being sailed by unskilled or improperly trained or uncaring men whose minimal terms of employment are part of the basis for a profit for the shipowners and operators gross beyond any previous calculation of avarice." Already the traditional Plimsoll line has been in part set aside: tankers can legally sail around the Cape of Good Hope in winter loaded beyond winter standards. In those grim seas for five days between the long and less threatening tropical sectors, all tankers are by hasty recent international agreement exempted from obedience to the light-load old Plimsoll had prudently set for wintry waters. Worse, the Liberian flag and similar flags of convenience that now fly over most of the chartered superships exempt them from reasonable standards of training, work load, operation and design. Neither patched-up ships nor overworked master and crew ever see their declared "home port." It is these ships that suffer the most wrecks (such as the *Torrey Canyon*'s). No longer is it the seamen who have the most to lose, however. ("Helicopters get the sailors off, we clean up the muck.") The seas themselves are put now at increasing risk. Although we need the oil and the methane, we need even more to protect the sea. One clear means exists: the industrial nations that receive nearly all the ships must act unilaterally to enforce sounder new standards. There is, Mostert argues persuasively, no other way. We can no longer afford the free seas and the jealous independence of a hundred maritime states. Ships have grown too big; they crowd us all.

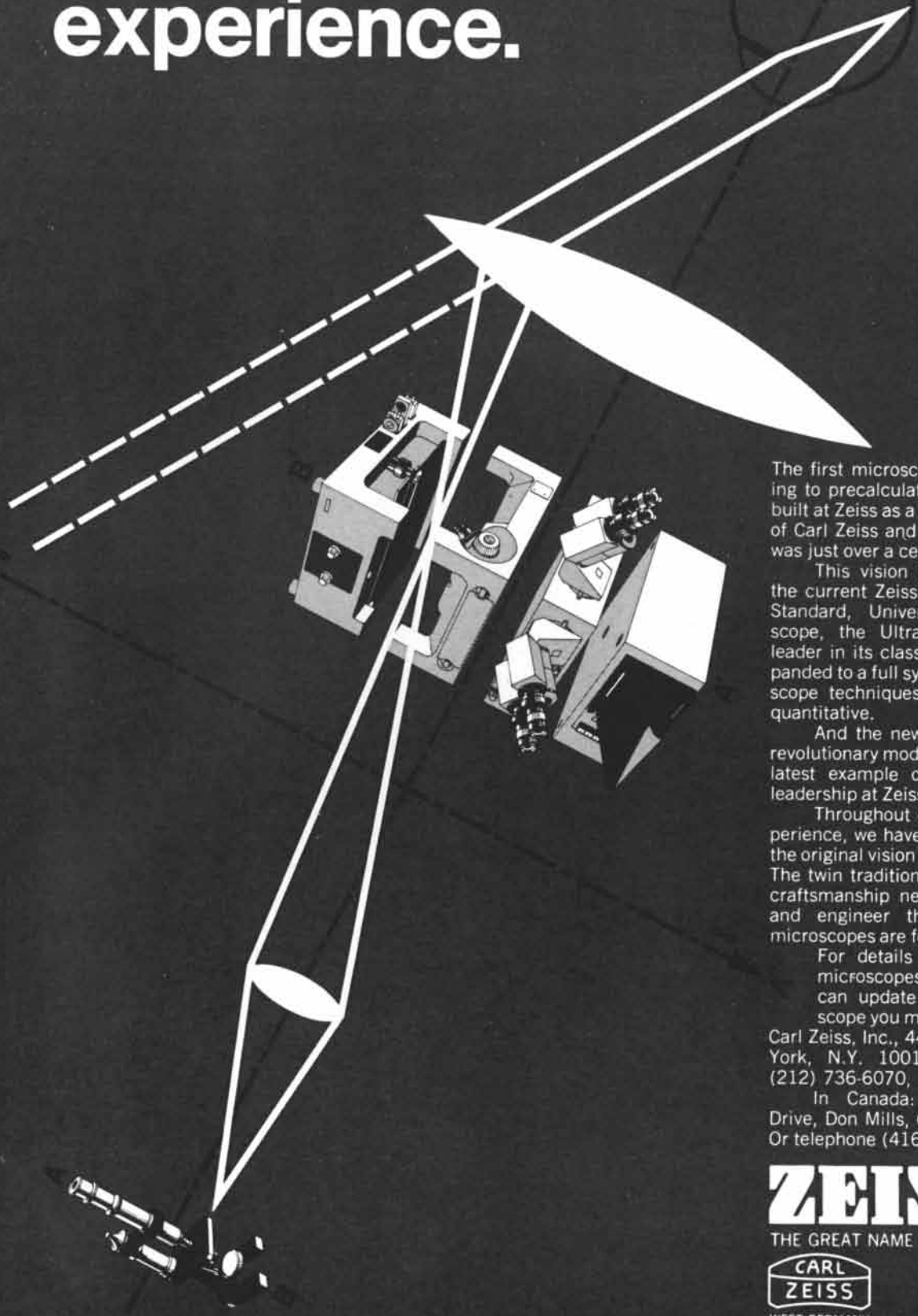
PRE-COLUMBIAN CITIES, by Jorge E. Hardoy. Translated by Judith Thorne. Walker and Company ($19.95). URBANIZATION AT TEOTIHUACÁN, MEXICO, edited by René Millon. VOLUME I: THE TEOTIHUACÁN MAP. PART ONE: TEXT, by René Millon. PART TWO: MAPS, by René Millon, R. Bruce Drewitt and George L. Cowgill. University of Texas Press ($30). They belong to the monumental legacy of our species: subtle Tikal in the dense forest on its limestone plain, many-walled Chan Chan in the coastal Peruvian desert, the frowning bastions of Paramonga north of Lima, Tenochtitlán, now entangled by the cathedral and the subway of Mexico City, and many more. These form the subject of the thick volume of the Argentine urban specialist Professor Hardoy. His fine book contains plans and aerial views of all these sites and a systematic personal examination of their nature in terms of the cultures of which they formed an essential part. From what lies on the ground and from old stories and a few old maps and chroniclers we can reconstruct—with much uncertainty—the size, nature and history of these truly wonderful places, which generally lack readable inscriptions or contemporary written accounts. Cuzco is still lively among its fitted masonry walls; Mexico City contains its Aztec past well. Cortez and his men saw that cruel and splendid city at its height, as new and as volatile as Los Angeles. It was then about the size of Paris, some 160,000 souls, as large as any city in the world outside of China. Tikal, like all Mayan "cities," was no dense, diverse habitation but a sacred ceremonial center, more early Vatican than Rome, its artisans and devotees simple corn farmers there for a visit or a season. Chan Chan, capital of the Chimú empire, was an assembly of five walled citadels, foursquare and distinct; it resembled the ancient cities of China but was less unified. Paramonga was a fortress. In the absence of cannon the bastions did not need to stretch out far from the quarters within, and so the plan provided platforms to control the high ground. Tenochtitlán was the most citified of them all in its density, plan and architecture and in the diverse specialization of its services and its inhabitants. There were a zoo and an aviary, hairdressers, apothecaries, porters, caterers, those who "sell colors for painters," judges and inspectors of weights and measures, flower sellers, noblemen and priests, artisans of consummate skill—a very Mexico City before wheat, horses or iron. Hardoy has visited the sites, studied the literature, tried hard to assess the evidences of population and diversity. It is first-class reading, and it will send many readers to the rich and conflicting sources themselves. Those who visit these sites can find no better overall account; individual cities and cultures have, of course, their own classics. The book first appeared in Spanish a decade ago, but it has been considerably updated in this interesting version.

The second book is the first volume of a work with several still to come. It is a meticulous firsthand piece of primary archaeology, a green opossum of a book, each part a foot square. The first part is a thinnish, very readable account of the work of mapping the famous pyramid-city site in the austere highlands just north of the Valley of Mexico. The second part, bearing three big maps stored in a pouch on the back cover, is a thickish volume of some 150 pages of map squares (500 meters on an edge) recording field data, every one with a clear red-printed overlay showing the archaeological interpretation—evidence and conclusion, richly presented.

Professor Millon has been at this task ever since he studied irrigation in the area as a graduate student 25 years ago. In 1962, with financing by the National Science Foundation, he organized a modern aerial photogrammetric survey of the site from 4,000 feet. That survey now maps some 40 square kilometers, with each tree plotted (anguish seized the cartographic contractors at that demand!), the maguey plants drawn only by rows and the nopal cactus only by orchards. (Cochineal grows on nopal and was an ancient product of the city along with obsidian and cinnabar.) Ground-control points were set up with care, and years of field studies searched out every unexcavated mound under which a dwelling, a shop or some public structure might be hidden. The survey showed up some large unexcavated precincts too big to note from the ground.

Most exciting, perhaps, is the finding that there are more than 500 craft workshops among the nearly 3,000 apartment compounds mapped. Most of them are obsidian workshops, but there are others where skillful people once fired pots, made figurines of clay or worked shell, basalt, slate and hard stones. Their tools and their scraps reveal their work. Their shops and dwellings are made known either by visible walls or floors or by various building materials, particularly a "Teotihuacán concrete": crushed volcanic scoria with mud mortar. This was a planned city that was begun at about the time of Christ in a village settlement area and that collapsed for no clear reason some eight centuries later. It was influential throughout classical Middle America; its wares and even its people are found or figured in many places. For centuries there existed within it a small quarter of Oaxacans who used the domestic wares and followed the burial practices of Monte Albán, 200 miles away. We have no evidence that they were traders; their out-of-the-way barrio shows they were of no high status. Much more is to come: pottery, other craft evi-

Visionary experience.



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dence, excavations in plenty and computer-aided studies of it all. A sense of power is beginning to arise from this kind of archaeology.

Most moving of all that the mappers show is a marker pecked as dots into the plaster floor of a room. It consists of a cross with two concentric circles superposed, a foot or two wide. It would be very much in place on any modern map as a target symbol, a key reference. It was an ancient surveyor's mark. Three kilometers west another such mark is pecked into a rock! The line the two define is at right angles to the main axis of the city "within less than one-quarter of a degree."

VEGETATION OF THE EARTH, by Heinrich Walter. Translated by Joy Wieser. Springer-Verlag ($5.90). The subtitle to this rich little volume reads, rather modishly: "In relation to climate and the eco-physiological conditions." No doubt the language here, and throughout the book, is less than simple, but the preface by a California plant ecologist puts it fairly in a capsule review: "The book is short but replete with facts. It places these facts in a consistent frame of reference.... It is also neat, precise, very readable, an excellent summary of two larger books, and current." Professor Walter has traveled out of Stuttgart to every continent, and he has distilled his knowledge in two big recent volumes in German that are indispensable to the plant ecologist but are scholarly, richly detailed and tough. Here now is his careful sketch, still not easy but fascinating if the reader brings to it some grasp of botanical terms and ideas. The small photographs (there are 20 of them, nearly all made by the author or his wife) give you a look at the forest near Victoria Falls as it begins to turn green, at the strange tussock pampa of the Argentine or at the peat hummocks of Finland. This is biology at the grass roots, yet with wide generalization. Evolutionary history has made the plants of the world, but that process has been so effective over the eons that history now plays only a secondary role: plants of distinct lineage converge on the tasks they have to perform. The succulents in Africa and America are not closely related but are similar in function. Tumbleweeds of half a dozen genera roll across open steppe everywhere.

The issue is really one of access to water. The sun is everywhere, more or less; all rocks make soil. And so water—or ice—determines. As birds and mammals are warm-blooded, so most plants higher than the fungi are wet-celled: their internal environment somehow or other stays watery while the plant lives; only a few forms can really dry out and survive. Extremes of environment may prevent a species from living at some location, but in every botanical garden it is plain that protected plants can thrive far beyond their accustomed range. It is open competition with other species that determines the populations of plant communities, in a complex dynamic equilibrium.

The great theme of the work is climate. Cold and drought both slow growth; the interplay of rain and temperature determines the climate. It is not merely means or extremes but the time course, which is represented here in seasonal diagrams in which rainfall and temperature are plotted over 12 months for each station. The most summary of all the results at hand is this: The net dry weight aboveground of plant substance that each year yields is just one part in 1,000 of the weight of rainfall! Here are the neat points on a linear graph for the grassland of southwestern Africa, confirmed by the creosote-bush deserts of southern California, fitted over a rainfall ratio of nearly six to one. The rule works also for beech forest in Central Europe, for tropical rain forest in the Ivory Coast and broadly wherever other severe limitations are absent. It is an adequate rule of thumb for the entire world; to be sure, most primary production takes place in favored conditions. Of the total world yield, about a fourth is in the ocean and a third in the humid Tropics (the valleys of the Amazon-Orinóco and the Niger-Congo and the band from the Ganges-Irriwady-Mekong to the Fly in New Guinea). The Temperate Zone and cooler regions account for less than 15 percent; those northern evergreen forests that stretch from the Yukon to Finland and on across Siberia contribute less than 7 percent. It is striking that the standing biomass varies much more widely than the rate of replacement does. In the sea the mean lifetime of the one-celled plants is about a day; on land a mean lifetime amounts to 15 years. Animals and "decomposers" as a whole contribute less than a hundredth of the total biomass, although in the oceans they are generally larger in size and hence long-lived, and manage to outweigh sixfold the microscopic plants they feed on. The production of all mankind, with our crops and animals, is contained within the 1 percent of faunal biomass. (Fossil fuels add a couple of percent more in metabolic terms.)

All these important conclusions occupy a few final pages of summary; they

stem mainly from Russian workers. The text itself considers one by one the 10 vegetational zones, from the evergreen tropical forests to the region of winter-rain sclerophylls, the deciduous and the coniferous northern forests, the alpine mountains and the rest. Each is surveyed and described in its main examples, with lessons sought and drawn. Take one example: the Mediterranean folds deep into the Old World land mass a coastal region of hot, dry summers and cool, rainy winters without much frost. On this continent only the West Coast has such a climate. In that region of ancient civilizations the original forest was a tall closed canopy of the evergreen oak. That forest remains only here and there in the mountains of North Africa. Elsewhere we find the maqui, where many of the same oak species grow as bushes to the height of a man. The young trees are cut every 20 years for firewood or construction. In California an analogous community recurs: the chaparral. The species mix is distinct and rich, since not many were removed by glaciation, but the chaparral is a natural intruder, for fires caused by lightning preceded the advent of man. A fire every 12 years maintains the chaparral against trees. Our central prairie too can grow trees; fire, hordes of grazing buffalo and droughts a century apart are what preserve the grasslands.

CLIMATES OF THE STATES, by officials of the National Oceanic and Atmospheric Administration. VOLUME I, EASTERN STATES; VOLUME II, WESTERN STATES. Water Information Center, Inc. ($39.50). This knowing specialized publisher has assembled a valuable reference, a quasi book in two volumes, 1,000 pages mostly given over to outline maps and tables. Over the past two decades the on-the-spot experts of the National Weather Service (under one corporate name or other as the years went by) prepared summaries of the climate of each state: a few pages of general text, detailed tables on dates of freezing weather, maximum, minimum and normal values of rain, temperature and the like—always with simple maps bearing rather detailed contours. These reports are generally drawn from relatively recent data, but they amass detail to be found nowhere else except in the primary publications of the same sources. The publishers have merely assembled the 51 separate reports into two heavy offset books (very informal in appearance because the texts are typewriter-set in a variety of styles). They have thus created a reference resource out of a scatter of valuable reports.

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Goya, "Why?," The Disasters of War—Reproduced with permission of Prado, Madrid.

Kenneth Clark's new American television series will be less civilized than Civilisation.

Lord Kenneth Clark's new television series is about a group of great artists, some of whom had rather uncivilized views of the civilization they lived in.

It's called The Romantic Rebellion, the first episode of which will be the PBS Special of the Week on January 13.

You'll meet artists like Goya, Ingres, Delacroix, Degas, David, Piranesi, Fuseli, Blake, Gericault, Turner, Constable and Rodin.

You'll learn about the forces that caused many of them to shift, dramatically, away from classical art—moving them, instead, to create a new, romantic art with some of the most powerful visions of terror, madness and divine ecstacy ever put on canvas or cast in bronze.

Watch The Romantic Rebellion.

It's Lord Kenneth Clark's newest, slightly uncivilized contribution to our civilization.

The Romantic Rebellion

A 15-Part Weekly series on Public TV starting Jan. 13. Narrated by Lord Kenneth Clark. Starring Goya, Degas, David, Delacroix, Turner, Rodin and others.

Made possible by a grant from AMERICAN CAN COMPANY

Exxon representative takes Newark high school students on a guided tour of facilities at Exxon's Bayway Refinery.

In 10 years, these high school students may help America overcome a major new shortage.

The 1980's. You'd expect them to be years of tremendous technological growth. But they may not be. Because by 1980, the U.S may face a severe shortage of scientists and engineers—even though we have the talent to prevent such a shortage.

The problem, however, is that much of this talent sits underdeveloped in the classrooms of our urban areas, especially where minorities comprise a major segment of the student body. And yet, this is where new technology could have its greatest impact—both on solving urban problems that need urgent answers—and in helping minority students gain new opportunities for careers in the upper levels of industry.

Unfortunately, many students with aptitudes for successful careers in science or engineering don't recognize their potential. Or if they do, their schools often lack the academic facilities to prepare them for university science curriculums. Exxon is trying to change this situation in several ways.

For example, in cooperation with the National Science Foundation, Exxon recently funded an innovative summer engineering program for high school students in the Newark, N.J. area.

During the six-week program, conducted at the Newark College of Engineering, the students held classroom chalk-talks; went on fact-finding field trips; analyzed the data on a computer and formulated theoretical engineering solutions to problems facing Newark today. These included problems in transportation, recreation, housing, sanitation and pollution.

While it's impossible to say how many of these students will eventually pursue careers in science and engineering, it's a fact that they all expressed more interest in these fields after the program. Next summer Exxon will be back in Newark. Until then, we'll continue our other programs to aid and promote engineering.

We'll again be working with the National Academy of Engineering to identify the critical factors limiting the enrollment and retention of minority students in engineering. We'll also be funding new engineering programs for minorities at 15 major colleges and universities—and helping to strengthen the engineering programs at predominately minority schools, such as Howard University, North Carolina A&T, Tuskegee Institute, Prairie View A&M, Tennessee State University and Southern University.

If we can help it, engineers and scientists are one shortage this country isn't going to have. We believe giving minority students equal opportunities in these fields is the way to prevent it.

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