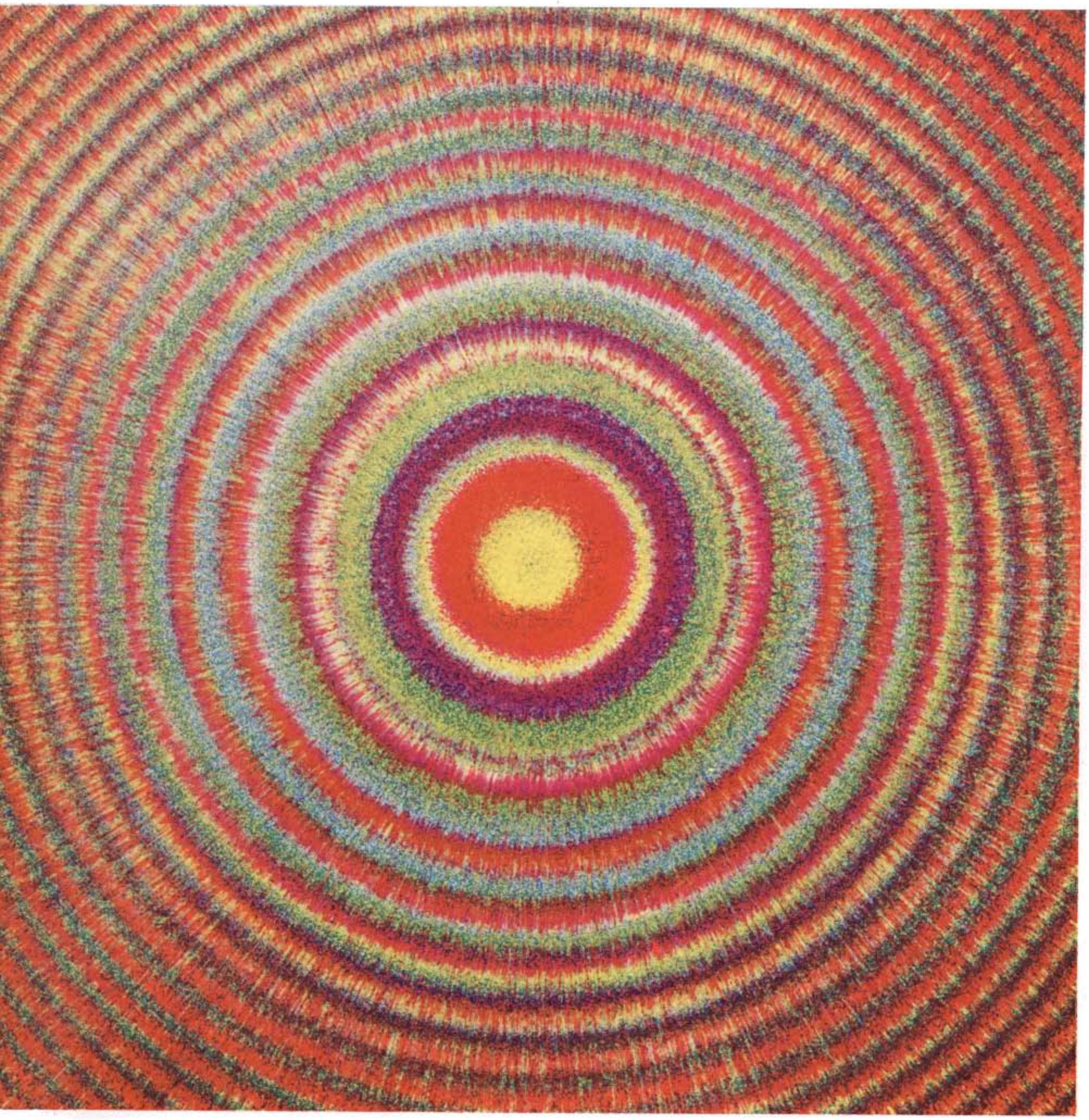
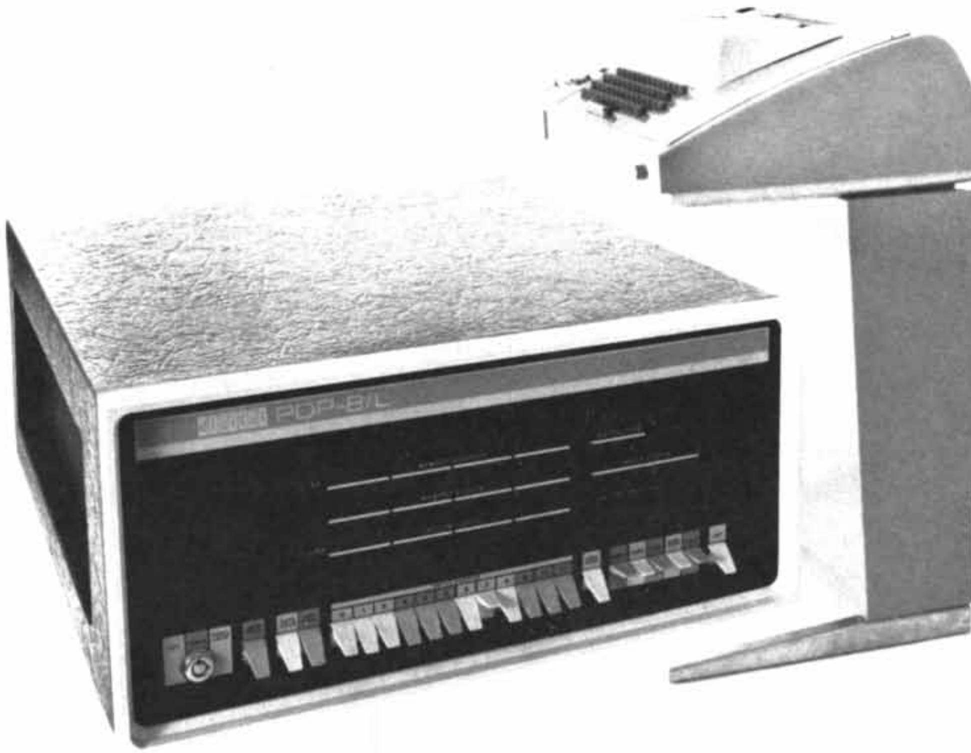
SCIENTIFIC AMERICAN



LIGHT

SEVENTY-FIVE CENTS

September 1968



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Established 1845 **SCIENTIFIC AMERICAN** September 1968 Volume 219 Number 3

ARTICLES

DEPARTMENTS

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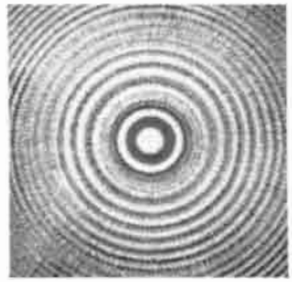

THE COVER

The photograph on the cover symbolizes the theme of this issue of Scientific American: light. The rings in the photograph were formed by the beam of a krypton-ion laser directed into the camera through an interferometer of the Fabry-Perot type. The krypton-ion laser generates light of several different colors, and constructive and destructive interference between these wavelengths in the interferometer created the ring pattern. The photograph was made at the firm of Spectra-Physics in Mountain View, Calif.

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Cover photograph by Jon Brenneis

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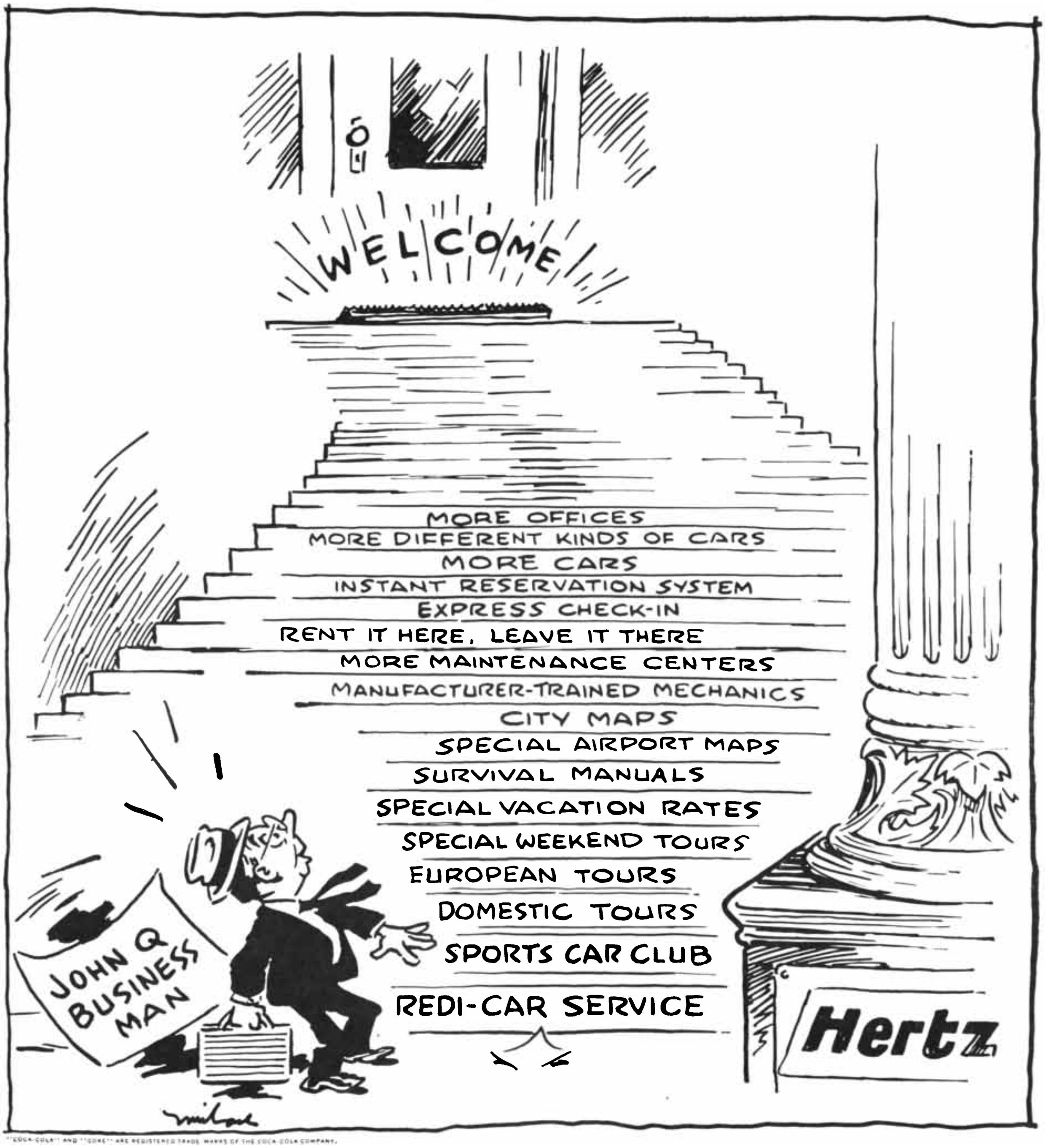
The biggest
It's only right.



should do more.

In this age of skepticism, when you say to people, "We do more," they tend to put their tongues in their cheeks and roll their eyes skyward.

Perhaps this is because people have come to suspect that saying you do more in ads and actually doing more can be horses of different colors.

At the risk of provoking further skepticism, we'd like to say here and now we do do more.

We don't ask your undying gratitude for this. After all, since we got to be the biggest on your money it's only right that we should give some of it back in good service.

In that light, we've listed here some of the things we do more of.

Our car's better than your car.

It would be foolhardy to try your patience with the nuts and bolts of our car maintenance.

(How we keep our cars in good running order is our problem and we intend to keep it that way.)

There are, however, two short nuts and bolts we think you might find interesting.

One, on the average, a Hertz car is rented just 71 times before we get rid of it. And between those 71 rentals our mechanics have orders to give it more babying than even the factory warranty calls for.

And two, if there is a question about how a car is running we tell our people not to give you the car. We think if you have to be disappointed you should be disappointed at the counter, not on the road.

There's a Hertz office in the vicinity of this ad.

It's hard to go anywhere in this world without being near a Coke® machine or a Hertz counter.

A fact which cannot be fully appreciated until such time as you want to pick up or drop off a car in some town where the major industry is the Hertz office.

A fact, which you can start appreciating right now, is that you can rent a Hertz car in one city and drop it off in virtually any other city in the United States. And between over 50 major cities, you can rent a Ford sedan in one and drop it off in another and you won't get hit with a drop-off charge. (If you want to know what we call a major city, call any Hertz office.)

If you're ever not in the neighborhood, give us a call.

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Or if you're talking to an airline or a travel agent, you don't have to talk to us at all. Have them call us.

Behind every smile, a brain.

Good Hertz girls are made not born. They're also good for more than handing out keys.

We put them through a most exhaustive (they claim the most exhausting) training program in the business.

And when they're through, our girls can help you with everything from figuring out the lowest possible rate for the time you're going to be using the car—to the fastest way back to the airport during rush hours.

Man cannot live by four-door Fords alone.

There's nothing wrong with four-door sedans per se. Unless, of course, the car you left at home happens to be a four-door sedan.

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Hard-tops, convertibles and station wagons. Mustangs, Mercurys, Thunderbirds, Continentals and even some $8,000 Mark III's.

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The A. S. P. C. C. R. (American Society for the Prevention of Cruelty to Car Renters).

We've said it before: traveling for a living is no way to live.

Since more than half of our business comes from men who travel on business, we don't think it's going to kill us to help out where and when we can.

If, for example, you know where you're going but aren't too sure how to get there, tell the Hertz girl. She'll give you specially made maps on how to get around the city. And if you're no Daniel Boone at reading maps she'll even diagram them for you.

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And if you're temporarily embarrassed for cash—and have a Hertz credit card—we'll even lend you $10 on your IOU.

After all, we couldn't in all conscience claim to do more if we only paid attention to the car the man rents and ignored the man who rents the car.

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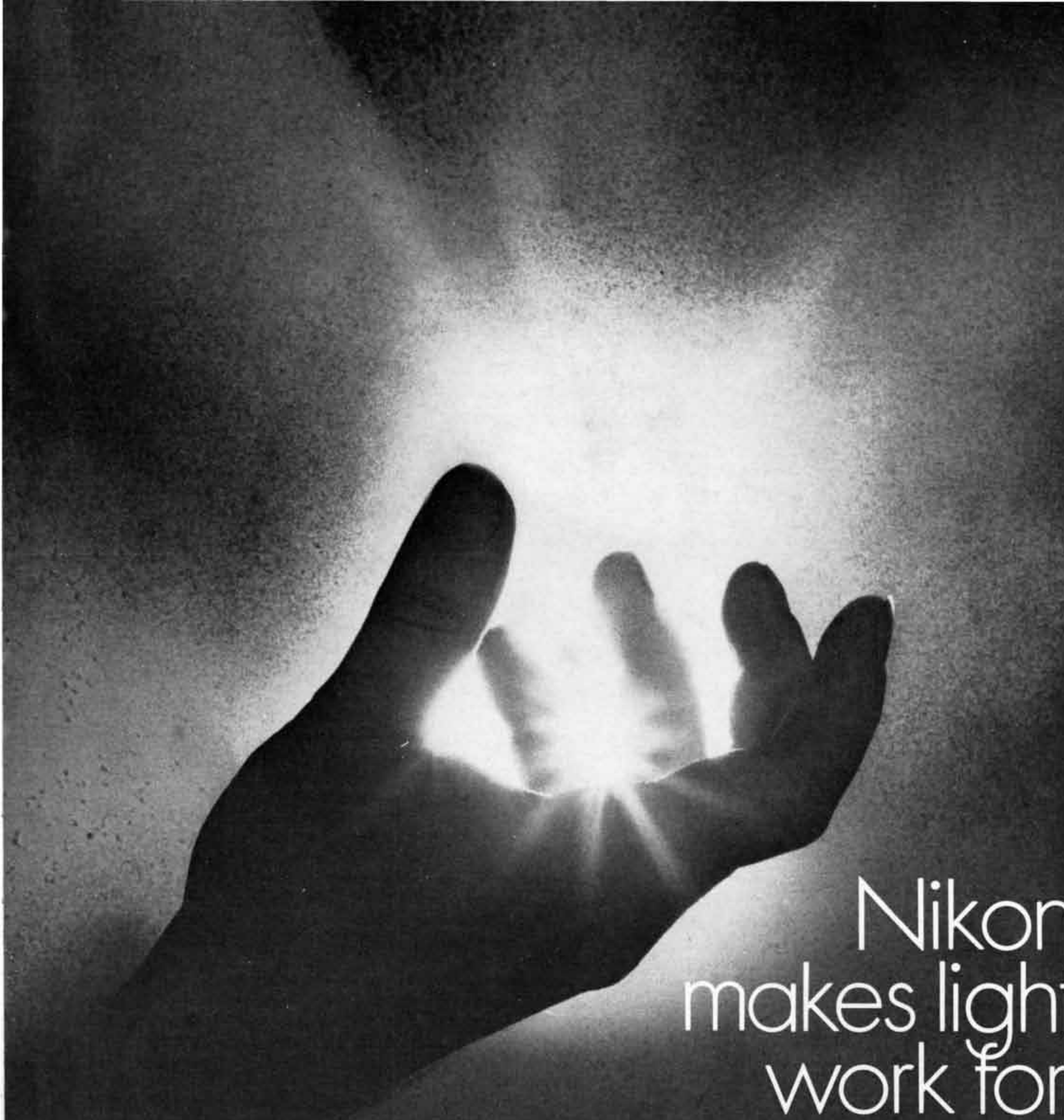
LETTERS

Sirs:

The late Professor H. E. Wulff's "The Qanats of Iran" [SCIENTIFIC AMERICAN, April] is a clear and valuable exposition of an ancient technology dealing with the location, development and transport of ground waters. However, I find it difficult to agree that the technological principle of the qanat was first developed in ancient Iran (Persia). The Semitic character of the word and the archaeological evidence appears to be at least as convincing that this technology evolved in the land of Canaan during the third and second millenniums B.C.

Much ancient evidence in the Canaanite areas of Palestine, Arabia and Phoenicia supports the view that control of ground water by tunneling was applied first in rock and later to boring in alluviums. This evidence supports an evolution of the technology that seems to have been roughly the following. The ability to harden copper (bronze) was perfected early in the third millennium B.C. and led to the art of quarrying and shaping stone. This art was concurrently applied to the development of dispersed and weeping springs. Nearly all the springs in the area were excavated during early antiquity sufficiently to isolate and control each rock fissure supplying stable flow. This kind of activity provided third-millennium man with a valuable opportunity to observe and study the nature of ground waters. By the advent of the second millennium this knowledge was applied to the sinking of open wells, generally with spiral stairs, through the rock to sufficient depth to intercept predetermined water-bearing strata. Similarly, horizontal shafts were driven into water-bearing strata to intercept the flow and to lead it by tunnel to underground reservoirs centrally located for public use. The pressure of population growth dictated the constant expansion of such works. Finally, the exigencies of recurrent wars fostered the ultimate development of this technology. It was perceived that walled towns located on hills (steep spurs abutting a mountain mass), or otherwise located for defensive purposes, were the only safe havens during attack. In order to supply such sites with water a qanat system was located outside the fortification and the water was brought in by tunnel.

Many of the old towns of Palestine were dependent on such water systems



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Light illuminates and reveals. Aided by optics it is a tool, a yardstick, a language. It can perform a thousand tasks.

The name *Nikon* figures prominently in this. Nikon achievements in theoretical optics, optical glass chemistry and optical instrumentation have become something of a legend in their own time.

A photographer is poised for an exposure. His picture may chronicle a great moment in history; depict a fashion trend; show a new plant installation; record a surgical procedure; or simply capture a likeness. The camera is a Nikon.

A sportsman watches the favorite down the stretch; a yachtsman sights a channel marker. A hunter spots a buck; a birder identifies an uncommon specie. Through Nikon binoculars.

A biologist observes the miracle of mitosis; a medical student, the characteristics of cell abnormality. A metallurgist inspects a turbine blade; a pathologist readies a specimen for photo-micrography. In each case, a Nikon microscope.

A QC inspector gages an intricately shaped component with a Nikon Profile Projector. It is capable of repeat measurement accuracy to 0.0001." A maintenance man checks the flatness of a lathe bed with a Nikon Auto-Collimator. He can d[illegible] than ½ second of arc. A cameraman shoots a set of process negatives, the first critical step in graphic arts color reproduction. The lens, a Nikon Apo-Nikkor.

An electronic engineer studies the drawings for an integrated circuit. They will be reduced optically to the miniscule proportions of an IC chip. Most likely with a Nikon Ultra-Micro Nikkor lens. And a Nikon Mask-Alignment microscope will probably be used for registration.

Nikon can make light work for you, too. For wherever light has a job to do, you will find Nikon optics and optical instruments in evidence and in use.

Write: Special Applications/Nikon Incorporated, Garden City, N.Y. 11530. Subsidiary of Ehrenreich Photo-Optical Industries, Inc. (In Canada: Anglophoto Ltd., P.Q.)

dating back to the second or first millennium B.C. The Biblical story of David's capture of Jerusalem recites that David's men crept up the gutter to capture the citadel. Here the word "gutter" is better translated as "the way to water"—a tunnel leading from the hilltop citadel to a hidden chamber excavated under the hill to trap the flow from the "Spring of Virgins." It was most likely constructed between 1600 and 1200 B.C. as part of the defenses against Egyptian armies, or to defend against the continuous raids of Joshua in this area. This ancient work can be seen in Jerusalem today. Old Shechem (modern Nablus) possesses a qanat that follows a water-bearing stratum deep under Mount Gerizim. This was probably a very ancient work, but the Romans rebuilt and improved the system in A.D. 100–200. It is still in use today.

Bethlehem's old qanat appears to have been in use for perhaps 3,000 years. Some miles to the south of the hilltop town of Bethlehem is an extensive qanat that now discharges into a reservoir built, or rebuilt, by Herod the Great, thence the water passes to Bethlehem by tunnel. The old qanat shows signs of several styles of workmanship, some of which may go back to the Canaanites. The stonework in the oldest reservoir matches that of Herod, who appears to have been the last ancient to expand the qanat. Later Pontius Pilate had much of the water brought all the

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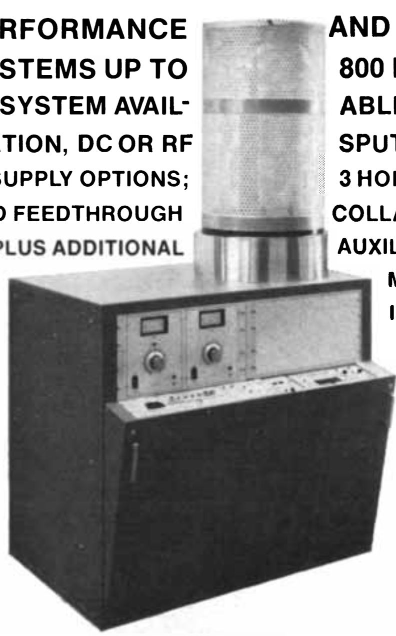

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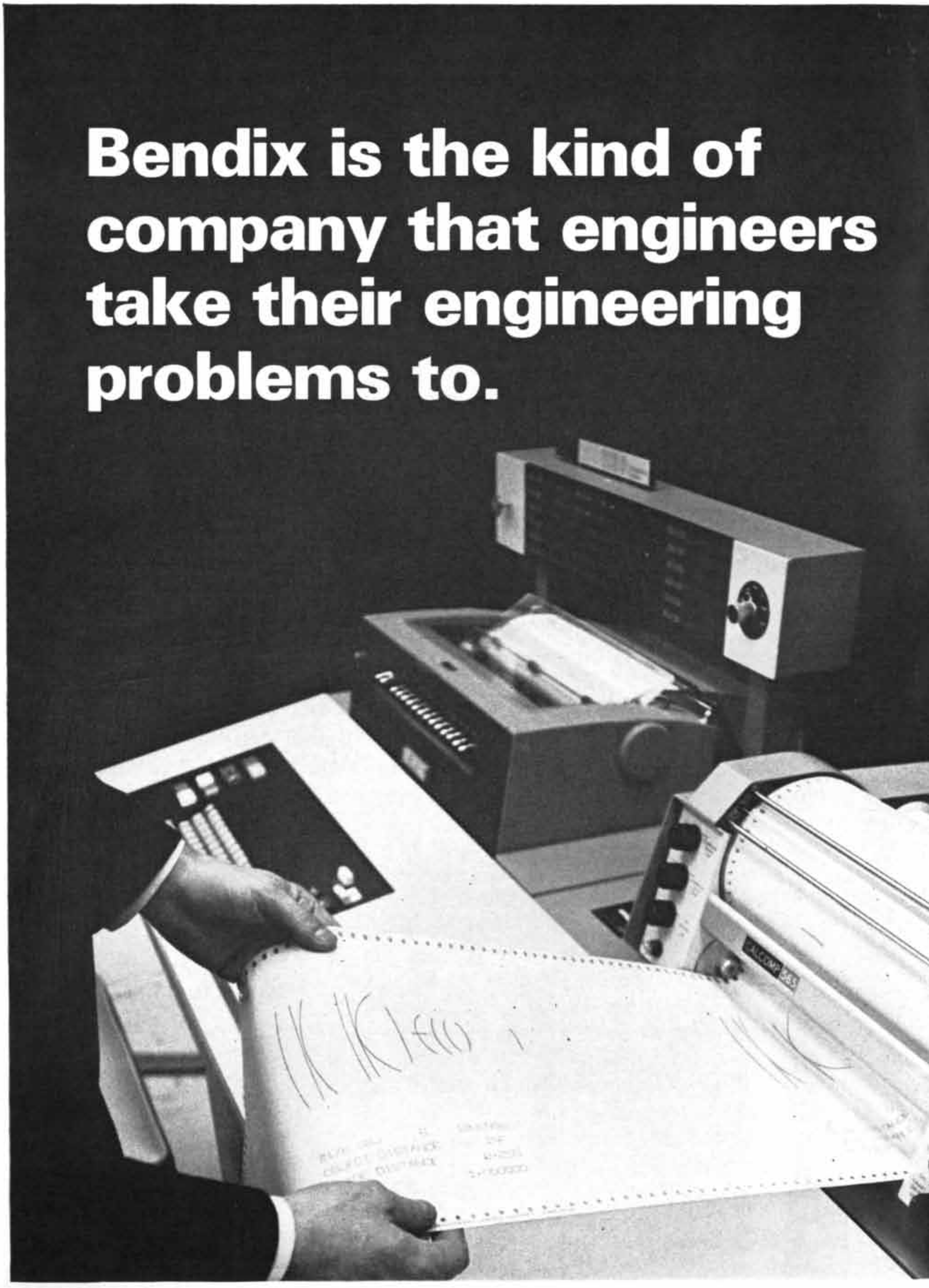
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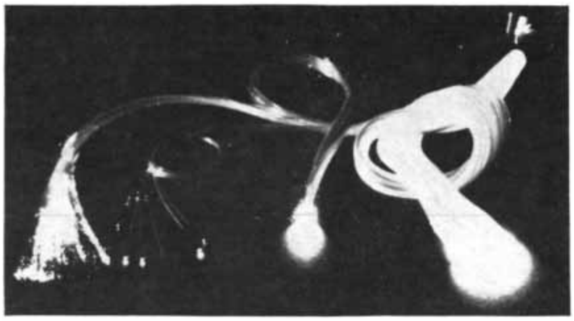
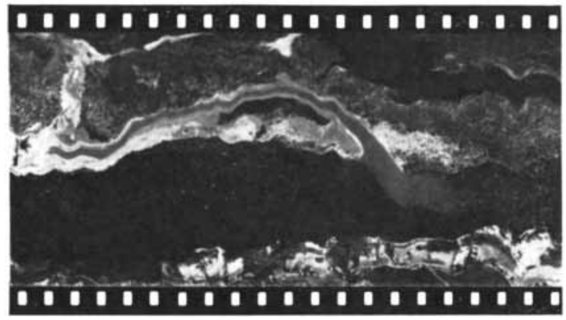


Seeing around corners. A typical example of our optics capabilities are glass fibers that literally "pipe" light around corners. Capabilities include illuminating a car's instrument panel with the light from a single bulb. Fiber optics can be made to transport useful images, too.



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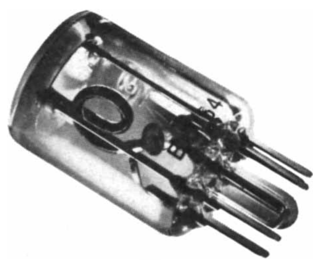

"Counting" light photon by photon. Bendix is putting its Channeltron® electron multiplier to work in new photomultiplier tubes. This one, the Photon Counter, is so sensitive it can "see" a 50-watt light bulb in Washington, D.C., through a one-inch telescope from Los Angeles, California.

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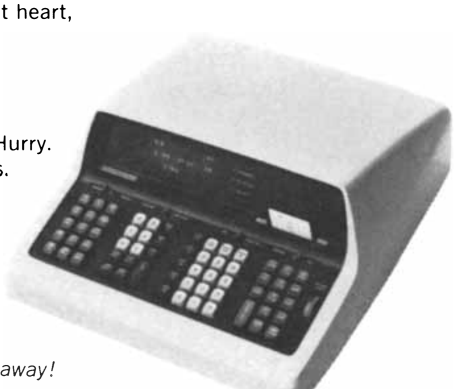

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098/20

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way to Jerusalem. The qanat is technically interesting. The ancients here perceived that a fractured limestone formation overlaid a massive bed of unfractured rock. They drove the qanat tunnels just on top of the massive formation and thus intercepted just about all of the infiltration passing the fractured zones.

Perhaps the most striking qanat in the region is the one that supplied Biblical Gadara. Gadara is situated on a high spur that projects out into the Jordan River valley. Here the ancients bored a horizontal well, with the usual manholes, through the rock to the east for a distance of more than 30 miles. This was probably a very ancient system, but the present structure is Roman in character and was most likely built by Pompey the Great when he had Gadara rebuilt in 63 B.C. The history of Gadara goes back to the time of the Biblical King Og, when, after its capture by Moses, it was fortified by Joshua. Several ancient writers note that Greek Gadara was the strongest city of the area from about 330 B.C. to 101 B.C., when it was destroyed by the Jewish king Alexander Jannaeus after a 10-month siege. This old qanat functions and supplies pure water to some of the hilltop inhabitants today.

Modern engineers who have had the opportunity to examine and study these ancient applications of the qanat principle are amazed to observe the technical proficiency in ground-water geology and the precision of the surveying methods that made possible the construction of these extensive works more than 2,000 years ago.

JAMES H. RIVES

Formerly Chief Engineering Adviser,
U.S. Mission to Jordan 1954–1956
Chattanooga, Tenn.

Sirs:

Edmund L. Epstein ["Letters," SCIENTIFIC AMERICAN, July] left a false impression about the passage in *Faust* he quoted referring to *quark*. The reference (*In jeden Quark begräbt er seine Nase*) is about man, the grasshopper, "the little god of earth," who sticks his nose into every mess, and not about God.

The line occurs at the end of Mephistopheles' opening speech in "Prologue in Heaven." Before Mephistopheles speaks the archangels sing a hymn of praise that equates God and nature as mysteries no one can understand by physical causality. The song establishes

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sun and light as the supreme symbols of an ordered cosmos.

But Mephistopheles cannot see the cosmic order of which the angels sing. He holds up man as the supreme example of irrationality in the material world. He contends that man's every misery, even his bestiality, are results of the "gleam of heavenly light" man calls reason. "Opp, I never open mamouth but I pack mafood in it." (James Joyce, *Finnegans Wake.*)

Physicists and cosmologists occasionally spring above the undergrowth of ignorance on the frontiers of the very small and the very large, but, like Goethe's grasshoppers, they fall again into the grass to continue gnawing away at the undergrowth and to sing their same old songs.

The enigmatic quark, adduced as the key to the microcosmic world of elementary particles, has led its hunters on a merry chase down quarkways to oblivion, from outer space (grinding up meteorites to find quarks) to the bottom of the ocean (grinding up oysters to find quarks). The quark, if found, could clear up the mess in elementary-particle physics, whose study has shown us that the fundamental quality of nature has become its dynamic complexity, rather than the simple order philosophers have hoped for. Physicists seem bound to live by another quotation from *Faust:* "We'll see the small world, then the great."

FRED LEE WILSON

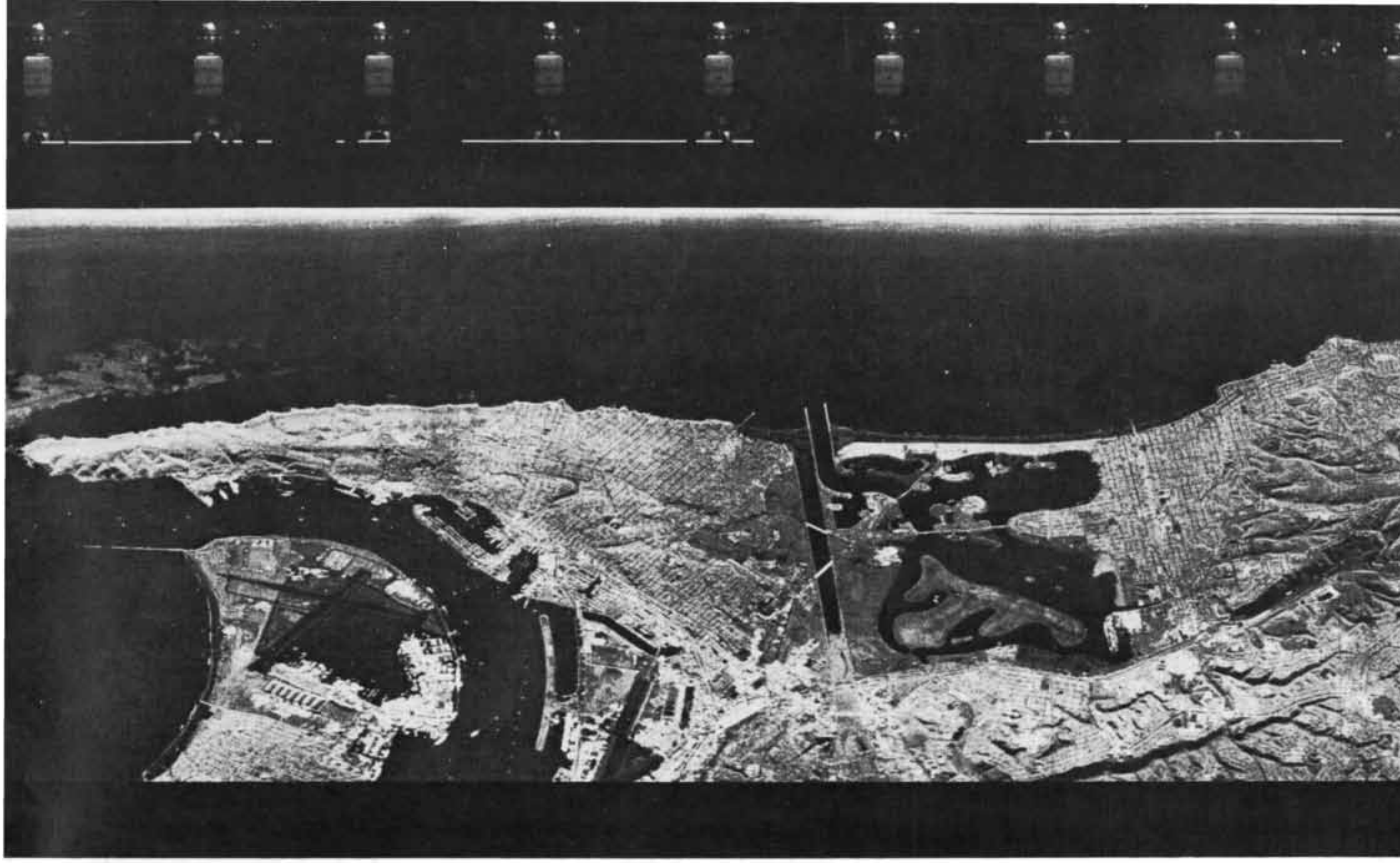
Houston, Tex.

Sirs:

In his recent letter to the editor Edmund L. Epstein traces the origin of the now popular word "quark" to Goethe's *Faust*. Epstein's interpretation of "quark" as a German slang expression is not entirely correct. *Quark* is the basis for cheese, essentially cottage cheese, and only as such may sometimes be messy. Not too long ago it was a staple food in some parts of Germany (*Kartoffeln mit quark macht stark:* Potatoes with quark makes strong) and hence omnipresent. Epstein should therefore translate "God sticks his nose into every mess" as "God sticks his nose into every triviality," not necessarily messy.

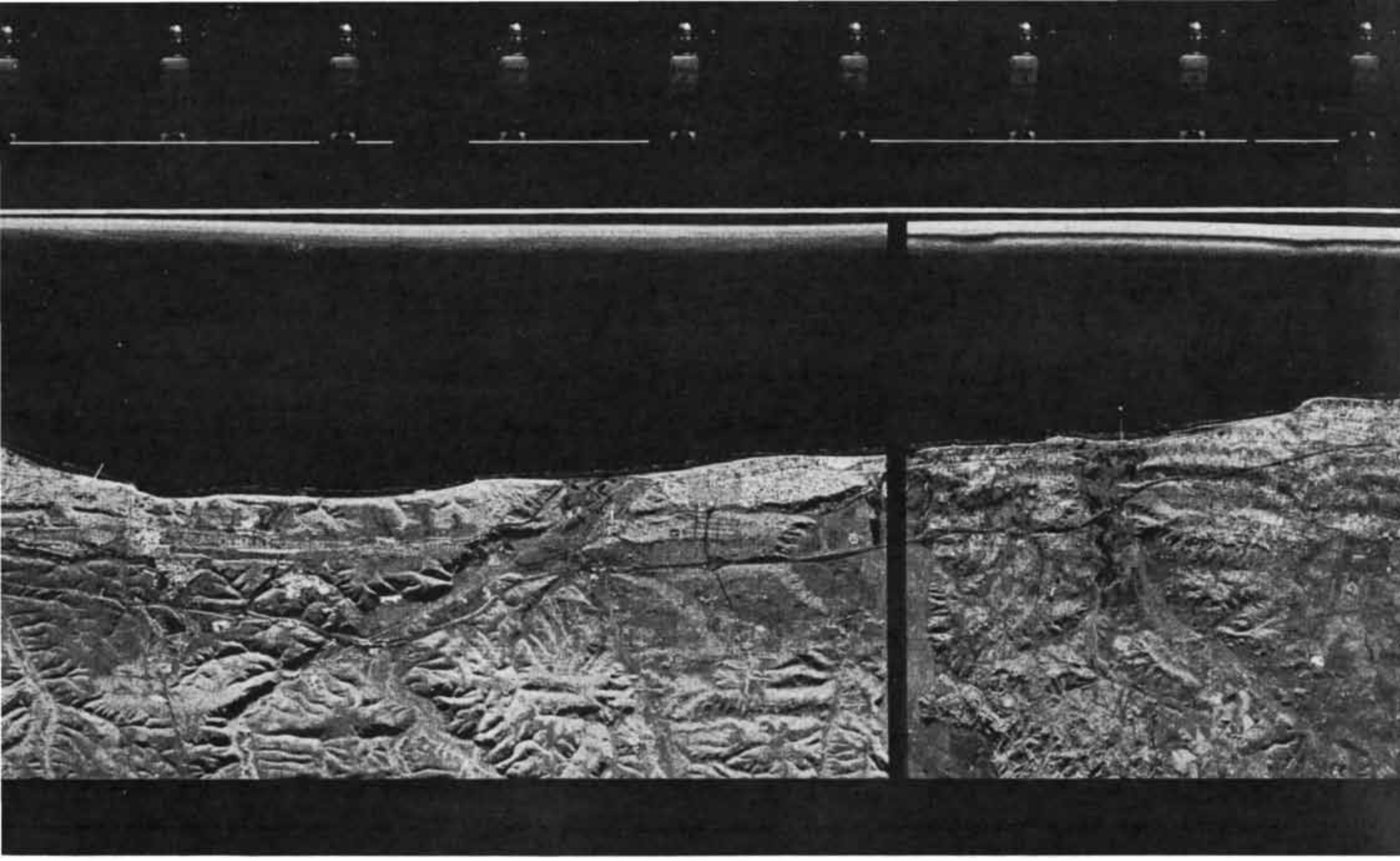
D. H. WEICHERT

Division of Seismology
Department of Energy, Mines and Resources
Ottawa



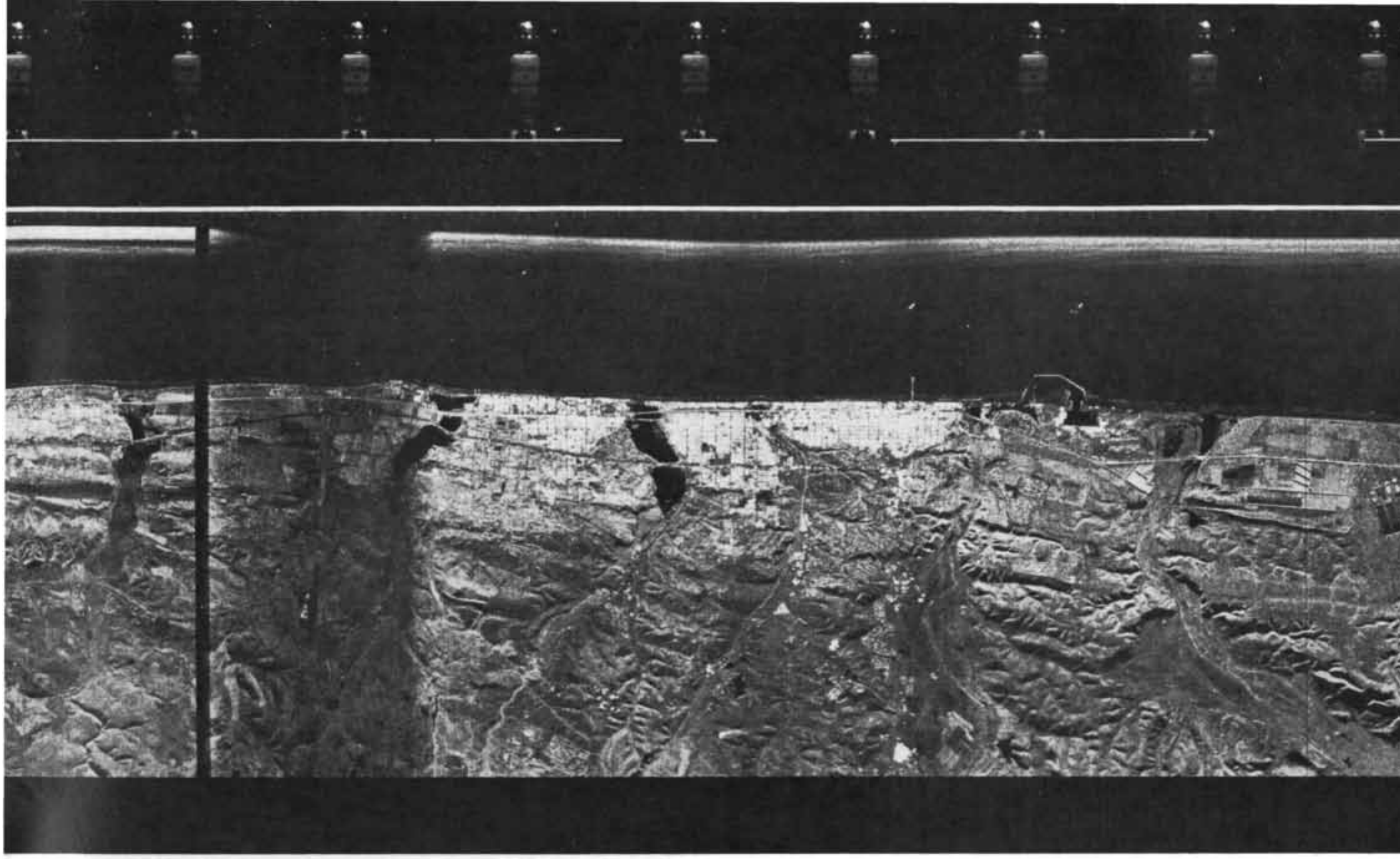
Standing out with photographic clarity . . . such details as the kelp beds off Point Loma (upper left) . . . piers and ships at Coronado and Mission Bay . . .

On this page and the following seven Westinghouse brings you a remarkable radar image of the coast of California from San Diego to Los Angeles...



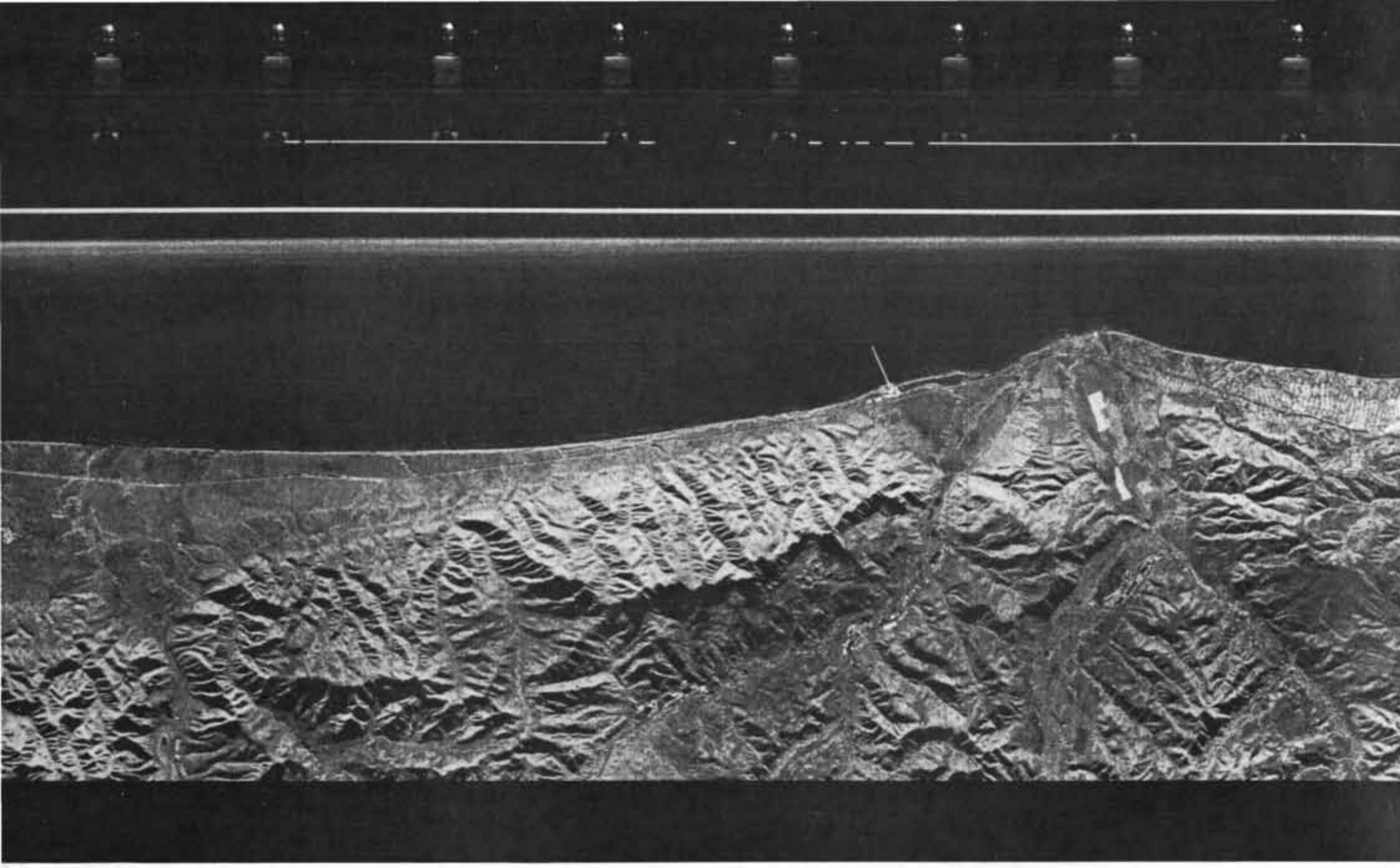
. . . breakers off La Jolla (upper left) and Solana Beach (upper right). The jutting Scripps Institute Pier (upper left) . . .

It was taken in minutes from a jet aircraft making one continuous pass...



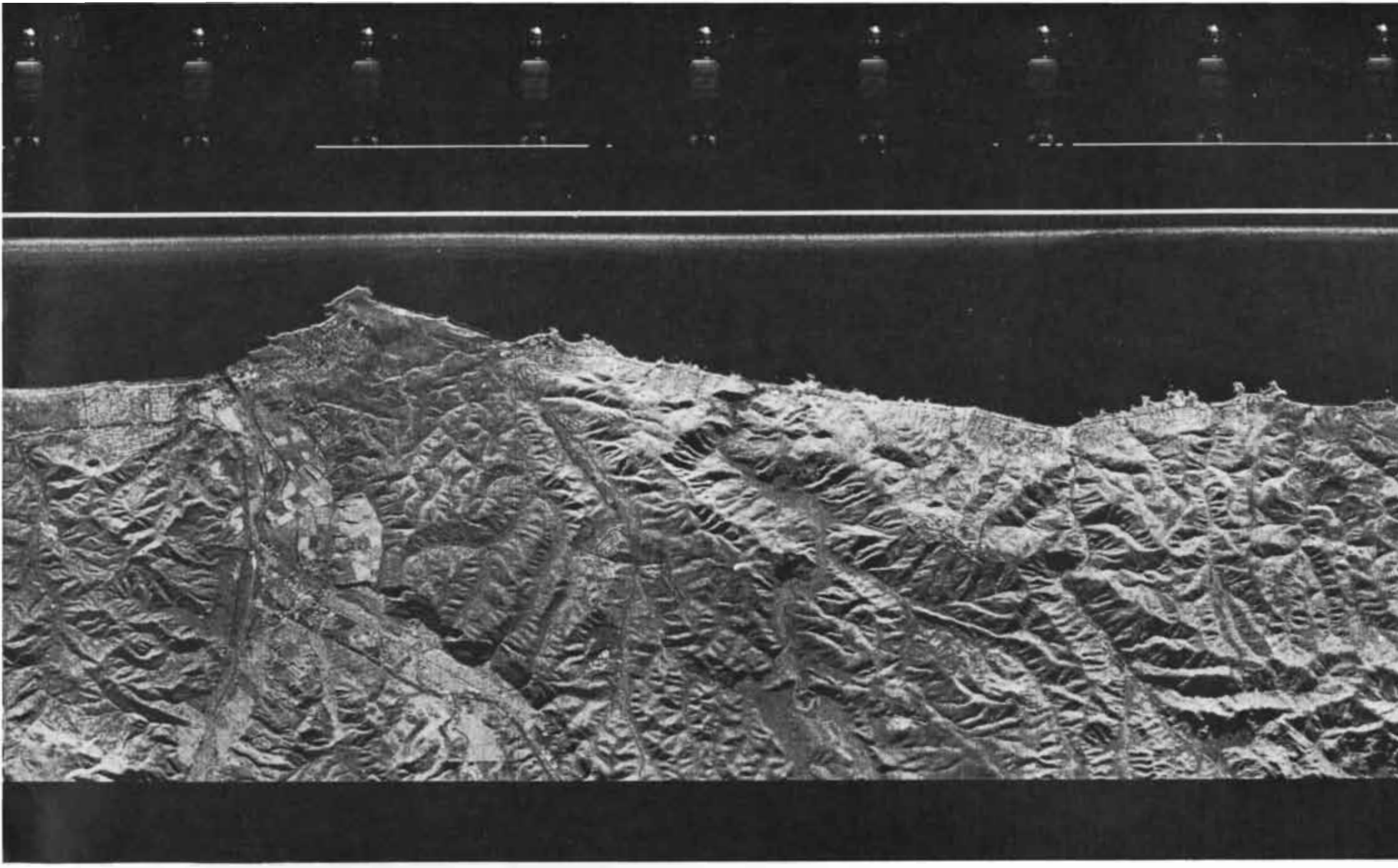
. . . near-street-map representation of towns like Encinitas (upper left) . . . Oceanside (upper middle) . . . the distinctive delta of the Santa Margarita River (upper right) . . .

It is reproduced here (at 4/5 scale) just as it came from the flight film...



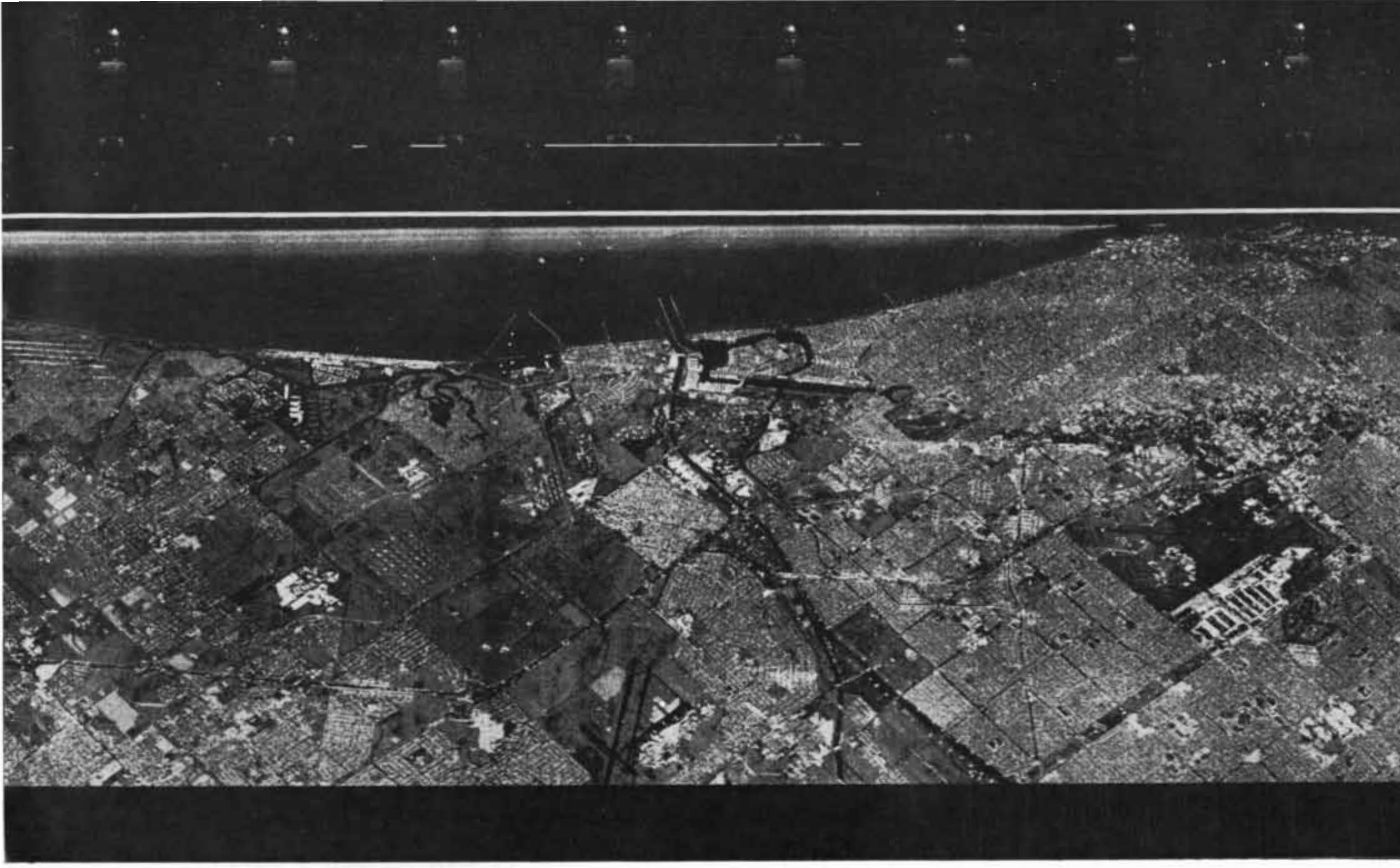
. . . the deep, sheer walls of Las Plugas Canyon (lower left) . . . the temporary construction pier used to install water intake and discharge for the San Onofre Nuclear Generating Station, built by Westinghouse for Southern California Edison Company and San Diego Gas & Electric Company (upper middle) . . .

It is an example of the high resolution you get with Westinghouse Side Look Radar...



. . . the peninsular jut of Dana Point (upper left)
. . . the sandy expanses of Laguna Beach (upper right) . . .

...day or night, good weather or bad...



Native Angelenos can quickly pick out such familiar landmarks as Seal Beach . . . Long Beach Municipal Airport . . . (more ⟶)

Side Look Radar is just one example of the leadership in sensor systems you can expect from Westinghouse.

Here are other Westinghouse developments in handling light—and dark:

A 12-lb. TV camera sees in the dark. It operates down to 10^{-5} ft.-candles of light. Secondary electrons inside the tube multiply available light up to 100 times to produce a video image. Astronomers and commercial telecasters are using this tube right now.

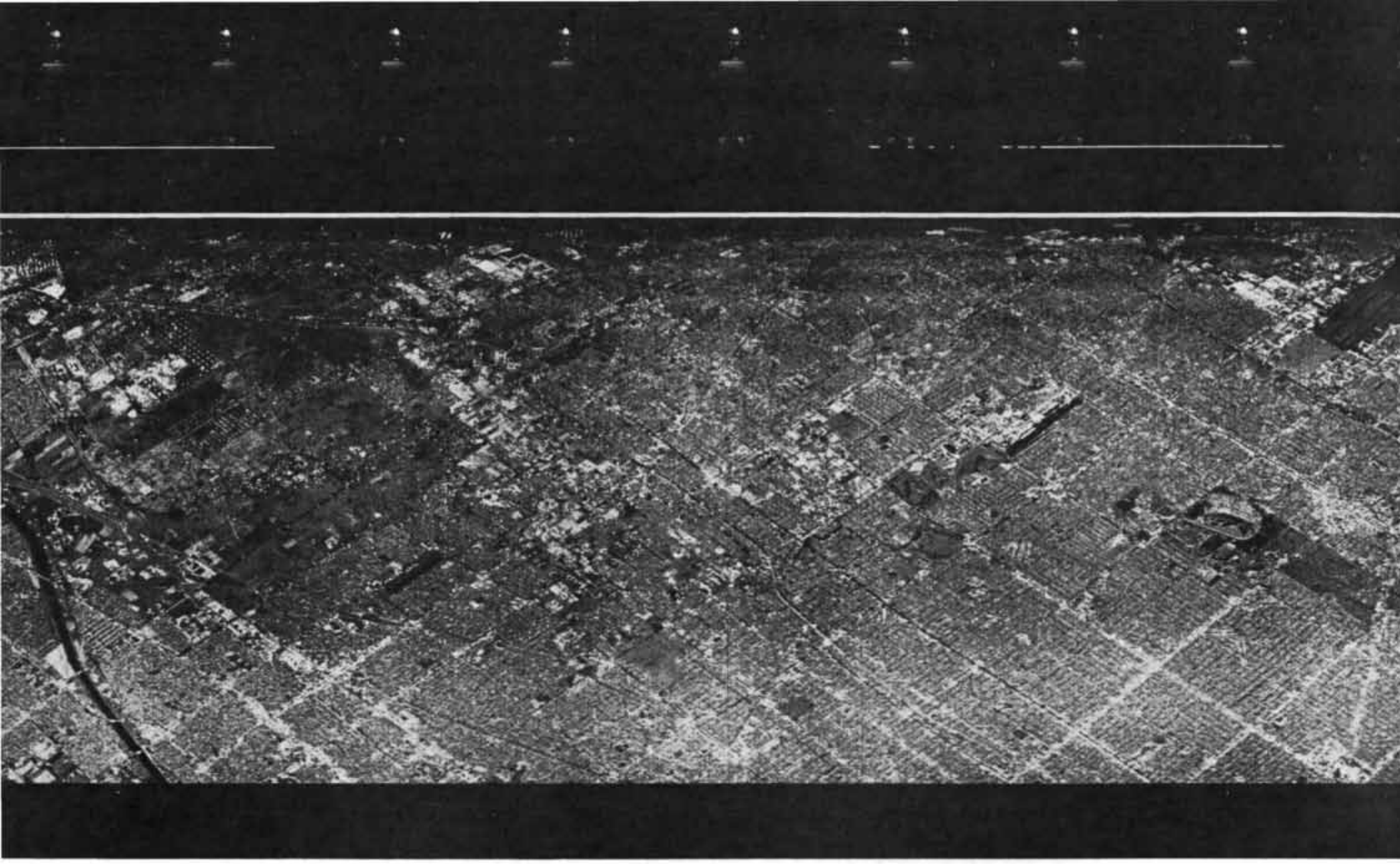
Another version of this camera will relay live pictures from the moon as part of the Apollo space program.

Two Westinghouse sonar systems map or photograph the dark ocean floor. A linear-scan system, towed by a ship, picks up reflections of acoustical impulses recorded as real-time images on electrosensitive paper. Angular-scan sonar, used on deep-submergence vehicles, produces a TV-type picture on a cathode-ray tube.

A new spherical laser configuration makes it possible to generate greater power output from smaller power input. This makes it possible to build smaller, more easily portable laser systems. A new crystalline laser material (FAP) increases efficiency and, in the process, reduces heat caused by wasted energy.

A fluorescent tube—called "Living White"—is revolutionizing fluorescent lighting. It uses rare earths—yttrium oxide and europium—to increase light output and improve the color spectrum, particularly in the orange-red end. Skin tones are more natural.

Tell us your light, or dark, problems. We may already have solved them.



... Compton Airport, the Hollywood Race Track — even their own home blocks, in the clear radar image of the Los Angeles area, shown above.

The continuous image on this and the preceding seven pages was obtained with equipment developed by Westinghouse for the U.S. Army Electronics Command. The San Diego-Los Angeles flight was an integral part of the NASA Natural Resources Program.

You can be sure... if it's

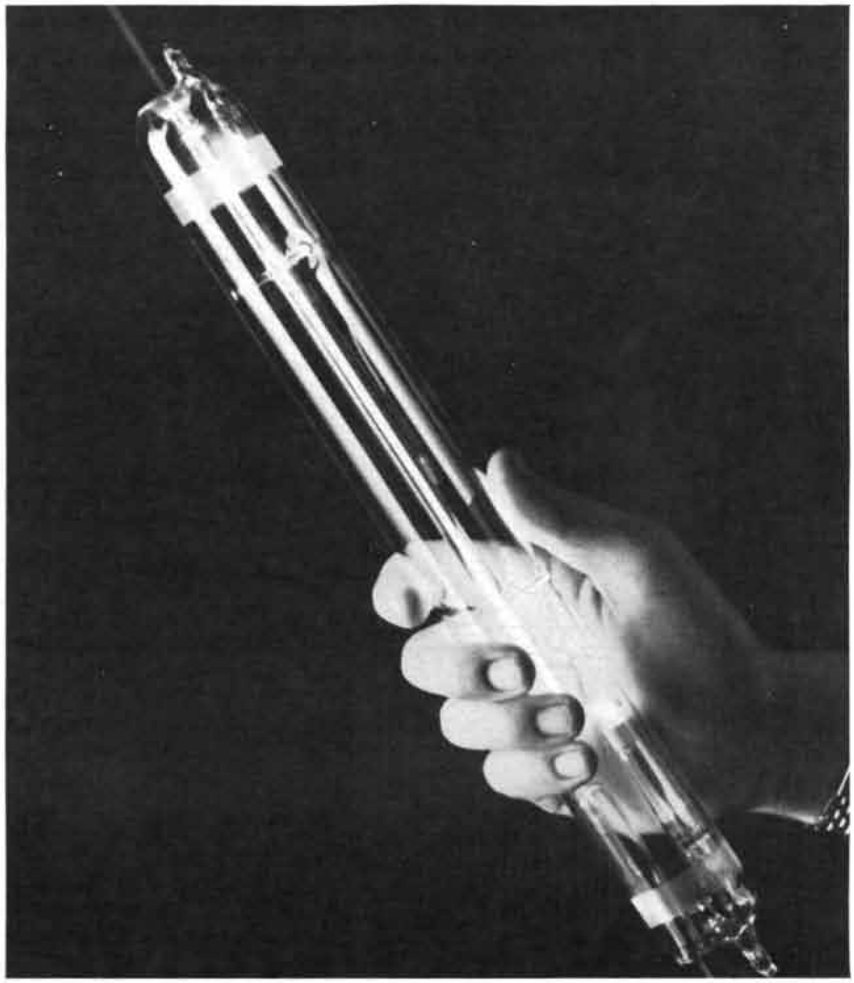
Westinghouse

50 AND 100 YEARS AGO

SCIENTIFIC AMERICAN

SEPTEMBER, 1918: "No period of the great world war, since its opening horrors in France and Belgium, has been marked by such dramatic results as the past spring and summer campaign on the Western front. From the 21st of March, when the German hosts, swollen with contingents from Russia, burst through the British lines, to the 18th of July, when for the second time they swept beyond the Marne River, each month of the year had brought its record of successive defeat and disaster to the Allied armies. Germany was jubilant, as well she might be, and her last great attack, hurled against a 50-mile front, was announced by the enemy as being his final peace offensive. The Germans struck with a confidence born of four successful drives into enemy territory, and, so far as an onlooking world might judge of it, she seemed to be in a fair way to blast a road into Paris itself. But over night, between Château-Thierry and Soissons, General Foch with a French-American army struck a blow which turned apparent defeat into indubitable victory, and from that momentous date, July 18th, on which the great counter-offensive was launched, down to the present hour, the German army has suffered an unbroken succession of defeats."

"Distinguishing the meteorites, the cosmic wanderers which are drawn down upon our earth, as siderites when they consist essentially of iron and nickel, and as aerolites when they are essentially silicates of the olivine type interspersed with nickeliferous iron, Sir William Crookes recently submitted some aerolites to spectroscopic examination. His paper, which he presented to the Royal Society, deals only with the spectroscopic analysis of 30 aerolites, mostly samples of two or three grammes' weight obtained from the Natural History Museum. The spectroscopic examination shows that only 10 elements occurred in the aerolites: iron, chromium, nickel, magnesium, silicon, sodium, manganese, potassium, aluminum and calcium. The first four were alone present in quantity



The friend of the woman in 17C.

As the big jetliner approaches the airport at London, the young woman in seat 17C grows nervous. It's her first flight and as she looks out the window, she sees nothing but fog.

She reaches out to touch her sleeping three-year-old daughter. How can the pilot possibly see the airport?

When the jetliner's wheels touch down gently on the runway, the woman smiles and turns to her daughter. But her daughter sleeps on.

One reason the landing was easy and gentle is because the pilot used an electronic guidance system called ILS—for Instrument Landing System. It was developed by International Telephone and Telegraph Corporation, or ITT. Every 30 seconds somewhere in the world an aircraft lands safely using an application of ILS.

In fact , without ILS and other of our developments, air travel as we know it today would be impossible.

The woman in seat 17C didn't know it, but the day she boarded her jet, ITT had already played a part in her life.

How many ITT's?

When she cabled her husband in London to confirm the date and time of her arrival, the message was sent via ITT.

The car she drove to New York's Kennedy International Airport from her parents' home in New Jersey was rented from one of our companies.

Yet the woman possibly had never even heard of ITT.

The "International" in our name is well deserved. We do business in 123 countries around the world and employ more than 241,000 people.

Telephone and Telegraph?

But what about the "Telephone and Telegraph"? What's a communications company doing in so many other areas of business?

Originally, we were a telephone and telegraph company. Even after we became one of the largest diversified manufacturing and service organizations in the world, the name stayed.

As ITT has grown since those early days, it has made history.

During World War II, for example, an ITT-developed radio direction finder was credited with bringing the Nazi submarine wolfpacks to a standstill, shortening the war by at least two years.

In 1963, using earth terminals designed by us for communicating via satellite, we helped open up the first experimental satellite link between North and South America.

In 1965, one of our satellite-communication earth terminals, aboard a Navy aircraft carrier, helped make it possible for millions in the U.S. and Europe to see on TV the recovery of Gemini astronauts at sea, live, as it happened.

Five times more during 1966 a terminal was installed aboard a carrier and five times more millions saw actual splashdown and recovery operations.

Last year during the Arab-Israeli war, the White House used the Washington-Moscow Hot Line—for the first time in a crisis. One of our companies keeps the Hot Line ready.

Another of our companies runs the Kilmer Job Corps Center in New Jersey for the Office of Economic Opportunity. This same company operates and maintains the strategic Distant Early Warning (DEW) Line which stretches from Alaska to Greenland.

ITT today

ITT today is composed of more than 200 associated companies around the world.

By bringing to bear our total expertise, these companies have generated increased competition within industries and, consequently, have generated more efficient use of manpower and material resources.

The fields in which we operate were selected for growth potential as well as present needs. And last year, more than 50 percent of our earnings were derived from domestic sources.

Much of this U.S. growth can be traced to our interest in the service industries.

People's desire for service keeps growing. So we've put increasing emphasis on it. Our U.S. sales and revenues are now split about 50-50 between manufacturing and service activities.

In addition to renting cars (Avis, to be exact), educational training services, and airport and hotel parking, ITT offers consumer loan services, mutual fund management, and data processing—just to name a few.

Sheraton, a system of hotels and franchised motor inns, in the U.S. and abroad, is now part of ITT. So is Levitt & Sons, world's largest international home and community builder.

We also operate a communications network made up of thousands of cable, radio and satellite circuits, and can transmit a message to almost any point on the globe.

Recently, we entered the field of natural-resource conversion with ITT Rayonier Inc. and Pennsylvania Glass Sand Corporation. These two operations take raw material from the earth and its forests and make them useful to manufacturers of cellophane, textile fibers, tire cord, photographic film, paper, glass, chemicals, and other related products.

ITT and you

With all these services—plus thousands of consumer, industrial and military products and services—ITT is helping you and people all over the world to enjoy a better, safer, more comfortable life.

Just as it helped the woman in seat 17C.

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

ITT

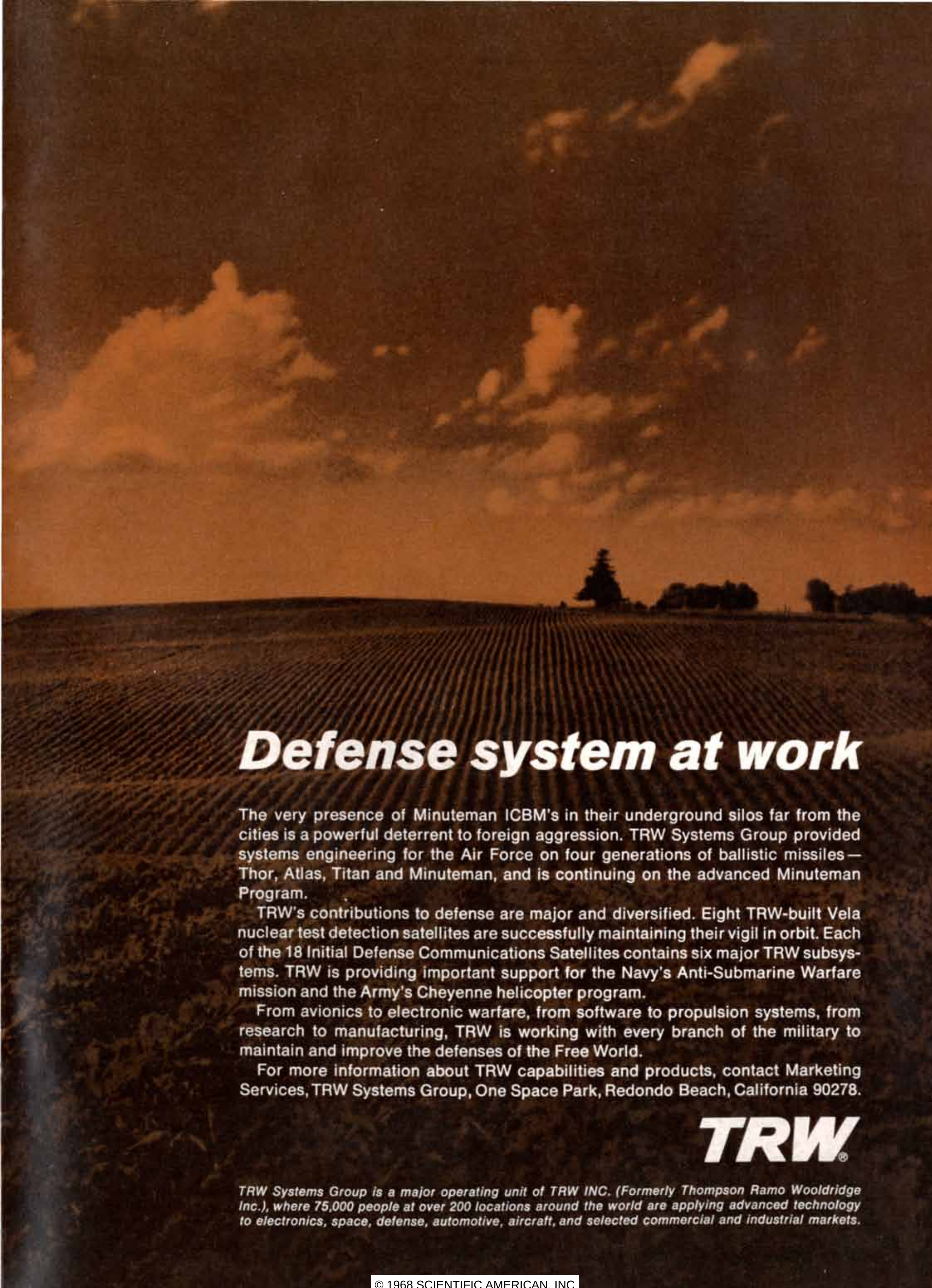
and with three exceptions always in nearly the same proportions. That, Sir William writes, seems to suggest that the different aerolites had a common origin in the disruption of some stellar body which had completed its cosmical evolution, in other words, that the aerolites were fragments of a finished, cooled planet."

"According to Sir Bernard Mallet, the registrar-general of England, the loss of potential lives in England and Wales since the beginning of the war due to the diminished birth rate amounts to 650,000. The proportional loss in the other belligerent European countries has probably been even greater. Sir Bernard estimates that the war has cost all of these countries no less than 12½ million potential lives; in other words, the number of births has been smaller, by this number, than it would have been if the war had not occurred."

SCIENTIFIC AMERICAN

SEPTEMBER, 1868: "Few phenomena are more remarkable, yet few have been less remarked, than the degree in which material civilization—the progress of mankind in all those contrivances which oil the wheels and promote the comfort of daily life—has been concentrated in the last half century. It is not too much to say that in these respects more has been done, richer and more prolific discoveries have been made, grander achievements have been realized, in the course of the 50 years of our own lifetime than in all the previous lifetime of the race. It is in the three momentous matters of light, locomotion and communication that the progress effected in this generation contrasts most surprisingly with the aggregate of the progress effected in all generations put together since the earliest dawn of authentic history."

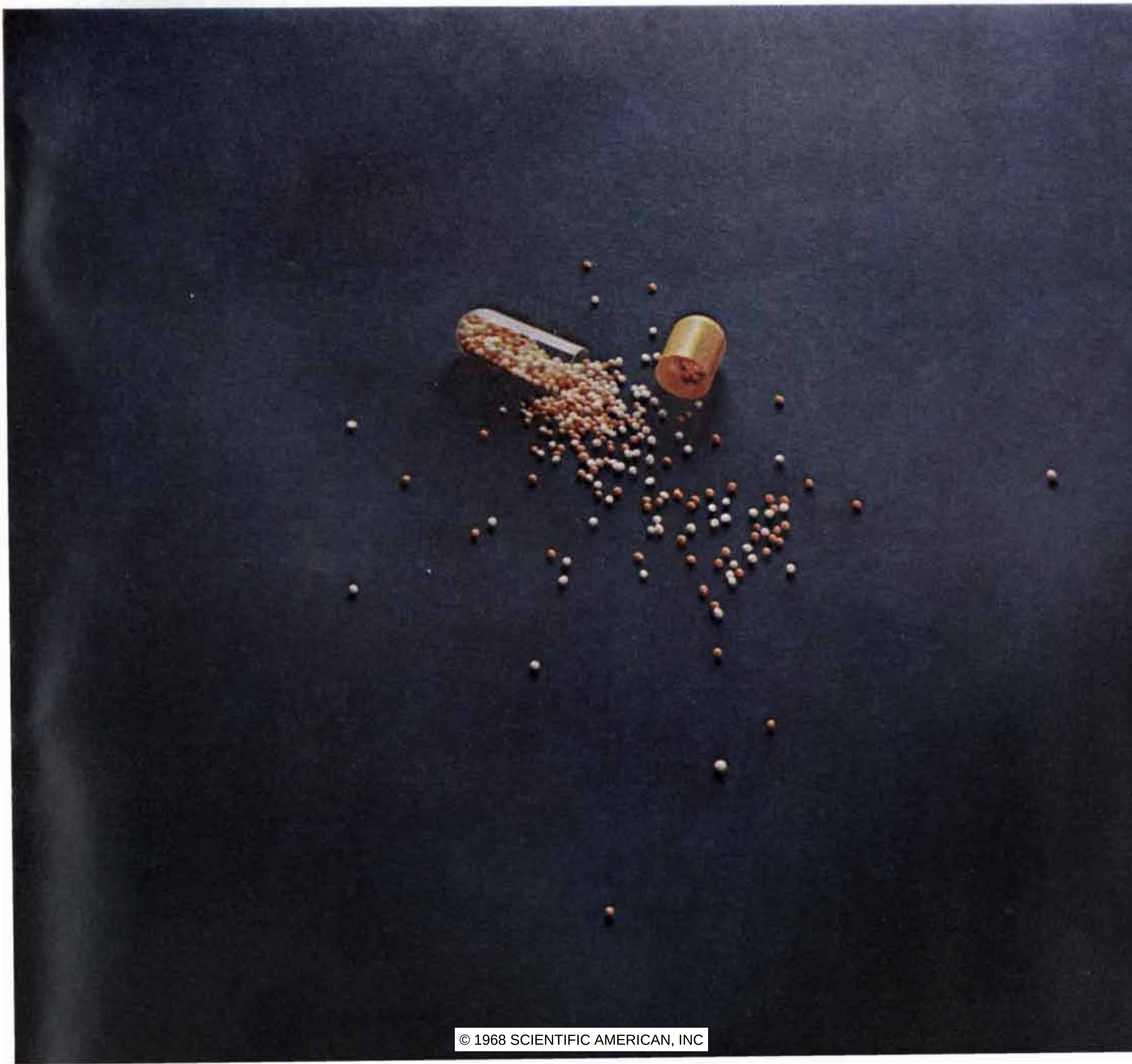
"M. Becquerel finds that chloride and bromide of silver deposited on plates of platinum, when acted upon by light, give rise to a strong current of positive electricity, which is just the reverse of the kind of current which would be afforded by the platinum plate alone under the same circumstances. Now, the chloride and bromide of silver are actually decomposed by light—the former obviously so, the latter less visibly—yet the bromide indicates a current of even higher intensity than the former does.


Defense system at work
The very presence of Minuteman ICBM's in their underground silos far from the cities is a powerful deterrent to foreign aggression. TRW Systems Group provided systems engineering for the Air Force on four generations of ballistic missiles—Thor, Atlas, Titan and Minuteman, and is continuing on the advanced Minuteman Program.
TRW's contributions to defense are major and diversified. Eight TRW-built Vela nuclear test detection satellites are successfully maintaining their vigil in orbit. Each of the 18 Initial Defense Communications Satellites contains six major TRW subsystems. TRW is providing important support for the Navy's Anti-Submarine Warfare mission and the Army's Cheyenne helicopter program.
From avionics to electronic warfare, from software to propulsion systems, from research to manufacturing, TRW is working with every branch of the military to maintain and improve the defenses of the Free World.
For more information about TRW capabilities and products, contact Marketing Services, TRW Systems Group, One Space Park, Redondo Beach, California 90278.
TRW®
TRW Systems Group is a major operating unit of TRW INC. (Formerly Thompson Ramo Wooldridge Inc.), where 75,000 people at over 200 locations around the world are applying advanced technology to electronics, space, defense, automotive, aircraft, and selected commercial and industrial markets.

The conclusion is that a precisely similar action takes place when the light acts on the chloride and on the bromide of silver, viz., reduction to a subchloride and subbromide respectively. In following the various stages of the discussion of this vexed question, it is singular to notice the changes in the bearings of the numbers of facts presented from time to time. Until recently all the evidence seemed to be tending to support the purely mechanical theory of the formation of the latent image; latterly the complexion of affairs has quite altered, and the evidence all tends in the direction of a distant chemical change as being the result of the action of light, the experiments of M. Becquerel forming a strong link in the chain."

"Ruskin, the eminent art author of England, who has lately turned his attention to political economy, in a recent letter urges the purchase of all the railroads in England by the government. He argues that private persons should not be permitted to own the railroads of a nation; that all means of public transit should be provided at public expense; that neither railroads nor canals should ever pay dividends to anybody, but should pay their working expenses and no more, and that the whole work of carrying persons or goods should be done as the carriage of letters is now done."

"It is a commonly received notion that hard study is the unhealthy element of college life. But from tables of mortality of Harvard University, collected by Professor Pierce from the last triennial catalogue, it is clearly demonstrated that the excess of deaths for the first 10 years after graduation is found in that portion of each class inferior in scholarship. Every one who has seen the curriculum knows that where Æschylus and political economy injures one, late hours and rum punches use up a dozen, and that the two little fingers are heavier than the loins of Euclid. Dissipation is a swift and sure destroyer, and every young man who follows it is, as the early flower, exposed to untimely frost. A few hours of sleep each night, high living and plenty of 'smashes' make war upon every function of the human body. The brain, the heart, the lungs, the liver, the spine, the limbs, the bones, the flesh, every part and faculty are overtasked, worn and weakened by the terrific energy of passion loosed from restraint until, like a dilapidated mansion, the 'earthly house of this tabernacle' falls into ruinous decay."



Protecting life in hostile environments.

For vehicles that move in hostile environmental worlds, Lockheed has devised some unique features and systems to help support human life over extended missions—like long-sustained flight at a searing Mach 3+, or days in the ocean deeps, or an entire year in outer space.

Guarding the Deep Divers. To work at great depths, new special undersea craft must contain life-support systems no less critical than those used in outer space. Such systems must be self-contained, since these deep-diving vessels can neither snorkel nor carry bulky equipment loads.

Deep Quest life-support system functions as specified in dive to 8,310 feet.

For Deep Quest, the Lockheed-funded submersible designed for missions down to 8,000 feet, a system was devised to sustain 4 men for a normal 12-hour cruise and to deliver an added 36 hours of emergency support if needed.

Deep Quest's complex has 9 subsystems. Simpler functions include fire protection, waste management, removal of CO_2 and trace contaminants, and control of carry-on food, water and first-aid supplies. Three features, however, are notably sophisticated:

(1) Fully automatic control of total cabin pressure and O_2 partial pressure cuts operator involvement to a minimum. A differential regulator works with a temperature-compensation reference chamber to maintain this control, but crewmen can manually override the system if malfunction occurs.

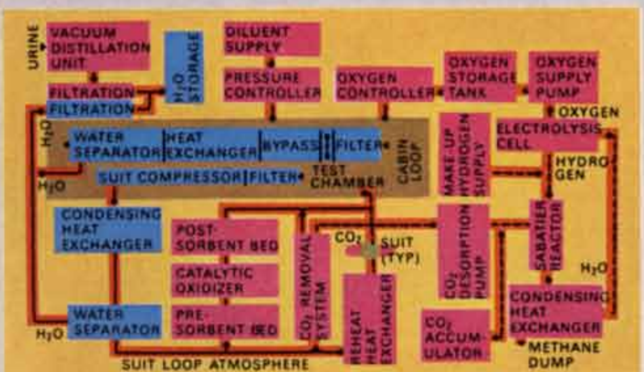
(2) Since existing open and semi-closed emergency breathing systems would excessively increase pressure in the small cabin, Lockheed developed a closed-loop system that works up to 3 hours without noticeably affecting pressure. Full face-masks and breathing bags assure complete personnel protection, easy gas circulation, and minimum breathing resistance. Activated charcoal and LiOH remove CO_2 and contaminants, and a differential pressure regulator automatically admits a fresh O_2 supply.

(3) A third subsystem exercises discriminating control

LOCKHEED
LOCKHEED AIRCRAFT CORPORATION

over temperature and humidity. By design, critical electronic gear is separated from the crew compartment. Since the equipment operates best at temperatures higher than comfortable for human beings, cooling is directed mainly to the "people space." This saves power, lessens atmosphere contamination, and improves effectiveness of fire prevention and extinguishing systems.

Following successful check-outs and manned tests, Deep Quest recently dived to an 8,310-foot depth. In all respects, the life-support system performed within tolerances.



Block diagram of TGRLSS, designed to help support 4 crewmen for up to year's duration in outer space.

Two-Gas Regenerative Life Support System (TGRLSS). Complications of sustaining human life grow by orders-of-magnitude as outer-space missions are planned to stretch over many weeks or months. Each facet of environment must be calculated and controlled to a point of fail-safe precision that has no precedent.

Anticipating long stays in space, Lockheed has developed the TGRLSS to help support a 4-man crew for up to a year. Embodying several unique Lockheed subsystems, the TGRLSS controls pressure, temperature, humidity, and O_2 partial pressure; removes CO_2 and toxic trace contaminants; processes CO_2 and H_2 to regenerate fresh O_2 stores; and, by filtering atmospheric condensate and vacuum-distilling urine, it supplies the crew with pure drinking water.

That last function involves a unique method for separating liquid from gas and reclaiming moisture under zero-gravity conditions.

Initially, atmosphere is fan-drawn from both the cabin and the crewmen's suits and is circulated into a humidity control system. A condensing heat exchanger, governed by preset limiting devices, extracts excess moisture from the gas stream and passes both gas and water downstream to a water separator. There the condensed moisture is formed into droplets, and these, along with the "dried" atmosphere, are passed to a final separation stage: a system of 2 screens and sumps, one hydrophobic and the other hydrophilic, that perform an effective "go and no-go" function. Cabin atmosphere is blocked by the hydrophilic system but allowed to flow freely through the hydrophobic screen and be routed back to the cabin. Water, restricted by the hydrophobic screen, passes through the hydrophilic screen and is withdrawn for filtration and storage.

During a recent 5-day manned test, the full TGRLSS functioned exactly as designed, keeping a constant pressure of 7.5 psia in a cabin atmosphere of 42% oxygen and 58% nitrogen.

Cooling Off Fiery Flight. Hurtling through the atmosphere 80,000 feet up at Mach 3+, the SR-71 must endure extreme heat. To protect this U.S. Air Force special-purpose plane, which maintains its speed for long periods of flight producing stabilized high-temperature oven-like conditions, Lockheed had to evolve new thermodynamic approaches.

The airframe itself and every internal component were vulnerable to heat. (Pumps, valves, switches, wires, sealants and others were designed to tolerate more than 600°F.) Of chief concern, however, was the assurance of a tenable cockpit environment just inches away from lethal heat.

New criteria were set for all materials and functions. A high-grade titanium formed both structure and skin, and a high-emissivity external black paint increased external radiative heat losses and reduced the skin temperature. New techniques were developed to block or limit each heat leak path. But the major problem was finding a downstream heat sink for the super hot engine bleed air—primary cooling alone by ram air at over 700°F was far from adequate.

Schematic environmental diagram of SR-71 cockpit in flight conditions of Mach 3 speed at 80,000-foot altitude.

Expandable evaporants were out; the SR-71 could not take their extra volume and weight and still perform at top capability. The solution was a bold step taken for the first known time in aircraft: a direct air-to-fuel heat exchange through a specially designed fail-safe system. Graphic proof of its success is that the SR-71 crew operates in a 60°F environment despite the searing, oven-like external conditions.

The activities described here are only a few of Lockheed's R&D projects in environmental controls. If you are an engineer or scientist interested in this field of work, Lockheed invites your inquiry. Write K. R. Kiddoo, Lockheed Aircraft Corporation, Burbank, California 91503. An equal opportunity employer.

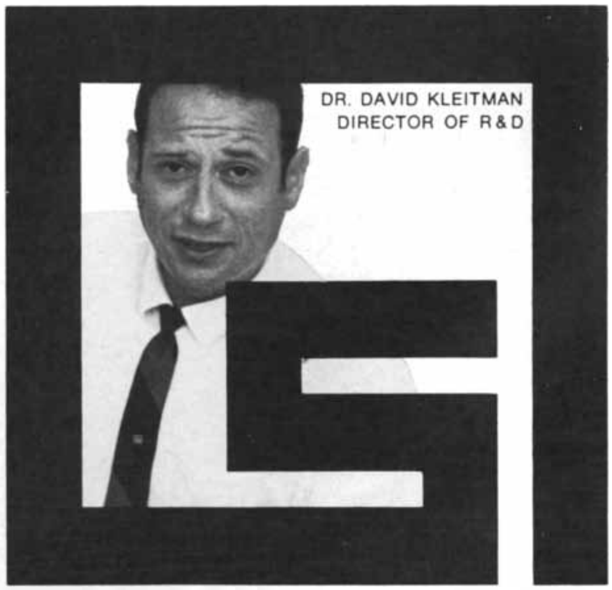
THE AUTHORS

GERALD FEINBERG ("Light") is professor of physics at Columbia University. He was graduated from Columbia College in 1953 and remained at the university from 1953 to 1956 as a National Science Foundation fellow. Obtaining his Ph.D. at Columbia in 1957, he spent a year as a member of the School of Mathematics of the Institute for Advanced Study in Princeton and two years as a research associate at the Brookhaven National Laboratory before returning to Columbia as a member of the faculty. During the academic year 1966–1967 Feinberg was at Rockefeller University. His major field of research is elementary particle physics. Another of his interests is treated in his forthcoming book, *The Prometheus Project,* which deals with ethical problems associated with technological advances.

VICTOR F. WEISSKOPF ("How Light Interacts with Matter") is professor of physics at the Massachusetts Institute of Technology. Born in Vienna, he received a Ph.D. in physics from the University of Göttingen in 1931. He worked in Europe until 1937, when he moved to the U.S. and joined the faculty of the University of Rochester. During World War II he was a group leader in the Manhattan project. He has been at M.I.T. since 1945, except for the period from 1961 to 1965, when he was director general of CERN, the European Organization for Nuclear Research. Weisskopf's research work deals with many aspects of theoretical physics, such as the quantum theory of interaction of light and atoms, the theory of the structure of the atomic nucleus and theoretical problems of elementary particles. With John M. Blatt he is the author of a textbook, *Theoretical Nuclear Physics.* He writes that his hobby is "finding clear and simple ways to explain modern physical theory."

PIERRE CONNES ("How Light Is Analyzed") is a spectroscopist at the Bellevue Laboratories of the French National Center for Scientific Research. After studying physics at the University of Dijon and teaching secondary school for two years he joined the Aimé Cotton Laboratory at the center. He designed and built several interferometric devices for high-resolution spectral analysis. His main field now is Fourier spectroscopy; his wife, Janine, specializes in the com-

"We must be able to tell our integrated circuit customers not only where we are, but where we're going. That's why our researchers keep one foot in today's problems and the other in tomorrow's key technologies."



SIGNETICS INTEGRATED CIRCUITS

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SIGNETICS CORPORATION, 811 EAST ARQUES AVENUE, SUNNYVALE, CALIFORNIA 94806. A SUBSIDIARY OF CORNING GLASS WORKS putation of the spectra. The Conneses first applied the Fourier technique to astronomy at the Mount Wilson and Kitt Peak observatories, while they were spending a year in the U.S. at the Jet Propulsion Laboratory of the California Institute of Technology. Connes writes that he is "currently engaged in the building of a large (but minimum-budget) infrared spectroscope for the Fourier spectroscopy of stars and planets."

F. DOW SMITH ("How Images Are Formed") is vice-president of the Itek Corporation, where he directs research programs and also does research in optics—particularly in interferometry, optical testing and the theory of image formation. Born in Canada, Smith took bachelor's and master's degrees at Queens University and a Ph.D. in optics at the University of Rochester in 1951. From 1951 until he joined Itek in 1958 he was at Boston University, beginning as instructor in physics and research assistant in the Physical Research Laboratories and ending as associate professor of physics, chairman of the department of physics and director of the Physical Research Laboratories.

R. CLARK JONES ("How Images Are Detected") is with the research laboratories of the Polaroid Corporation, which he joined in 1944 after three years at the Bell Telephone Laboratories. He writes: "Born 1916 in Ohio. Won a full-expense scholarship at Harvard. Covered all my expenses and I was not permitted to work. Held it seven years: A.B. in 1938, A.M. in 1939 and Ph.D. in 1941." Jones has a number of avocations, including riding in railroad locomotives ("I have traveled with the engineer on the locomotive a total of about 30,000 miles") and collecting cubic-inch samples of metals. He was in Europe when he prepared the material for his biographical note, and the only typewriter available to him had the *y* and *z* transposed from the order that is customary in the U.S. An example of the results is: "Mz wife and I celebrated our 25th wedding anniversarz in 1963 bz a 10-week visit in March through Maz to Egzpt, Israel, Jordan, Turkez, Greece and Italz."

ARTHUR L. SCHAWLOW ("Laser Light") is professor of physics in the School of Humanities and Sciences at Stanford University and executive head of the physics department. He was graduated from the University of Toronto in 1941 and received his Ph.D. there in 1949. After two years as a postdoctoral fellow and research associate at Colum-

a measure of progress

1. Light-emitting diodes
2. Of calculators, computers and time-sharing
3. Atomic absorption photometer
4. Diagnosis by ultrasound
5. Frequency & time standards

1. Solid-state light bulbs

If you want a light that won't blow out or a display that won't fail, you start thinking about devices with no parts to rattle. That immediately eliminates incandescent bulbs with filaments and even glass glow lamps filled with gas. Next, you consider solids or electroluminescent powders that glow when electric current is applied.

One such device Hewlett-Packard has some experience with is the gallium arsenide diode. But it glows in the infrared range, invisible to the eye. Used with a silicon detector it works very well in tape readers or encoders. Still, we wanted a visible light source—so our engineers developed a diode using gallium arsenide phosphide. A small chip 21 mils by 21 mils glows brightly with a soft red light visible for several yards. And it's almost indestructible. Put a diode beside each circuit on a plug-in card, and years from now if the circuit goes bad, the diode will glow to indicate the failure.

Better yet, line some chips up in a matrix five by seven on a side, add a tiny integrated circuit driver for logic control, and you have a device that will flash numbers (shown above, enlarged) from 0 to 9. A somewhat more sophisticated integrated logic circuit could handle letters of the alphabet, as well. The whole assembly mounted on a substrate measures only a half-inch wide, one inch high and less than two tenths of an inch thick. And an entire display needs only five volts to drive it.

This Hewlett-Packard solid-state readout device is ideal for counters, voltmeters or any display that must have high reliability and be insensitive to shock and vibration. But considering its small size, low voltage drive and inherent long life, it may become the economical choice for any small indicator. If you would like more information for your own applications, write for our Solid-State Display pamphlet.

2. How to bridge the whole computational gap

Depending on the volume and complexity of your mathematical problems, you might need machine help that runs the gamut from a small desk calculator to a time-shared computer with 16 terminals running simultaneously. Hewlett-Packard feels fortunate that now we can offer you just such a range of computing power.

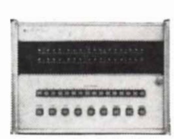
Our 9100A Computing Calculator, at $4900, is a desk model designed for ease and simplicity of operation, starting with the keyboard. Yet you can perform all the common math, algebra and trig functions on it without learning any special computer language. You simply press the *log* key, the *sin* key, the $\sqrt{}$ key and so on to call these functions out of memory. Using different levels of memory, you can build routines to solve rather sophisticated problems, such as computing the attenuation characteristics of electronic filters with hyperbolic functions. And on one wallet-size memory card, you can store two 196-step routines for future use.

For applications requiring greater power and flexibility, HP offers a family of three computers so you can buy the computer most suited to your needs. All of them can handle three high-level computer languages—FORTRAN, ALGOL and Conversational BASIC. The latter is so close to English you can learn it in three to four hours. The smallest computer, the HP 2114A, costs $9950. You can get it with 8000 words of memory and a teleprinter for $15,950. You also get 16-bit words, 2.0 microsecond memory speed, and 8 channels of input/output capability.

But if you have a number of people who need to use a computer at the same time, then for $89,500 you can get the HP 2000A Time-Shared BASIC System. It can handle up to 16 Teletype terminals at once, with each user thinking he has the computer to himself. In this system we use our largest computer, the HP 2116B, with 16,000 words of core memory and a disc memory with 348,000 words of storage. The same simple Conversational BASIC language is used, but here we have included additional safeguards. The system checks each input statement for format and syntax as it is entered. Additionally, the computer echoes the instruction back to the originator. If there's a transmission error, the originator knows immediately. With these features, 16 persons can have simultaneous error-safe computer power to solve 16 problems at once.

For additional information on any one or all of the Hewlett-Packard solutions to computing problems, write for the 9100A Calculator brochure, a more complete discussion of Hewlett-Packard small computers, or a brochure on HP time-shared computer systems.

9100A Calculator

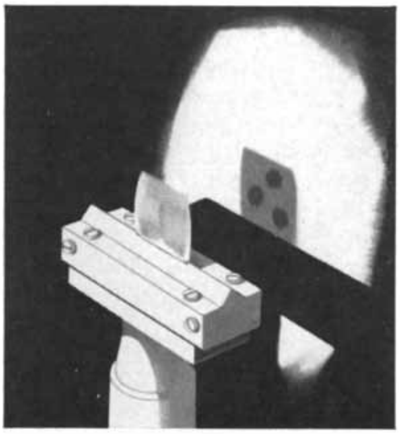


2114A Computer

2000A Time-Shared System

3. Measuring the shadow of an atom

More and more people today are tracking down very small amounts of metals dissolved in liquids. Doctors routinely test biological samples. Public health officials keep tabs on water pollution. Agronomists check traces of metals in soils, fertilizers and crops. Engine designers look for evidence of motor wear in oils. And industrial chemists scruti-



nize impurities in plastics and plating solutions.

There are a number of techniques and most are difficult and time-consuming. But one method—Atomic Absorption—is gaining vogue because it is fast, simple, specific and sensitive. You spray a sample solution into a very hot flame to release the metal as free atoms. You direct a beam of light through the flame into a very sophisticated light meter. The particular light source used emits a wavelength that is resonant with the natural frequency of the vaporized metallic atoms—and, hence, readily absorbed. The more atoms present, the more light is absorbed and the less gets through. The amount absorbed is read out on a meter already calibrated to tell the concentration of metal in solution.

Hewlett-Packard has developed a pushbutton atomic absorption instrument that is easier, faster, safer, more reliable and more economical. We installed six light sources for six different metals on one turret. The sources not in use at the moment are always at operating current. We designed a wide burner to spread the flame for quieter operation and greater sensitivity.

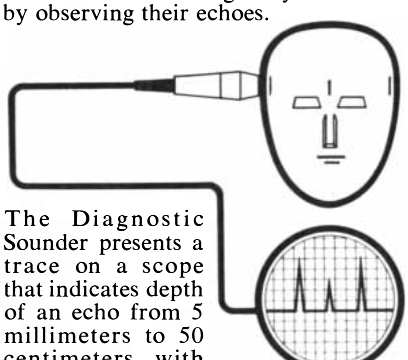
We developed a novel optical system which cancels out variations in flame intensity and electronic circuits. Filters in the optical system are changed by pushbutton to match each light source. And the electronic circuits provide both direct meter readout of concentration and a recorder presentation for a permanent record.

The advantages of the HP 5960A Photometer cost you $4400. If you'd like to make more measurements with less effort, write for Bulletin 5960.

4. Sounding out problems in the body

Bats, porpoises, sailors and engineers are old hands at using sound to search for objects the eye can't see. Bouncing echoes off things — in the depths of oceans, far underground, or inside metal castings — is often the simplest, easiest or safest way to detect and measure the unknown. Now doctors have joined these specialists in ultrasonics by applying echoes to problems of the human body.

Low-powered, high-frequency sounds bounced off the brain's midline can suggest to the doctor that a tumor or concussion has shifted the brain out of position. These sounds are painless and harmless. They bounce off plastic objects and soft tissues that X-rays can't detect. The echoes are viewed on the face of an oscilloscope immediately as the search is in progress. And distance to the object is measured directly. The instrument can be used for looking at both fixed and moving body structures by observing their echoes.

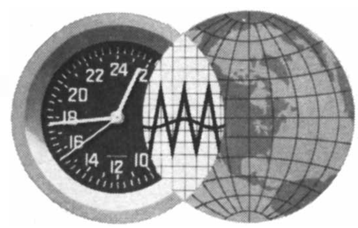


The Diagnostic Sounder presents a trace on a scope that indicates depth of an echo from 5 millimeters to 50 centimeters, with resolution up to 1 millimeter. A scope marker and counter dial make distance readings easy to record. An audible signal helps the operator discriminate between one target and another. Records may be made either by scope camera or by strip-chart recorder.

If you'd like more information about how the Diagnostic Sounder may be applied in cardiology, neurology, internal medicine, obstetrics, gynecology or surgery, write for the HP Diagnostic Sounder Brochure.

5. Can you spare a second in 3000 years?

If you want to keep time to the nth degree, you might come to Hewlett-Packard for one of our Frequency & Time Standards. We make four types: cesium beam atomic, rubidium atomic, quartz crystal — and for the most particular applications, research hydrogen masers. All generate frequencies so precisely known and controlled that they are used throughout the world as standards for frequency and its counterpart, time.



Take quartz oscillators. If you keep them turned on continually and protect them from shocks, the best of them make excellent frequency standards. The HP 106A, for example, is accurate to better than 5 parts in 10^{11} per day and costs $3750.

For people who need a primary standard with no known drift, we make the 5061A Cesium Beam Frequency Standard—one of the world's international standards for time. It has an absolute accuracy of ± 1 part in 10^{11} for the life of its cesium beam tube. That's equivalent to an error of 1 second in over 3000 years. We've flown this one around the world several times to coordinate primary timekeeping centers in as many as 18 countries. The cesium frequency standard costs $14,800.

In between is our newest atomic standard—the rugged, lightweight 5065A Rubidium Frequency Standard at $7500. The singular advantage of the rubidium standard is its superior electrical quietness over short periods.

There are technical data sheets for each of these standards, plus an article about the Flying Clock Experiment in the HP JOURNAL, Vol. 19, No. 4.

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Measurement, Analysis and Computation

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bia University he became a research physicist at the Bell Telephone Laboratories. He went to Stanford in 1961. Schawlow's research has been in the fields of optical and microwave spectroscopy, nuclear quadrupole resonance, superconductivity and optical masers. He is coauthor with Charles H. Townes, now professor-at-large at the University of California, of the book *Microwave Spectroscopy* and of the first paper describing optical masers.

DONALD R. HERRIOTT ("Applications of Laser Light") is with the Bell Telephone Laboratories. Having studied physics at Duke University, optics at the University of Rochester and electrical engineering at the Polytechnic Institute of Brooklyn, he joined the Bausch & Lomb Optical Company in 1949 to work in research on thin films, interferometry and the measurement of the modulation transfer function of lenses. He continued this work after joining Bell Laboratories in 1956 and also participated in the development of optical systems for flying-spot storage of information and for picturephones. In 1960 he built the first gas laser in collaboration with Ali Javan and W. R. Bennett, Jr. He collaborated in the development of the spherical-mirror cavity, the folded optical delay line, the scanning spherical-mirror interferometer and a number of other interferometers using the laser source.

GERALD OSTER ("The Chemical Effects of Light") is professor of biophysics at the recently established Mount Sinai School of Medicine. Previously he spent 17 years at the Polytechnic Institute of Brooklyn, where he often collaborated with his wife, Gisela Oster, on work in photochemistry. He writes: "My current interests center around the application of physical chemistry to biology and medicine. In particular I am studying the role of trace metals in biological oxidation and the formation of free radicals. I am concerned with molecular changes in mucoid substances as they relate to disease and to sexual reproduction. I also toy with visual psychology and its related field, art. Exhibitions of my constructions were shown this summer in an art museum in Milwaukee and will be shown this fall in Chicago."

STERLING B. HENDRICKS ("How Light Interacts with Living Matter") is chief scientist in the Mineral Nutrition Laboratory of the Agricultural Research

Canon invents the first electronic calculator for people scared of electronic calculators.

We call it the Canon 163. It's our answer to people who thought they couldn't use one.

This is the first *true* Integrated-Circuit (IC) calculator; the first to use more IC's* (170 of them) than transistors and diodes combined.

We did it for reliability. By using IC's, we were able to keep the number of components in the Canon 163 to a minimum (it has thousands fewer than any other electronic calculator—including those that use IC's).

Fewer components mean fewer sources of heat, fewer solder connections, fewer things that can go wrong—and a smaller and lighter calculator (the Canon 163 is about the size and weight of a small portable typewriter).

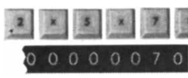
We added more capability. Simple and compact as it is, the Canon 163 incorporates several exclusive capabilites, such as: switch-selected round off, drop-off *and* round-up of digits following the last decimal place; and a memory with item count and sum-of-multiplicand features as well as ordinary storage. The other memory automatically accumulates subtotals without re-entry, and an additional register allows multiplication and division by constants.

The Canon 163 divides, multiplies, adds and subtracts any 16-digit numbers of up to 10 decimal places, raises them to any integral power, and automatically finds square roots. Instantly, accurately, silently.

And it has a host of safeguards to prevent, catch and correct human mistakes. These include an exclusive illuminated, automatic comma indicator every three places before and after the decimal point, automatic credit balance indication and an exclusive glare-preventing polarized display panel.

If you can write it, you can do it. Despite all its capabilities, the Canon 163 is a breeze to use. You "key" most problems just the way you'd write them.

To multiply 2 x 5 x 7, is as simple as



The answer shows up in lights almost before the last key is released.

More complicated problems are just as easy, just as fast; some take even less time to calculate than you'd take to write them down.

Another new Canon IC calculator. The Canon 163 sells for $1,395. For those who don't need so much calculator, we offer the new Canon 161S, for only $1,195. It has a single memory, and offers all the other features of the Canon 163 except square root, automatic comma indication, item count and sum of multiplicand.

We'll be happy to arrange a demonstration of either Canon. Just mail in the coupon. ***There's nothing to be scared of.***

Canon ELECTRONIC CALCULATORS

*IC's manufactured for Canon by Texas Instrument.

Canon 163. Shown one-half actual size.

Service of the U.S. Department of Agriculture. He obtained a Ph.D. in physical chemistry at the California Institute of Technology in 1926 and joined the Department of Agriculture in 1927 as a research scientist. In 1952 he was one of the discoverers of phytochrome, the pigment of photoperiodism that he describes in his article. He writes that he is "concerned with membrane function in all aspects of life but particularly with salt (nutrient) uptake by roots." Hendricks has been deeply involved in the development of knowledge about clays through his work on crystal structure with the techniques of X-ray and electron diffraction and about hydrogen bonding, which he has investigated through infrared spectroscopy. He has applied this knowledge to the properties of water in soils and to the isomerization of organic compounds.

JAMES MARSTON FITCH ("The Control of the Luminous Environment") is professor of architecture at Columbia University. He studied architecture at Tulane University and at Columbia. For several years he worked as a designer and a housing analyst, and then he turned to architectural journalism. From 1936 to 1941 he was associate editor of *Architectural Record*. After a period of military service he became technical editor of *Architectural Forum*, where he worked from 1945 to 1949. He was architectural editor of *House Beautiful* from 1949 until he began teaching at Columbia in 1954. Fitch is the author of several books in his field, including a biography of Walter Gropius and a two-volume work entitled *American Building: The Forces That Shape It*. Another of his books is *Architecture and the Esthetics of Plenty*.

ULRIC NEISSER ("The Processes of Vision") is professor of psychology at Cornell University. He received his bachelor's degree from Harvard College in 1950, his master's degree from Swarthmore College in 1952 and his Ph.D. from Harvard University in 1956. From 1957 to 1965 he taught psychology at Brandeis University; during much of that time he was also associated with the Lincoln Laboratory of the Massachusetts Institute of Technology as a summer staff member and as a consultant. From 1965 to 1967, when he went to Cornell, he was with the Unit for Experimental Psychiatry, which is affiliated with Pennsylvania Hospital and the University of Pennsylvania. He is the author of a book, *Cognitive Psychology*, which was published last year.

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Precision Metal-Grid resistor network shown approximately 1½ times actual size

The advanced capabilities—developed from years of manufacturing Allen-Bradley Metal-Grid resistors—are now applied to a new line of resistor networks. This technology enables the production of complex resistive networks on a single substrate.

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A-B Metal-Grid networks offer a wide range of values—with individual resistances as low as 25 ohms and as high as 2.0 megohms. Both the inductance and capacitance are low, permitting efficient operation at high frequencies.

A-B engineers will be pleased to cooperate in developing networks for your specific need. For additional details, please write to Henry G. Rosenkranz, Allen-Bradley Co., 1315 S. First Street, Milwaukee, Wisconsin 53204. In Canada: Allen-Bradley Canada Ltd. Export Office: 630 Third Avenue, New York, N. Y., U.S.A. 10017.

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Tolerances: ±1.0% to ±0.01%

Resistance Matching: to 0.005%

Temperature Range: −65°C to +175°C

Temp. Coef.: to ±5 ppm/°C

Load Life (Full load for 1000 hr @ 125°C)**:** 0.2% maximum change

Ladder Networks

Full Scale Accuracy: 10 bits or less, better than ±¼ least significant bit. More than 10 bits, better than ±½ least significant bit.

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Light

Presenting an issue about light: how modern developments such as lasers and the elucidation of the wave-particle nature of light flow from the great tradition of optics that began with Newton

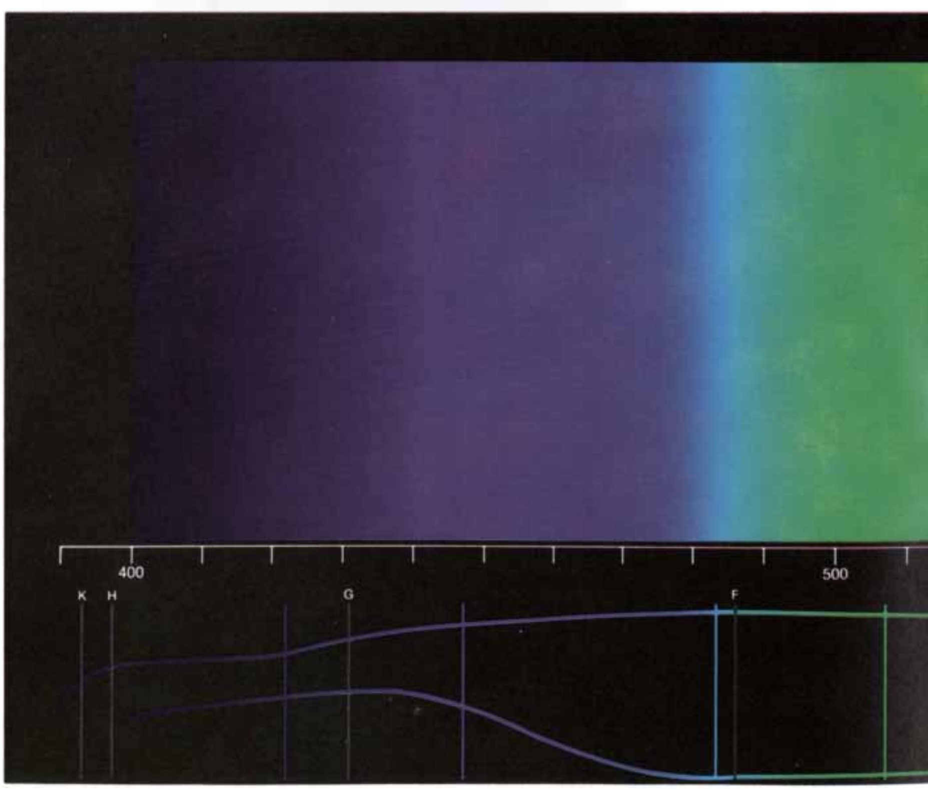
by Gerald Feinberg

The prevailing view of the nature of light has changed several times in the past three centuries. Each time the answer to the question "What is light?" has assumed more fundamental importance in the physicist's picture of the universe.

Isaac Newton (in his *Opticks,* printed in 1704) described light as a stream of particles, partly because it "travels in a straight line." Out of his experiments with color phenomena in glass plates ("Newton's rings") he also recognized the necessity for associating certain wavelike properties with light beams. These properties he called "fits of easy reflection and easy transmission." Careful not to make hypotheses, he let the matter rest. His authority was so compelling, however, that the corpuscular theory of light held sway for a century, his successors being more persuaded to this view than Newton himself.

Early in the 19th century the notion that light consists of waves, a view already expressed by Christiaan Huygens in the 17th century, came into ascendance. A decisive experiment performed in 1803 by Thomas Young, a London physician, demonstrated that a monochromatic beam of light passed through two pinholes would set up an interference pattern resembling those observed "in the case of the waves of water, and the pulses of sound." At about this time Augustin Jean Fresnel and Dominique François Arago came forward with the correct interpretation of an experiment performed by Huygens. They showed that the light transmitted by Huygens' blocks of calcite crystal is polarized and that light waves therefore cannot be longitudinal compression waves as Huygens had thought but must be transverse waves oscillating at right angles to their direction of propagation [*see bottom illustration on page* 53].

This elucidation of the wave nature of light fit nicely into the electromagnetic theory of light propounded later in the century by James Clerk Maxwell. In Maxwell's equations light is described as a rapid variation in the electromagnetic field surrounding a charged particle, the variations in the field being generated by the oscillation of the particle.



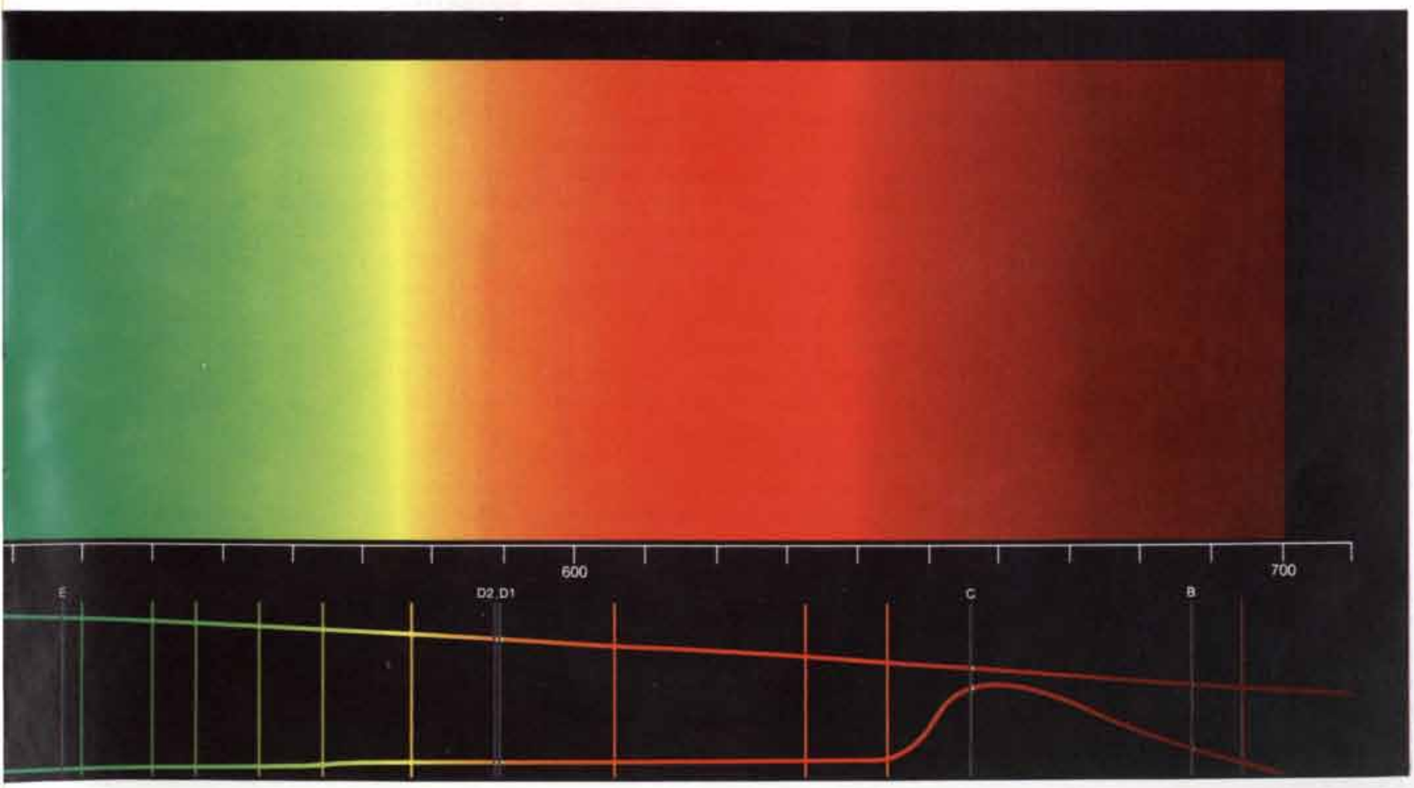
As such a varying field, light takes its place beside a number of other forms of radiant energy that were discovered in the 19th century. The different kinds of electromagnetic radiation—radio waves on one side of the spectrum of visible light and X rays on the other—correspond to different rates of variation of the field. Thus in Maxwell's theory light appears not as an independent element in nature but rather as an aspect of the fundamental phenomenon: electromagnetism.

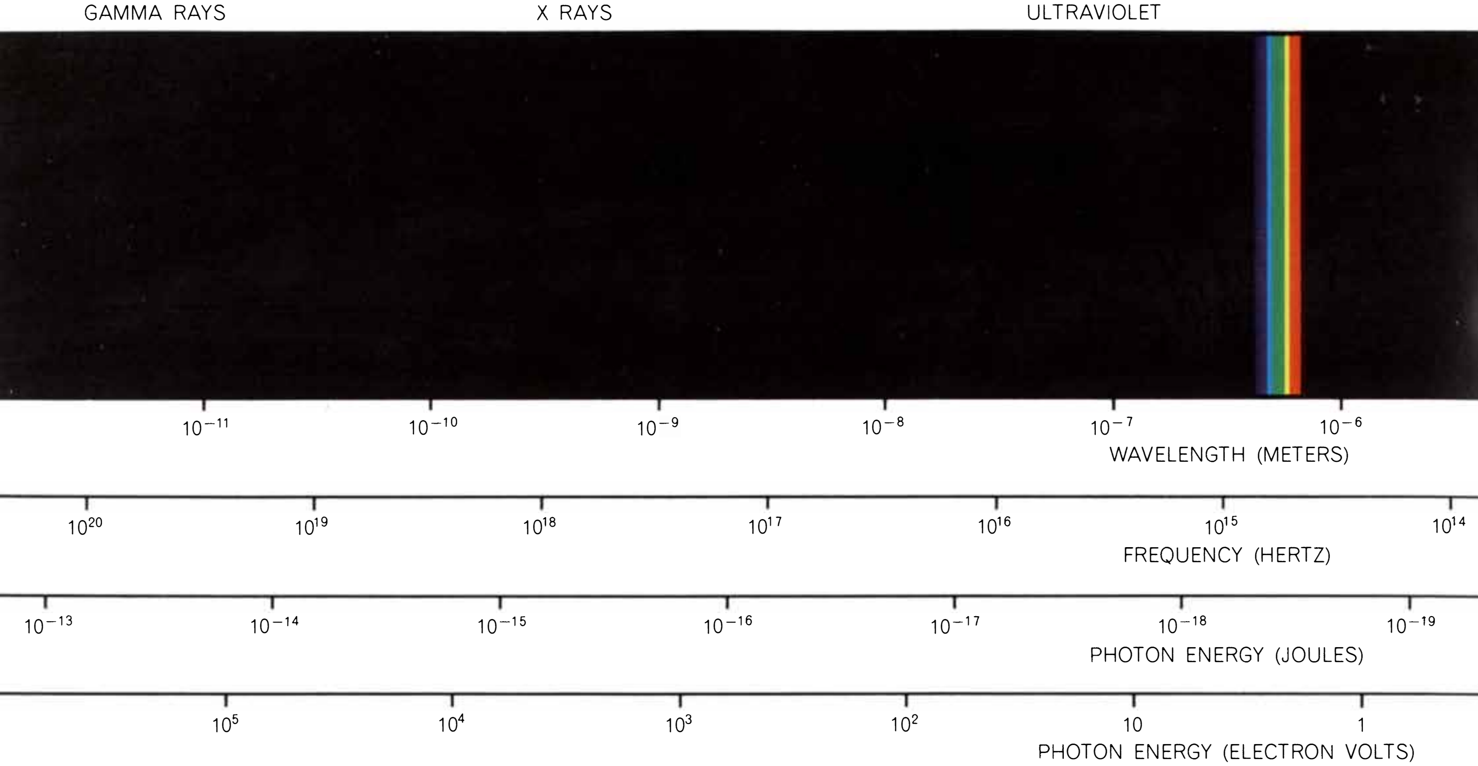
The momentous developments in physics in this century have reopened and then resolved the old wave-particle controversy. Whereas the association of light with electromagnetism remains valid, the interpretation of this connection has changed. It has been shown that such wave properties as interference and polarization, so well demonstrated by light, are also exhibited under suitable circumstances by the subatomic constituents of matter, such as electrons. Conversely, it has been shown that light, in its interaction with matter, behaves as though it is composed of many individual bodies called photons, which carry such particle-like properties as energy and momentum.

As a result of these developments most physicists today would answer the question "What is light?" as Newton would have: "Light is a particular kind of matter." The differences between light and bulk matter are now thought to flow from relatively inessential differences between their constituent particles. Particles of both kinds—of all kinds—exhibit wave properties.

Much of this understanding has been acquired, of course, by means of light. In this issue of *Scientific American* Pierre Connes observes that the analysis of light "provides the best evidence for our belief in the homogeneity of the universe." In a wider context Victor F. Weisskopf shows that sight is our most important link to the world around us. Indeed, life itself is a manifestation of radiant energy in the visible spectrum; Sterling B. Hendricks describes how light starts up life, governs growth and stimulates behavior by the excitation of specialized light-absorbing molecules. The occasion for these observations and for the dedication of this issue to the topic of light is provided by an unexpected departure in the classic discipline of optics. That is the discovery of ways to synchronize the oscillation of electrons and thus produce coherent light, waves of the same length propagating in step.

SPECTRUM OF LIGHT encompasses the narrow band of radiant energy to which the human eye is sensitive, a portion of the electromagnetic spectrum from about 400 to about 700 nanometers in wavelength that is reproduced on these two pages. (A nanometer is 10^{-9} meter, or a billionth of a meter.) The upper of the two curves, with its peak at 483 nanometers, gives the energy distribution in sunlight at the earth's surface. The lower curve is the double-peaked absorption spectrum of chlorophyll, the green pigment of plants. The Fraunhofer lines (*gray*) mark the chief wavelengths at which solar radiation is absorbed by elements in the cooler atmosphere of the sun: oxygen (*B*), hydrogen (*C, F*), sodium (*D1, D2*), iron (*E, G*) and calcium (*G, H, K*). At 530 is the green emission line of heavily ionized iron in the sun's corona that was once attributed to the hypothetical element "coronium." A helium emission line is at 422, the principal emission line of a mercury arc at 546. The three cone-cell pigments of human color vision absorb most strongly at 447, 540 and 577, setting the peak of daylight vision at 555; the rod cells of night vision have their absorption peak at 507. The "red shift" of the astronomer is represented here by the line at 564, to which the Fraunhofer *F* line is shifted in the emission spectrum of the quasar 3*C* 273. The world's standard of length, the emission line of krypton 86, is at 606; the standard was formerly a cadmium line at 644. The helium-neon and ruby laser emit their monochromatic, coherent light at 633 and 694 respectively. This printed spectrum is not a reproduction, as is usually the case, of an actual spectrum captured photographically. Instead the color separations were prepared at the Eastman Kodak Research Laboratories by calibrating color patches prepared with cyan (blue), magenta (red), yellow and black inks and then making four negatives, each with a calculated density for each wavelength of the spectrum.





ELECTROMAGNETIC SPECTRUM, of which the visible spectrum on the preceding two pages is only a small part, is a continuum of electromagnetic radiation, the energy of which is carried in the quanta called photons. This diagram extends from gamma rays to high-frequency radio waves. The upper scales give the radiation's frequency (in hertz, or cycles per second) and wavelength;

The laser has given physics a powerful instrument for study of the interaction of light and matter [see "Laser Light," by Arthur L. Schawlow, page 120]. In technology laser light is finding uses in surveying and metrology, in cutting and welding, in communication and information storage [see "Applications of Laser Light," by Donald R. Herriott, page 140].

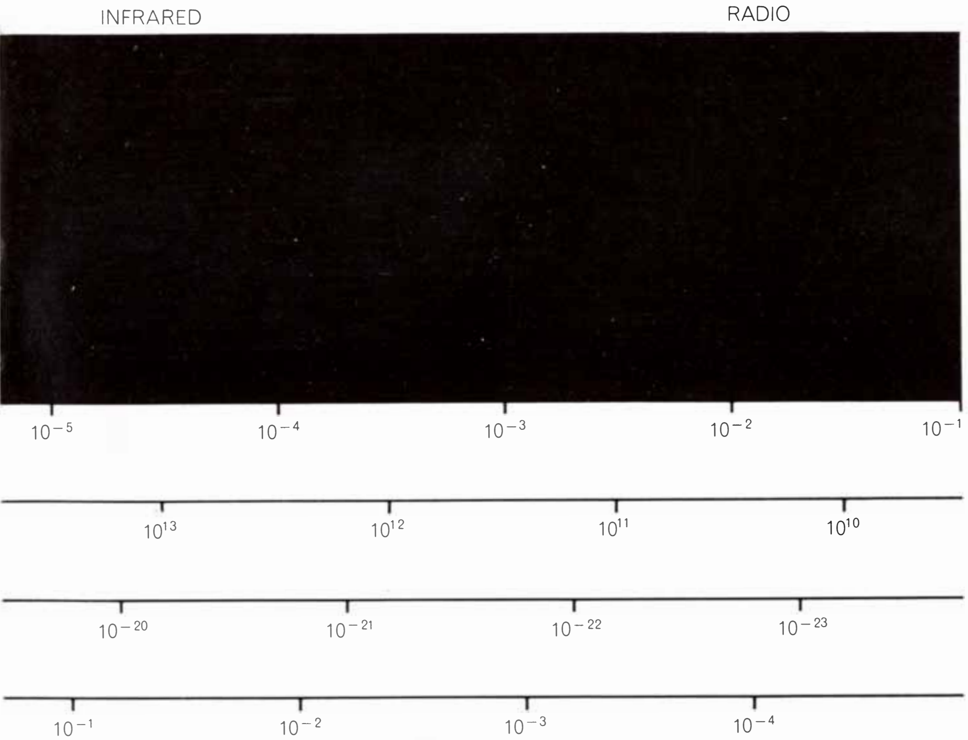
The operation of the laser exploits one of those inessential differences between photons and other particles. Let us now examine more closely the similarities and differences between the particles of light and ordinary matter and see how what is known about light can be understood in such terms.

One phenomenon that serves this purpose well is diffraction. It plainly demonstrates the wave properties of light and matter. If a beam of monochromatic light from a small source, or a stream of particles such as electrons, is directed at a screen with a small hole in it, the light or the particles that get through the hole will produce a characteristic pattern on a second screen placed beyond the first. The pattern is easy to understand in the case of light regarded as a wave, and it was cited in the 19th century as evidence in favor of the wave theory of light. Diffraction shows that light waves do not exactly travel in straight lines but diffract, or spread, as other waves do, and so find different pathways to the collecting screen. The interference of wavelets that in consequence arrive out of phase with one another at the collecting screen sets up the diffraction pattern.

In order to demonstrate the simple form of interference described above, a source of monochromatic light is required. Ordinary light sources are not monochromatic. Light from a luminous gas, for example, is emitted independently by many atoms in the gas. Furthermore, because collisions between the atoms excite and de-excite them, the light is emitted in pulses that have a finite length in time rather than an infinite length as is suggested by the textbook sine wave. Such a pulse can be resolved into a sum of pure sine waves of different wavelengths. The range of wavelengths in the pulse is inversely proportional to its duration; therefore the shorter the pulse in time, the greater the spread in wavelengths. Interference patterns are not usually detected in light from such a source. The reason is that the different wavelengths will interfere constructively in different places and the overall pattern will approximate constant illumination. Light of this kind is said to be incoherent. Conversely, light that yields interference patterns is said to be coherent. To obtain coherent light from natural sources one must narrow the range of wavelengths by means of a monochromatic filter and reduce the size of the source to a small area, as with a pinhole. With the advent of the laser we can now obtain highly coherent light without the loss of intensity involved in these procedures.

The exact shape of the diffraction pattern obtained from a given light source depends on the color of the light, objectively measured as wavelength. In the case of electrons the wavelength, and therefore the pattern, depends on the electrons' energy. In either case if diffraction is to be observed, the hole must be small with respect to the wavelength. For visible light, with wavelengths from 400 to 700 nanometers (4×10^{-7} to 7×10^{-7} meter), deviations from straight-line propagation are small unless the hole is very small. A barely visible pinhole will just produce a perceptible diffraction pattern. Electron and other subatomic particles usually have wavelengths of 10^{-9} meter or less, so that diffraction of these particles can be demonstrated only with crystals in which the "holes" are spaces between atoms about 10^{-10} meter apart.

It is this difference in the characteristic wavelength that explains why wave



their product at any wavelength is the speed of light. The lower scales give the energy of the corresponding photons first in joules, or watt-seconds, and then in terms of the electron volt, the energy imparted to an electron falling through a potential difference of one volt.

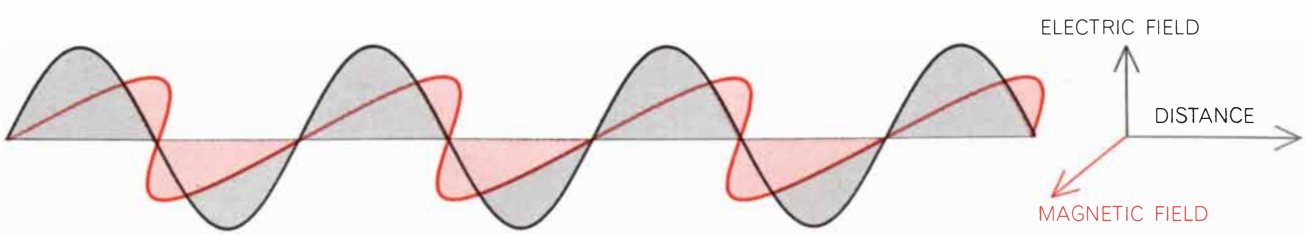
properties were so easy to demonstrate for light beams and so much harder to discover for matter beams. Diffraction was first shown in electrons in 1927. All the wave properties characteristic of light, however, have now been demonstrated in electron and neutron beams, and there is little doubt that they hold also for other particle beams.

An important step in establishing the underlying resemblance of the particles of matter to the particles of light was the recognition that for both kinds of particle wavelength is related to the momentum, and hence to the energy, of the particles constituting the beam. The same equations show for all cases that wavelength is inversely proportional to momentum [*see top illustration on page 56*]. The equations also bring out the difference between photons and the particles of ordinary matter. In the case of the electron, for example, the energy must include the rest mass of the particle. Photons, on the other hand, have zero rest mass, and so the term for rest mass drops out of the equations.

It is the rest-mass energy ($E = mc^2$) of the electron and other matter particles that gives them wavelengths so much shorter than light beams. A photon of blue light has an energy of about 3×10^{-19} joule, which corresponds to a wavelength of 4×10^{-7} meter. If this photon energy is transferred as kinetic energy to an electron, which starts with a rest-mass energy of 8×10^{-14} joule, the total energy is changed very little (by less than 10 parts in a million) and the wavelength is about 10^{-9} meter. The wavelength is still shorter, of course, for particles that have larger rest-mass energies.

The inverse proportionality of wavelength to momentum is governed in these equations by the constant h, known as Planck's constant. It may be helpful to recall how this constant entered physics; the story is a significant chapter in the recognition of the particle nature of light. In 1900 Max Planck was concerned to explain the relation between wavelength and intensity in the radiant energy from a hot body. According to classical electromagnetic theory, the intensity was supposed to increase as the square of the frequency; by this reckoning an infinite amount of energy should be radiated at the higher frequencies or shorter wavelengths. Actual measurement had shown a quite different distribution of intensity with respect to wavelength for any given temperature [*see bottom illustration on page 56*]. Planck found an empirical formula that described this distribution. It contained a constant, the value of which Planck chose in order to produce the best agreement with the observations. To explain why this formula should work he had to assert that light must exchange its energy with the matter of the hot body in quanta, or packets. His equation showed that the amount of energy in each quantum would be equal to the frequency multiplied by the constant $h = 6.63 \times 10^{-34}$ joule-second. (The frequency is equal to the speed of light divided by the wavelength.) The constant h has since proved to be a fundamental constant of nature.

In 1905 Albert Einstein was prompted by another failure of classical electromagnetic theory to extend Planck's quantum concept further. Einstein asserted that not only is the energy of the light exchanged in quanta; the energy of the light beam is itself always divided into discrete quanta. His argument was based on his analysis of the photoelectric effect. It had been observed that negatively charged plates of certain metals



ELECTROMAGNETIC WAVES, including light waves, are transverse: the electric and the magnetic fields are each at right angles to the direction of propagation. This illustration is a perspective view of a graph of the two fields at a given instant (*electric field is vertical, magnetic field horizontal*). The intensity of the radiation (light, for example) varies with the square of the peak amplitude of the electric field and is proportional to the number of photons in the field. The color of the light is governed by the wavelength.

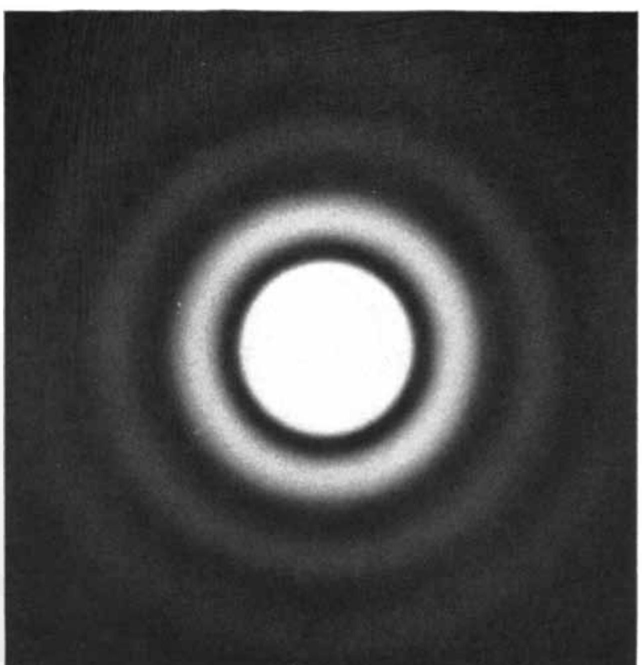
lose their charge when they are exposed to ultraviolet radiation; in other metals the reaction could be triggered by visible light. It is now known that every metal has a critical wavelength for the effect. The emission of electrons will occur only on exposure of the metal to light of this wavelength or a shorter one. The effect depends entirely on wavelength and is independent of the intensity of the light. Furthermore, even for very weak light sources, the ejected electrons may come out simultaneously with the incidence of the light, without any time being required for the accumulation of energy.

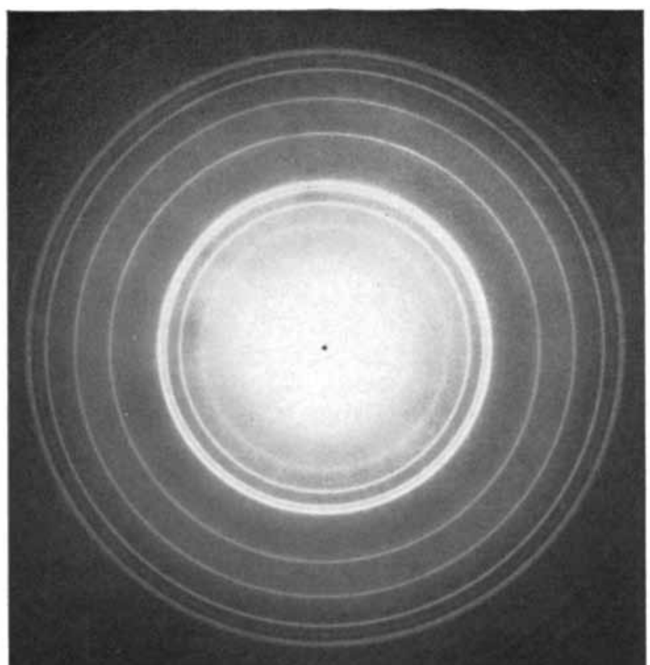
It was impossible to understand these aspects of the photoelectric effect on the basis of a model in which the energy of light is uniformly distributed over the whole of an incident wave. In light of low intensity there would be insufficient energy at any one place in the beam to eject an electron. On the other hand, the observed results follow directly from Einstein's description of the photoelectric effect, according to which each quantum of light, or photon, carries an energy inversely proportional to the wavelength of the light, the proportionality being governed by Planck's constant. In this model a light beam contains a large number of photons (about 10^{18} per second in the beam of a flashlight), and the photoelectric effect occurs when a given photon is absorbed by a particular electron, with the total energy of the photon being transferred to the electron. The relation between the energy transferred to the electron and the wavelength of the light has been precisely measured and found to be in accord with the prediction from Einstein's hypothesis.

The Compton effect provides further evidence that electrons interact with light through encounters with discrete bodies in the light beam that carry momentum and energy. Here it had been observed that X rays passing through matter often increase in wavelength. This was interpreted by Arthur Holly Compton as a loss of energy due to collisions between the highly energetic X-ray photons and the electrons. From the equation showing the relation of wavelength to energy Compton argued that the wavelength shift in the X rays would have a simple dependence on scattering angle, and this was in fact observed. It was shown soon afterward by the use of coincidence counting techniques that an electron recoils from each scattered photon and carries off the energy and momentum given up by the photon. These billiard-ball collisions plainly show that an X-ray beam behaves like a stream of particles. Similar behavior has been demonstrated for electromagnetic radiation of other wavelengths.

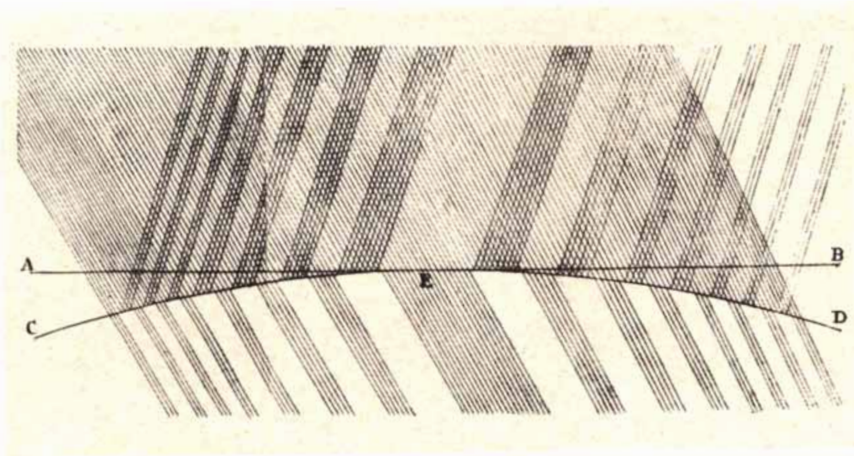
Although photons obey the same equations governing the relation of momentum and energy as other particles do, the relation is a special one in the case of the photon, owing to its vanishing rest mass [*see top illustration on page 56*]. The relative prominence of the wave properties of photons is therefore a consequence of the vanishing of the rest mass, rather than a qualitative difference between photons and other particles. The same characteristic accounts for the fact that the speed of light is independent of its energy. The velocity of particles with nonzero rest mass increases as their energy increases. For the photon velocity does not change with energy at all.

The discovery that both light and matter have wave and particle properties has made it easier to understand how these properties can exist together in either light or matter. This understanding is set out in the new description of nature, perfected in the 1920's, known as quantum mechanics. The basic objects described by the quantum mechanics of either light or matter are particles that are at least somewhat localized in space. The wave aspects of light and matter express the fact that these particles do not obey deterministic laws of motion, as they would in classical mechanics. Instead the laws they obey govern only

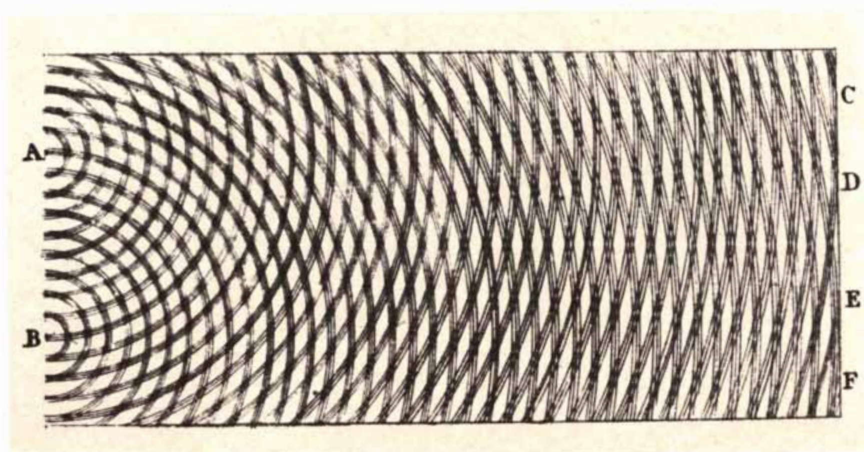




WAVE NATURE of light and of electrons is demonstrated by diffraction effects. The diffraction image (*left*) of light from a point source was caused by interference among waves from different parts of a .2-millimeter aperture. The photograph was made with coherent light by Brian J. Thompson of Technical Operations, Inc. An electron diffraction pattern (*right*) is created when a beam of electrons passed through a crystal lattice, in this case beryllium, forms an image. The photograph is from the RCA Laboratories.



NEWTON described light as corpuscular but noted wavelike properties in color phenomena such as the rings formed when glass plates are placed in contact. Lines *AB* and *CD* are glass surfaces in this diagram from the *Opticks*. The light, he suggested, undergoes "fits" of reflection and transmission as it passes through varying distances of air between the two plates.



YOUNG explained interference among light waves by analogy with water waves, as in this illustration from a book of his lectures published in 1807. Where the two sets of waves from two apertures are in phase (where the curves intersect), they reinforce each other.

the relative probabilities of motion at different speeds in different directions, even for a single particle in a known field of force. The waves associated with light and matter are a way of describing these probabilities. Hence when a light beam passes through a hole, there is some probability, related to the wavelength of the light, that the photons in the beam will not go straight through, giving a geometrical image of the hole, but instead will be deflected, ending up in the geometrical shadow region. The intensity of the waves in the diffraction pattern is a measure of this probability.

Let us see how the probabilities that quantum mechanics associates with particles (of light or other matter) explain the Young experiment that historically "proved" the wave nature of light. The experiment is usually performed with parallel narrow slits, to yield an interference pattern of alternating bright and shadowed lines. If the photons followed classical trajectories, the total probability of a photon's hitting a given point on the collecting screen would be the sum of the probabilities of this happening for each path; in other words, the light pattern would be a simple sum of the independent intensities of the two parts of the divided beam. Instead the collecting screen displays an interference pattern. The pattern is perfectly intelligible according to laws governing wave motion, in which the intensity at any given point is the sum of the amplitudes of the waves (whose squares are the intensities) reaching that point along paths of different length and thus in different phase. In quantum theory this experiment is interpreted as indicating that the motion of the photons depends on the complete physical system. If we allow the photon to go through either slit without determining which, the experiment will yield the interference pattern that reflects the probabilities—or rather the interference of probabilities—that a photon will find this or that path to the collecting screen. If we could instead monitor the photons to find out which slit they passed through on their way to the screen, the interference pattern would disappear and we would see the sum of the independent intensities [*see illustrations on page* 59].

The development of the pattern does not depend at all on the intensity of the beam, that is, on the number of photons going through the slits. As long as 50 years ago G. I. Taylor of the University of Cambridge performed an experiment with a light source so attenuated that most of the time there was no more than one photon on its way to the collecting screen. Yet after an exposure time of several months the photographic plate showed the interference pattern!

A similar experiment, employing laser light, has recently been performed by Robert L. Pfleegor and Leonard Mandel of the University of Rochester. Monitoring the arrival of each photon as they came through one by one, the counters showed that each photon found a random location at the detector. Yet when a sufficient number of photons had come through, they formed the expected interference pattern. Thus the number of photons arriving at a given position on the screen is proportional to the intensity of the interference pattern at that point, calculated according to the wave theory for the wavelength of the light in question. This shows that the wave properties must be associated with each photon rather than with the entire beam.

The wave properties of light are examples of a universal behavior of objects, contained in the quantum-mechanical description of nature. From this standpoint contemporary physicists interpret experiments such as Young's interference experiment as showing not that light is a moving wave but rather that the probabilities of various photon motions are described by a wave equation. We might say that photons are the components of a light beam whereas the wave is a description of it. The waves are not vibrations of a new substance distinct from matter, as in the old ether theories. Rather they are a means of mathematically describing the probabilities that particles will do various things. No

	GENERAL CASE	PHOTONS (m = 0)
p	$= \frac{\sqrt{E^2 - m^2c^4}}{c}$	$= \frac{E}{c}$
$\lambda = \frac{h}{p}$	$= \frac{hc}{\sqrt{E^2 - m^2c^4}}$	$= \frac{hc}{E}$
$v = \frac{pc^2}{E}$	$= c\sqrt{1 - \frac{m^2c^4}{E^2}}$	$= c$

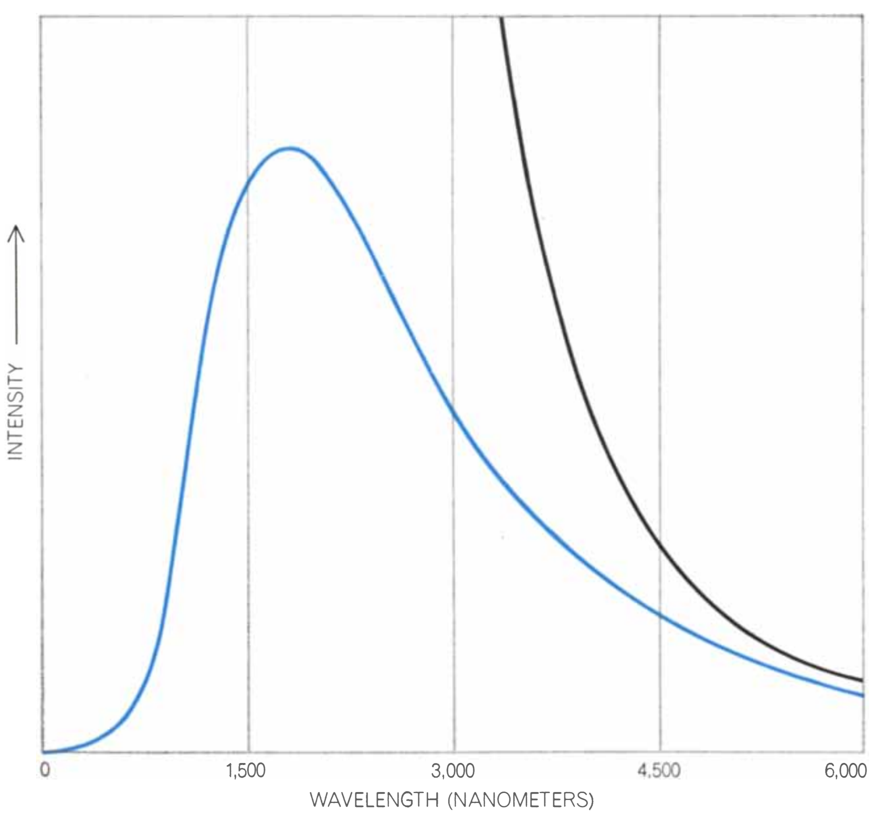
LIGHT differs from other forms of matter primarily in that photons have zero rest mass. The relation between momentum (p) and energy (E) takes on a special form for photons (*top row*). Wavelength (λ) depends on momentum and Planck's constant (h); when this universal relation is reexpressed as a dependence on energy, two forms result (*middle*). Similarly, particle velocity (v) depends on energy except in the case of photons (*bottom*).

ether-like carrier is needed for them. Nor is there any paradox involved in the occurrence of both wave and particle phenomena in light. The particles composing light and matter do not follow classical laws. If anything is surprising, it is that the behavior of the particles can be described by a concept that is as familiar as a wave satisfying a simple equation.

It is natural to ask how this picture of light as a stream of photons can be made to conform with the relation between light and electromagnetism, the discovery of which was a high point of 19th-century physics. Perhaps the most instructive way to view the relation is to say that, rather than considering light as an aspect of electromagnetism, we now think of electromagnetic phenomena as one manifestation of photons. It is easy enough, in accordance with this policy, to think of the transmission of radiant energy from place to place as being due to photons traveling across the gap. With a little more difficulty we can visualize the static electric and magnetic forces that occur between charges and currents as being due to an exchange of photons between them. In this latter case the photons are called virtual photons because the relation between their energy and their momentum is different. Quantum physics invokes this notion of virtual-particle exchange to account for forces between particles in cases other than electromagnetic forces. Nuclear forces, for example, are described as being due to the exchange of virtual mesons. Here again we are dealing with a special case of a general phenomenon.

Carrying the generalization further, we can say that all electromagnetic fields are to be thought of as being composed of photons. One result is that electromagnetic fields cannot always be taken as having determined values in space and time. Instead their values generally have associated indeterminacies; it is impossible to measure exactly the value of both the electric and the magnetic fields at the same point in space and time. The exact knowledge of one generates a necessary uncertainty in the value of the other.

Although this reduction of electromagnetism to optics can be carried through generally, it must be recognized that in many circumstances there is justification for thinking of the electromagnetic field as a special entity, as Faraday and Maxwell did. Again this is a result of specific properties of photons. Because the photon has zero rest mass it is possible for a physical system to contain many low-energy photons without its total energy becoming very great. That is the situation, for example, with the electric field between macroscopic charges. If we analyze such a field into photons, there will be a high probability of finding many photons of low energy, and also varying probabilities that different large numbers of photons of other energies are present. In these cases it is more useful to use the older field description, since the addition or subtraction of a single photon makes little difference in a state containing many photons. To put the statement another way, the fluctua-



QUANTUM NATURE of light was recognized as a result of Max Planck's explanation of the spectral distribution of electromagnetic radiation from a hot, black (fully absorbing) body. The classical theory predicted infinite radiation at short wavelengths (*black curve*). The observed distribution (*color*) was explained by introduction of quantum constant h.

tions in the field strength arising from the quantum properties of the photons that compose it are small compared with the average value at the field. In short, the particle aspects of electromagnetism and light are unimportant in many cases.

There is another property of photons that is important in situations involving many similar photons. It is termed Bose statistics. Most other stable subatomic particles, such as electrons, follow Fermi statistics. As a consequence electrons must satisfy the Pauli exclusion principle, which forbids the existence of more than one electron with any given value of momentum and angular momentum at any given time. For photons, on the other hand, not only is it allowed but also there is a tendency for photons to be produced in this way—in large numbers of the same momentum. Of all the stable elementary particles (except for the hypothetical graviton, or quantum of gravity), photons alone can occur in the combinations necessary to produce classical fields that have well-defined values over large regions. It is therefore not surprising that electromagnetism is the only case where the field aspects were recognized first.

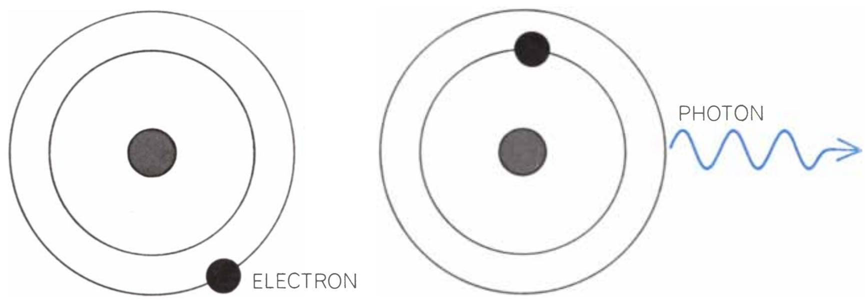
This is the property, incidentally, that is exploited in the laser. What the laser does is to produce vast numbers of particles of exactly the same energy and wavelength. With no other stable particle but the photon is such a feat possible. The laser beam's remarkable macroscopic properties arise from the fact that its constituent photons are precisely identical. Whether the laser could have been invented without quantum mechanics is an interesting question!

In order to fully understand the properties of light it is important to know about the fundamental interaction process through which light and matter particles influence each other. Although photons do interact with most other subatomic particles, whether charged or neutral, it is believed (it is not completely proved) that the basic interaction is between photons and charges. According to this model, sometimes called Ampère's assumption, the fact that photons can be emitted and absorbed by electrically neutral objects such as neutrons is a consequence of the fact that these objects, although neutral as a whole, have a structure of opposite charges distributed throughout their volume. Supposedly it is these internal charges that do the emitting and absorbing of photons.

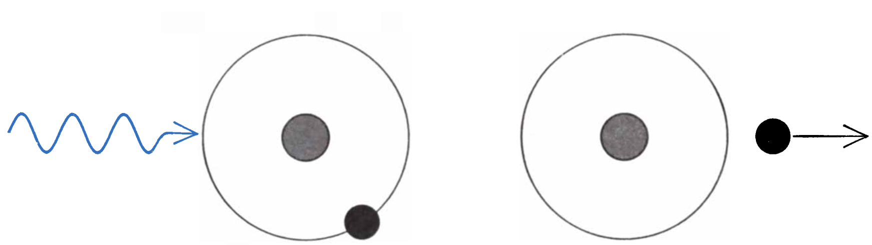
The simplest charged particle to consider is the electron, which does not have any known structure. An electron at rest can be taken as a point charge, and its fundamental interaction with light is the emission and absorption of photons, one at a time, from this point. If there is a photon at the point where the electron sits, there is some probability that the photon will be absorbed by the electron and so will disappear. Similarly, an electron can spontaneously emit a photon even if no photon was present. The probability of these events is proportional to the square of the charge of the electron.

It should be noted that in the fundamental interaction process the number of photons changes while the number of electrons remains the same. There is no conservation law for photons as there is for charged particles. As a consequence of this fact, and of the fact that photons can have arbitrarily low energy because of their vanishing rest mass, it is easy to produce them in very large numbers, as in a flashlight beam. All of the many photons in such a beam, however, are produced one at a time by individual electrons in the atoms of the flashlight's incandescent-lamp filament.

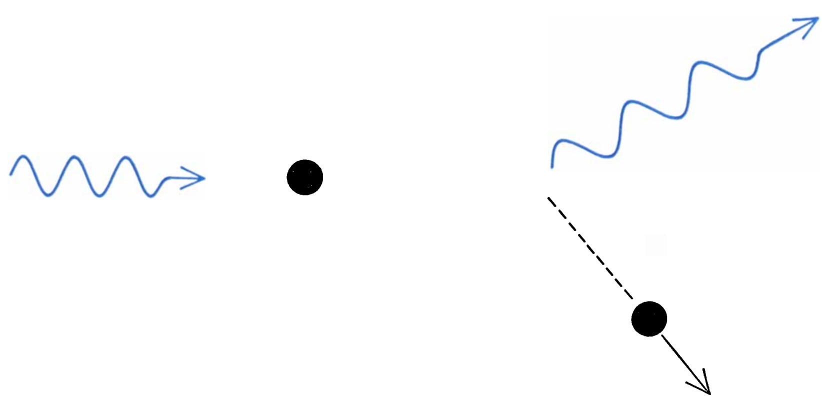
Starting with Ampère's assumption that photons interact only with charges, and applying the principles of special relativity and quantum mechanics, a mathematical theory known as quantum electrodynamics has been developed that provides detailed and accurate pre-



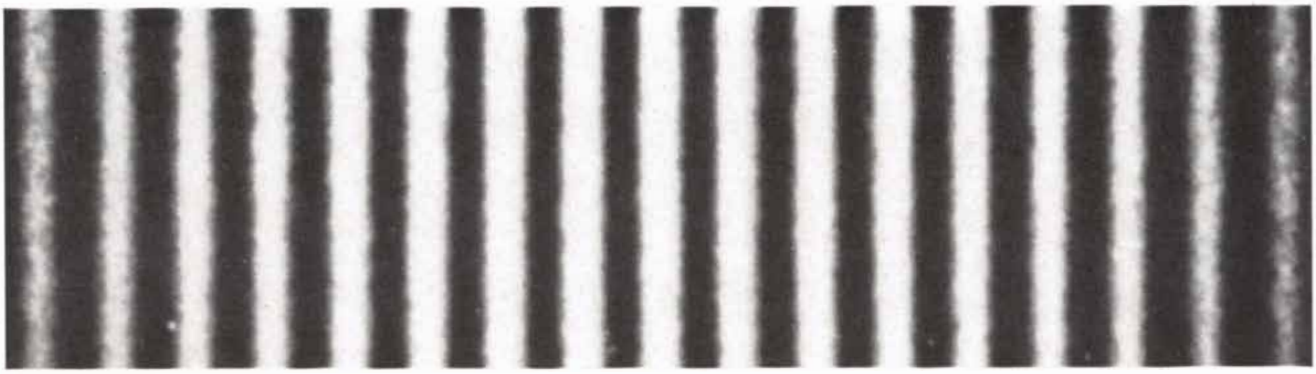
LIGHT IS EMITTED when an electron drops from a higher energy state to a lower state in an atom or a molecule. This process is reversed in most cases in which light is absorbed.



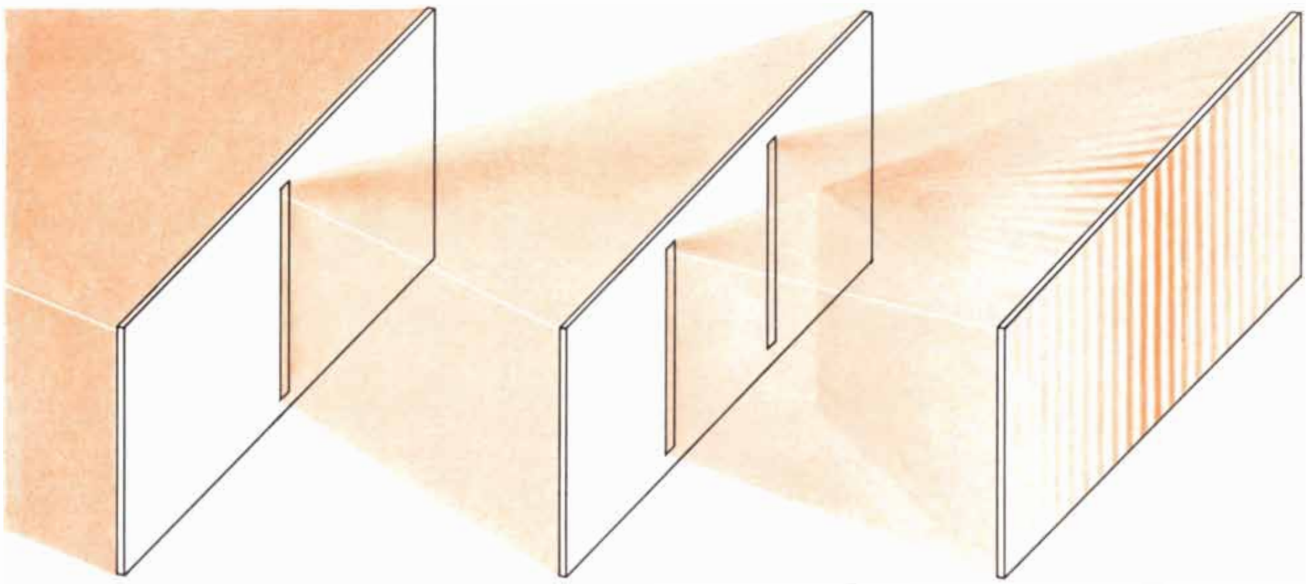
PHOTOELECTRIC EFFECT is an alternate means of light absorption, in which an electron is knocked out of an atom or a molecule by a photon. It was Einstein's explanation of the photoelectric effect as the absorption of a quantum of energy and the emission of an electron carrying the same amount of energy that established the quantum nature of light.



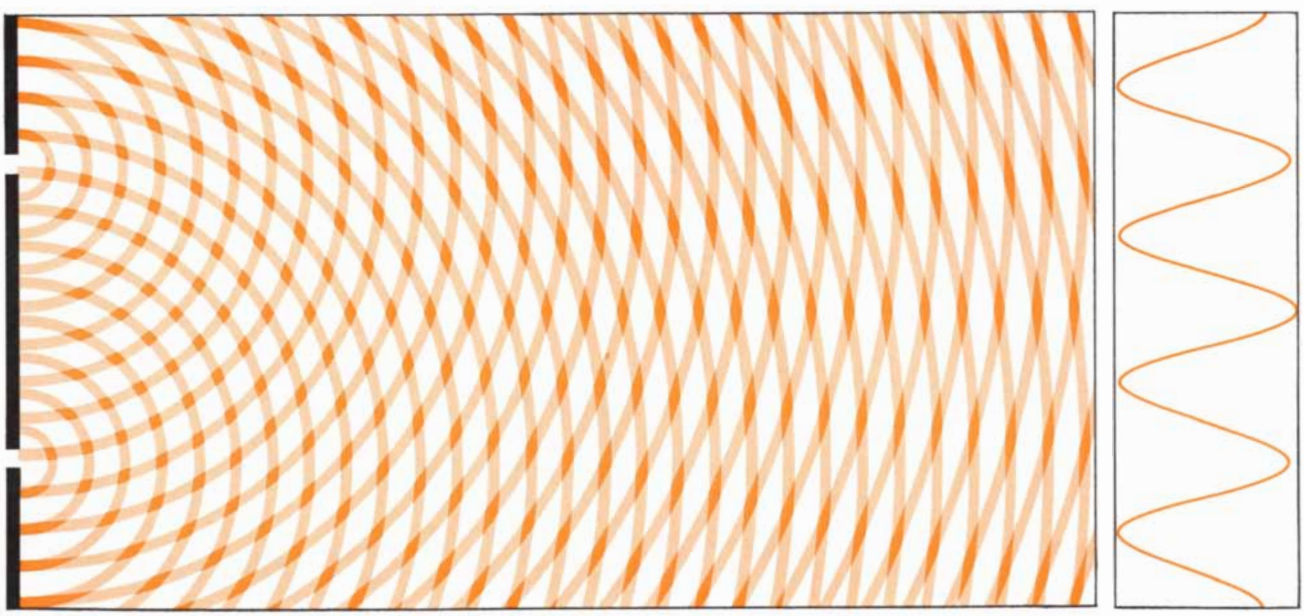
COMPTON EFFECT explained how X rays passing through matter may increase in wavelength. An X-ray photon that strikes an electron is deflected and loses energy; the wavelength shift and scattering angle are related by the dependence of wavelength on energy.



INTERFERENCE FRINGES from an experiment like Young's were photographed by Brian Thompson. Two apertures 1.4 millimeters in diameter, 22 millimeters apart, were set in front of a lens (focal length 1.52 meters) and illuminated with mercury-arc light.



FORMATION OF FRINGES is evident in this diagram, in which slits are used instead of holes. Light from a source is passed through a single slit to attain some coherence and then diffracted into fans by two slits. The fans interfere to form fringes (*right*).



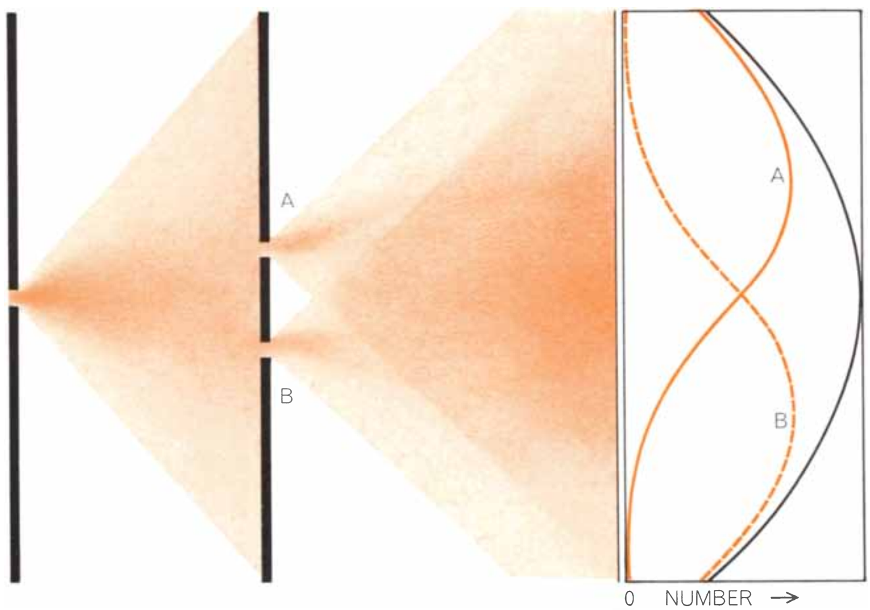
WAVE EXPLANATION OF FRINGES is evident in a plan view of the two sets of wave fronts that emerge from the slits. As the wave fronts move outward, "beams" of high intensity (*solid color*) develop where wave crests from both slits travel together and are therefore in phase (as are the troughs also along the same directions). At right is a plot of the resulting wave intensity: the fringes.

dictions for the entire range of phenomena involving light and electrons. Some of these predictions (for example the response of hydrogen atoms to microwaves) have been verified to one part in a billion. Indeed, of all the theories physicists have constructed, the quantum electrodynamics of electrons is rivaled only by the gravitational theory of planetary motion in its agreement with observation. Since a large fraction of the phenomena involving ordinary matter occur through the interaction of light with matter, or through the play of the electromagnetic forces between charges that this interaction produces, we can agree with P. A. M. Dirac in his statement that this theory "explains all of chemistry and most of physics." As the present discussion has emphasized, the theory uses the same criteria to describe and distinguish photons as it does to specify the other particles. The success of the quantum electrodynamics of electrons can therefore be taken as testimony to the idea that all matter is similar, insofar as it is described by the same general principles.

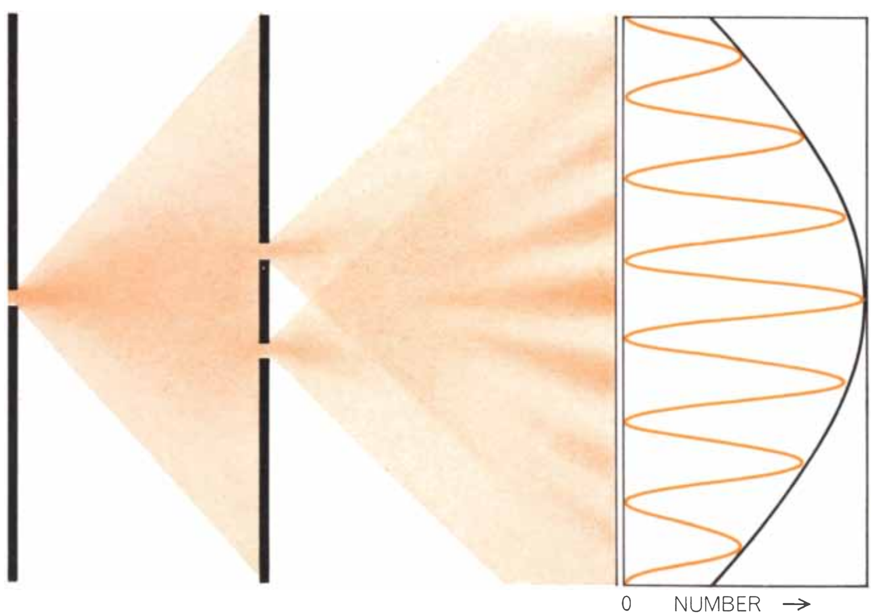
The interaction of light with other charged particles, such as protons, is less well understood theoretically. These particles have a spatial structure arising from their rapid conversion into one another through the strong interaction that generates the force holding the atomic nucleus together. The details of the scattering of light by protons have not been adequately derived from any theory. Most physicists, however, consider this a result of our inability to deal with strong interactions rather than of a failure in our understanding of the properties of light. It is believed the interaction of light with charges is basically simple and universal, even when these charges have strong interactions as well. Techniques have been devised in the past few years to circumvent in part our inability to deal with the strong interactions, and some progress has been made in calculating the interaction of light with all the other charged particles. Whether or not our understanding of this interaction will approach our understanding of the interaction of light with electrons remains to be seen.

At several times in the past physicists have thought they understood the fundamental nature of light, and they were mistaken. Is it possible that our present view is also mistaken, that it will be radically modified in the future? Predicting the future of physics is a hazardous task; the most likely outcome of such predictions is that they will provide a source of amusement for future physicists. The question nevertheless must be faced. Since our present description holds light to be similar to other forms of matter, it seems likely that any fundamental modification in the description would include all kinds of matter, not just light. The need for such a new description is perhaps indicated by the bewildering number of types of matter and of laws governing their behavior that the study of "elementary" particles has revealed. It could be that particles are not the ultimate constituents of light and matter after all but rather manifestations of something deeper.

At present the photon theory gives an accurate description of all we know about light. The notion that light is fundamentally just another kind of matter is likely to persist in any future theory. That idea is the distinctive contribution of 20th-century physicists to the understanding of light, and it is one of which we can well be proud.



CLASSICAL PARTICLE DESCRIPTION of the two-slit experiment would say that the distribution of all particles that arrive at the screen is the sum (*black curve*) of the distribution curves for particles from the upper slit (*solid color*) and lower slit (*broken color*).



QUANTUM PARTICLE DESCRIPTION says the distribution of particles will show a distribution pattern typical of wave phenomena, but only if *each* particle can go through *both* slits. Observation shows clearly that this description, and not the classical one, is correct.

How Light Interacts with Matter

The everyday objects around us are white, colored or black, opaque or transparent, depending on how the electrons in their atoms or molecules respond to the driving force of electromagnetic radiation

by Victor F. Weisskopf

The overwhelming majority of things we see when we look around our environment do not emit light of their own. They are visible only because they reemit part of the light that falls on them from some primary source, such as the sun or an electric lamp. What is the nature of the light that reaches our eyes from objects that are inherently nonluminous?

In everyday language we say that such light is reflected or, in some cases, transmitted. As we shall see, however, the terms reflection and transmission give little hint of the subtle atomic and molecular mechanisms that come into play when materials are irradiated by a light source. These mechanisms determine whether an object looks white, colored or black, opaque or transparent. Most objects also have a texture of some kind, but texture arises largely from the interplay of light and shadow and need not concern us here. I shall restrict my discussion mainly to the effect of white light on materials of all kinds: solids, liquids and gases.

White light, as it comes from the sun or from an artificial source, is a mixture of electromagnetic radiation, with wavelengths roughly between 400 and 700 nanometers (billionths of a meter) and an intensity distribution characteristic of the radiation from a body that has a temperature of about 6,000 degrees Celsius. When such light impinges on the surface of some material, it is either reemitted without change of frequency or it is absorbed and its energy is transformed into heat motion. In rare instances the incident light is reemitted in the form of visible light of lower frequency; this phenomenon is termed fluorescence. In what follows I shall take up the commonest forms of secondary light emission. I shall undertake to answer such familiar questions as: Why is the sky blue? Why is paper white? Why is water transparent? What causes objects to appear colored? Why are metals shiny?

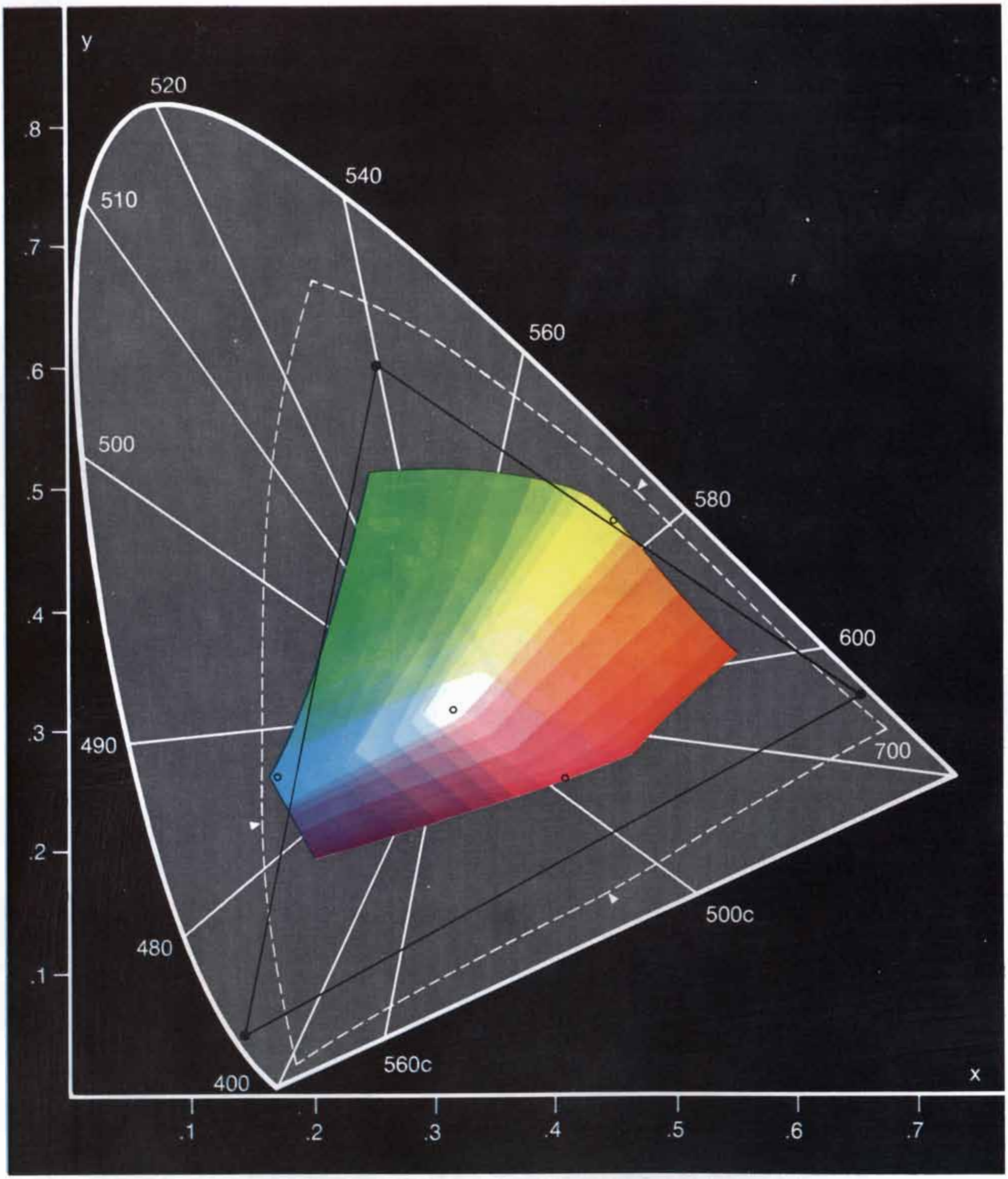
The answers are all based on the fact that the electrons of atoms are made to perform tiny vibrations when they are exposed to light. The amplitudes of these vibrations are extremely small: even in bright sunlight they are not more than 10^{-17} meter, or less than 1 percent of the radius of an atomic nucleus. Nevertheless, all we see around us, all light and color we collect with our eyes when we look at objects in our environment, is produced by these small vibrations of electrons under the influence of sunlight or of artificial light.

What happens when matter is exposed to light? Let us go back to the simplest unit of matter and ask what happens when an isolated atom or molecule is exposed to light. Quantum theory tells us that light comes in packets called photons; the higher the frequency of the light (and the shorter the wavelength), the more energy per packet. Quantum theory also tells us that the energy of an atom (or a system of atoms such as a molecule) can assume only certain definite values that are characteristic for each species of atom. These values represent the energy spectrum of the atom. Ordinarily the atom finds itself in the ground state, the state of lowest energy. When the atom is exposed to light of a frequency such that the photon energy is equal to one of the energy differences between an excited state and the ground state, the atom absorbs a photon and changes into the corresponding excited state. It falls back to a lower state after a short time and emits the energy difference in the form of a photon [*see illustration on page 63*].

According to this simple picture the atom reacts to light only when the frequency is such that the photon energy is equal to the difference between two energy levels of the atom. The light is then "in resonance" with the atom. Actually the atom also reacts to light of any frequency, but this nonresonant reaction is more subtle and cannot be described in terms of quantum jumps from one energy level to the other. It is nonetheless important, because most of the processes responsible for the visual appearance of objects are based on responses to nonresonant light.

Fortunately the interaction of light with atoms can be described rather simply. One obtains the essential features of that interaction—in particular the reemission without change of frequency—by replacing the atom with electron oscillators. An electron oscillator is a system in which an electron vibrates with a certain frequency designated ω_0. One can imagine the electron bound to a center with a spring adjusted so that there is a resonance at the frequency ω_0. The electron oscillators we are using to represent an atom are designed so that their frequencies ω_0 correspond to transitions from the ground state to higher states.

LIGHT AND COLOR were brilliantly manipulated by the medieval artisans who created the stained-glass windows of the Gothic cathedrals. The photograph on the opposite page shows a detail of the Passion Window, in the west façade of the Cathedral of Notre Dame at Chartres. The window was made in the 12th century. Stained glass is given its color by adding metal oxides directly to molten glass or by burning pigments into the surface of clear glass. Both coloring methods are evident in the example on the opposite page. The details in the faces and in the folds of the garments were produced by painting the glass with an opaque brown pigment, which was then permanently fused to the glass.



COLOR-QUALITY MAP, technically known as a chromaticity diagram, indicates how closely the colors of printing inks, color film and color television can approach the fully saturated colors of the visible spectrum, represented by the boundaries of the white horseshoe-shaped curve. The numbers around the curve indicate wavelength in nanometers. The straight line at the bottom of the horseshoe marks the boundary of the nonspectral colors from bluish purple to purplish red. When mixed with the spectral color at the opposite end of the axis, these "c" (for "complementary") colors form white. Inward from the horseshoe colors decrease in saturation, meaning that they contain more than one wavelength. The area printed in color shows the range of hues and saturations attainable with inks of three colors: magenta ("red"), yellow and cyan ("blue"). The open circles at the perimeter indicate the pure inks at full density. The open circle in the center is the white of average daylight. The colored area is actually a continuum; the steplike structure simplified the specification of ink combinations. An optimum set of dyes for color film (*white triangles*) can reproduce all the printing-ink colors plus all the more saturated tones that lie between the colored area and the broken white outline. The red, green and blue phosphors (*black dots*) used in color television picture tubes can re-create all the colors inside the black triangle. The x axis specifies the proportion of red in a particular color, the y axis the proportion of green. The rest is blue and need not be specified.

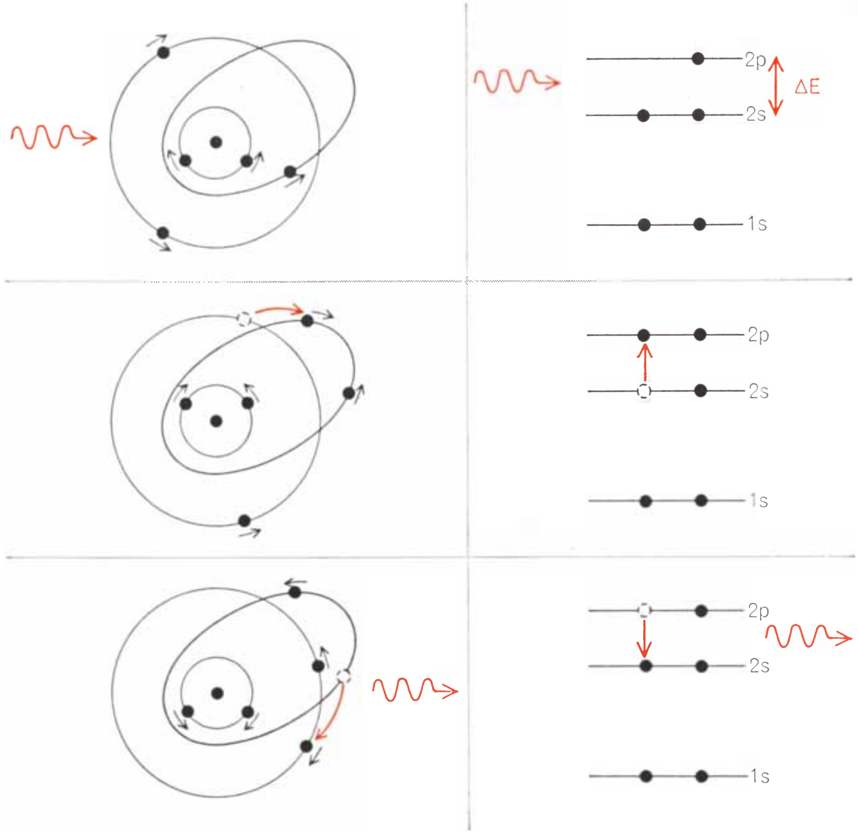
They represent the resonance frequencies of the atom in the ground state. Each of these oscillators has a certain "strength," a measure of the probability of the transition it represents. Usually the first transition from the ground state has the largest strength; that being so, we can replace the atom with a single oscillator.

Another quantity that characterizes these oscillators is their resistance coefficient, or friction. Friction causes a loss of energy in the oscillating motion. It describes a flow of energy away from the vibration into some other form of energy. It indicates that energy is being transferred from the excited state by some route other than the direct transition back to the ground state. Thus whenever the excited state can get rid of its energy by means other than reemission of the absorbed quantum, the corresponding oscillator must be assumed to suffer some friction. This is an important point in our discussion, because excited atoms in solids or liquids transmit their excitation energy mostly into heat motion of the material. Unlike the isolated atoms found in rarefied gases, they have only a small chance of returning directly to the ground state by emission of a light quantum.

Henceforward I shall discuss the effect of light on atoms in terms of this oscillator model. We can now forget about photons and excited quantum states because one obtains correct results by considering the incoming light as a classical electromagnetic wave acting on classical electron oscillators. The effects of quantum theory are taken care of by the appropriate choice of oscillators to replace the atom. One can interpret the results of the oscillator model in such a way that under the influence of light the motion of the oscillators is superposed on the ordinary state of motion of the electron in the ground state. Whenever a light wave passes over the atom, a general vibration is set up in the ground state of the atom, a vibration of a kind and strength equal to the vibrations the oscillators of our model would perform if they were exposed to the light wave. The electron cloud of each atom vibrates under the influence of light. The cloud vibrates with the same frequency as the incoming light and with an amplitude corresponding to that of one of the model oscillators. It is this vibration, amounting to less than 10^{-17} meter in amplitude, that reemits the light by which we see the objects around us.

The light from the sun or from artificial sources is a mixture of light of many frequencies. The motion of an oscillator exposed to such a mixture is simply a superposition of all the motions it would perform if exposed separately to light of each frequency contained in the mixture. Hence all one needs to know for the study of atoms under the influence of light is the motion of oscillators driven by an electric wave of a specific frequency.

If an electromagnetic wave of frequency ω passes over an electron oscillator, the electric field exerts a periodic force and leads to certain characteristic responses [*see illustration on next page*]. First of all the periodic electric field induces a vibration of the oscillator so that it oscillates with the frequency ω of the field, not with its own resonance frequency ω_0. The amplitude and the phase of this motion depend on the relative values of ω and ω_0. If ω is much smaller than ω_0, the oscillation is weak and in phase with the driving electric force of the light. If ω is much larger than ω_0, it is also weak but opposite in phase to the driving force. If ω is in resonance (in which case ω equals ω_0), the oscillation is strong and out of phase. That is, when the driving force is at its crest, the oscillation goes through the zero point. The amplitude of the oscillation follows a fairly simple mathematical formula that need not concern us here. The formula shows that if ω is much smaller than ω_0, the amplitude is small but is almost independent of the driving frequency ω. If ω is much larger than ω_0, the amplitude decreases with increasing ω at a rate proportional to $1/\omega^2$. Only the resonance case ($\omega = \omega_0$) corresponds to the simple picture of a transition to another quantum state.



INTERACTION OF LIGHT WITH MATTER involves the absorption of a photon, or quantum of light, by an atom or a molecule. If the photon has the required energy, the atom or molecule will be raised from a low energy state to one of higher energy. After a short time the atom or molecule falls back to a lower state and the energy difference is emitted as a photon. Two simple pictures of the interaction are presented here. At the left a photon (*wavy arrow*) interacts with a Bohr model of an atom with five electrons (*top*). The photon raises an electron from the second, or 2*s*, orbit to the third, or 2*p*, orbit (*middle*). When the excited electron drops back to its former orbit, a photon is emitted (*bottom*). At the right the sequence is depicted in terms of energy-level diagrams. The photon supplies exactly the energy (ΔE) required to raise an electron from the 2*s* to the 2*p* level. These simple pictures are inadequate, however, for describing the typical interaction of visible light with matter, dealt with in this article. First, photon energy usually does not correspond to the energy difference between orbits. Second, when atoms in bulk matter are excited, they normally get rid of their energy by means other than the emission of a photon.

What are the resonance frequencies in different atoms and molecules? Most of the simple atoms such as hydrogen, carbon, oxygen and nitrogen have resonances with frequencies higher than visible light; they lie in the ultraviolet. Molecules, however, can perform vibrations in which the atoms move with respect to one another within the molecule. Because of the large mass of the nuclei, such vibrations have very low frequencies; the frequencies are lower than those of visible light, in the infrared region. Hence most simple molecules such as O_2, N_2, H_2O and CO_2 have resonances in the infrared and ultraviolet and no resonances in the visible region. They are transparent to visible light. Nevertheless, visible light has an influence on them, which can be described by our oscillator picture. We replace the molecules by two kinds of oscillator, one representing the ultraviolet resonances, the other the infrared resonances. The latter are not really electron oscillators; they are "heavy" oscillators in which the mass of the oscillating charge is as large as the mass of the vibrating atoms, since they are supposed to represent the motions of atoms within the molecule.

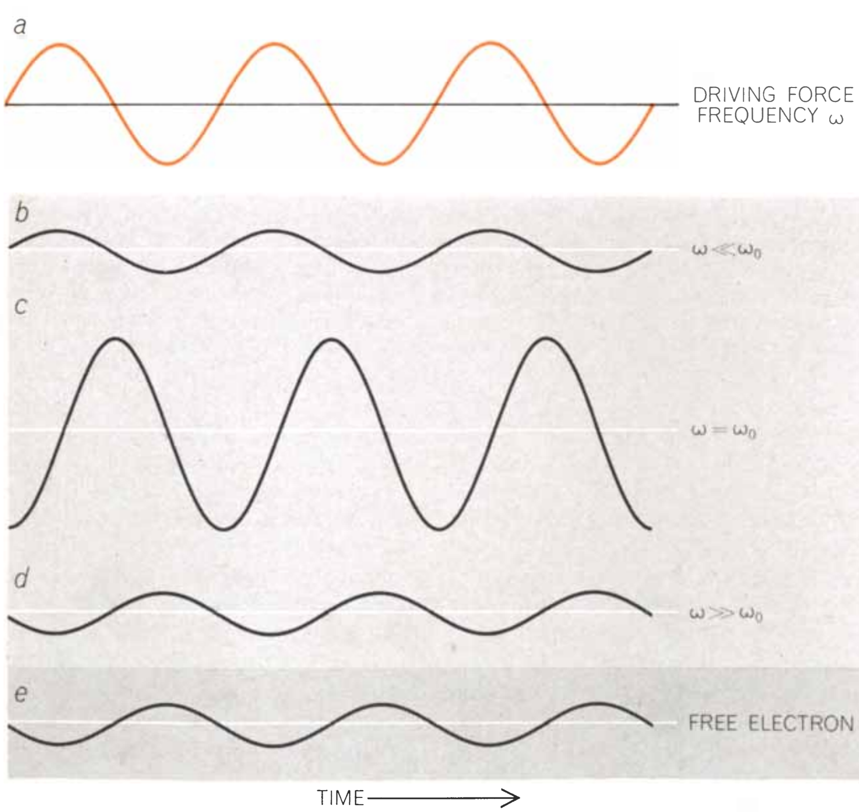
We are now ready to understand one of the most beautiful colors in nature: the blue of the sky. The action of sunlight on the molecules of oxygen and nitrogen in air is the same as the action on the two kinds of oscillator. Both oscillators will vibrate under the influence of visible sunlight. The amplitude of the infrared oscillators, however, will be much smaller than the amplitude of the ultraviolet oscillators because of their higher vibrating mass. Accordingly we need to consider only the oscillators with ultraviolet resonance. When the oscillators are under the influence of visible sunlight, the force that drives them is below the resonance frequency. Therefore they vibrate with an amplitude that is roughly equal for all visible frequencies [*see illustration on opposite page*].

We must now take into account the fact that a vibrating charge is an emitter of light. According to a principle of electrodynamics an electron oscillating with an amplitude A emits light in all directions with an intensity given by a formula in which the intensity of the radiation is proportional to the fourth power of the frequency. (The formula is $1/3(e^2/c^3)\omega^4A^2$, where e is the charge of the electron, c the velocity of light and ω the frequency of oscillation.) Hence the molecules of air emit radiation when they are exposed to sunlight. This phenomenon is known as Rayleigh scattering. It is called scattering because part of the incident light appears to be diverted into another direction. Whenever we look at the sky but not directly at the sun, we see the light radiated by the air molecules that are exposed to sunlight. The scattered light is predominantly blue because the reradiation varies with the fourth power of the frequency; therefore higher frequencies are reemitted much more strongly than the lower ones.

The complementary phenomenon is the color of the setting sun. Here we see solar rays that have traveled through the air a great distance. The higher-frequency light is attenuated more than light of lower frequency; therefore the reds and yellows come through more strongly than the blues and violets. The yellowish tint of snowy mountains seen at a distance is a similar phenomenon. The stronger attenuation of higher frequencies is a consequence of the conservation of energy: the energy for the reradiation must come from the incident sunlight, and because there is stronger reradiation at the higher frequencies more energy is taken from the sunlight at higher frequencies.

In actuality Rayleigh scattering is a very weak phenomenon. Each molecule scatters extremely little light. A beam of green light, for example, goes about 150 kilometers through the atmosphere before it is reduced to half its intensity. That is why we can see mountains at distances of hundreds of miles. Lord Rayleigh exploited the phenomenon of light scattering to determine the number of molecules in a unit of volume in air. In 1899 he was admiring the sight of Mount Everest from the terrace of his hotel in Darjeeling, about 100 miles away, and he concluded from the dimness of the mountain's outline that a good part of its light was scattered away. He determined the scattering power of each molecule from the index of refraction of air, and he found the number of air molecules per cubic centimeter at sea level to be 3×10^{19}, which is very close to the correct value.

Now we know why the sky is blue. Why, then, are clouds so white? Clouds are small droplets of water suspended in air. Why do they react differently to sunlight? The water molecule



RESPONSE OF OSCILLATOR TO PERIODIC DRIVING FORCE serves as a model of how the electrons of an atom respond to the driving force of light. The response of each oscillator (*b, c, d, e*) depends on its particular resonance frequency, ω_0. The driving force (*a*) has a frequency of ω. When ω_0 is much greater than ω, the oscillator responds in phase but only weakly (*b*). When ω_0 equals ω, the response reaches a maximum and is 90 degrees out of phase (*c*). When ω_0 is much less than ω, the response is again weak and 180 degrees out of phase (*d*). This weak response closely resembles the response of a free electron (*e*).

also has resonances in the infrared and in the ultraviolet, resonances not much different from those of oxygen and nitrogen molecules. Water molecules should react to sunlight in a similar way. There is, however, an essential difference. We determined the scattering of sunlight in air by assuming that each molecule reradiates independently of the others, so that the total scattered intensity is the sum of the individual molecular intensities. That is correct for a gas such as air because gas molecules are located at random in space, and thus there is no particular interference among the individual radiations of the molecules in any direction other than the direction of the incident sunlight.

That is no longer the case when the molecules or atoms take on a more orderly arrangement, as they do in solids and liquids and even in the droplets of a cloud. In order to understand the effect of light on matter in bulk, we must study how electromagnetic waves react to a large number of more or less regularly arranged oscillators, when the average distance between the oscillators is small compared with the wavelength of visible light. As we have seen, under the influence of incident light every oscillator emits a light wave. Because the oscillators are no longer randomly spaced, however, these waves tend to interfere with one another in a definite way: there is constructive interference in the forward direction (the direction of the light path) and destructive interference in all other directions. The individual waves build up to a strong wave called the refracted wave; in any other direction the waves tend to cancel one another. If the oscillators are in a regular array, the cancellation is complete [*see illustration on next page*].

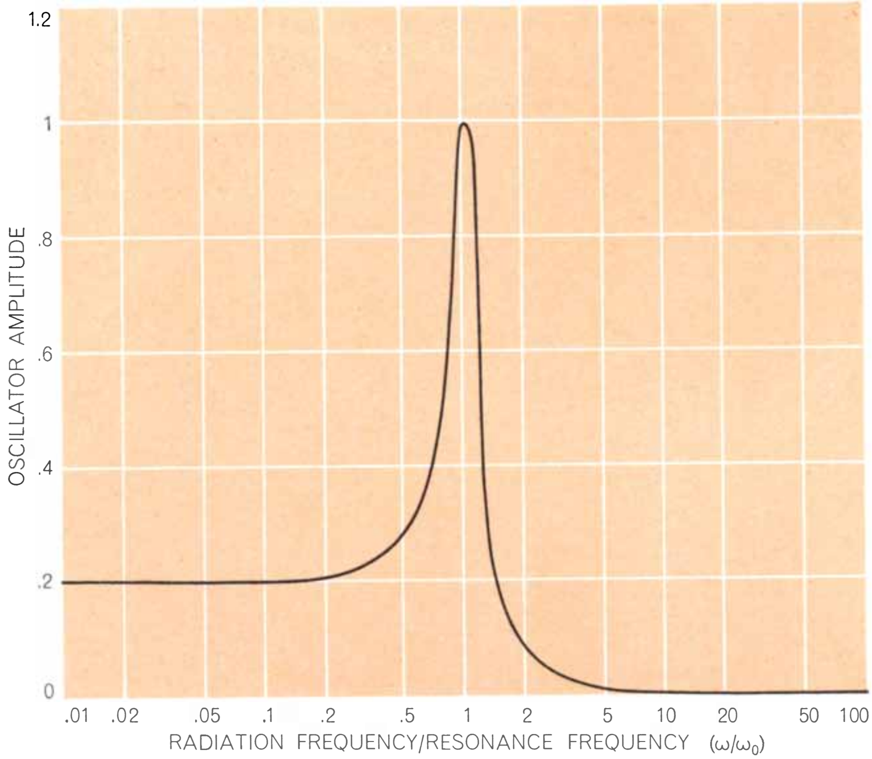
The refracted wave travels with a velocity v that differs from the ordinary light velocity c. The ratio c/v is called the refractive index n of the medium. There is a simple relation connecting the value of n with the amplitude A of the oscillator vibrations. The greater this amplitude is under the influence of a given and fixed driving force, the more n departs from unity. Knowing the refractive index of air, Lord Rayleigh used this relation to find the amplitude in sunlight of the oscillators representing the air molecules.

In a regular and uniform arrangement of atoms the reemitted waves build up to a single refracted wave. There is no individual, or incoherent, scattering by each oscillator, as occurs in a gas such as air. As long as a crystal or a liquid contains heat it cannot be completely regular. The atoms or molecules are constantly vibrating, and in addition there are always some irregularities and imperfections in the crystal structure. These irregularities scatter some of the light away from the direction of the refracted wave. This scattering, however, is much weaker than the scattering in air, assuming equivalent numbers of atoms. For example, water is 1,000 times denser than air, but its incoherent molecular scattering is only five times greater per unit volume than the scattering in air that makes the sky blue.

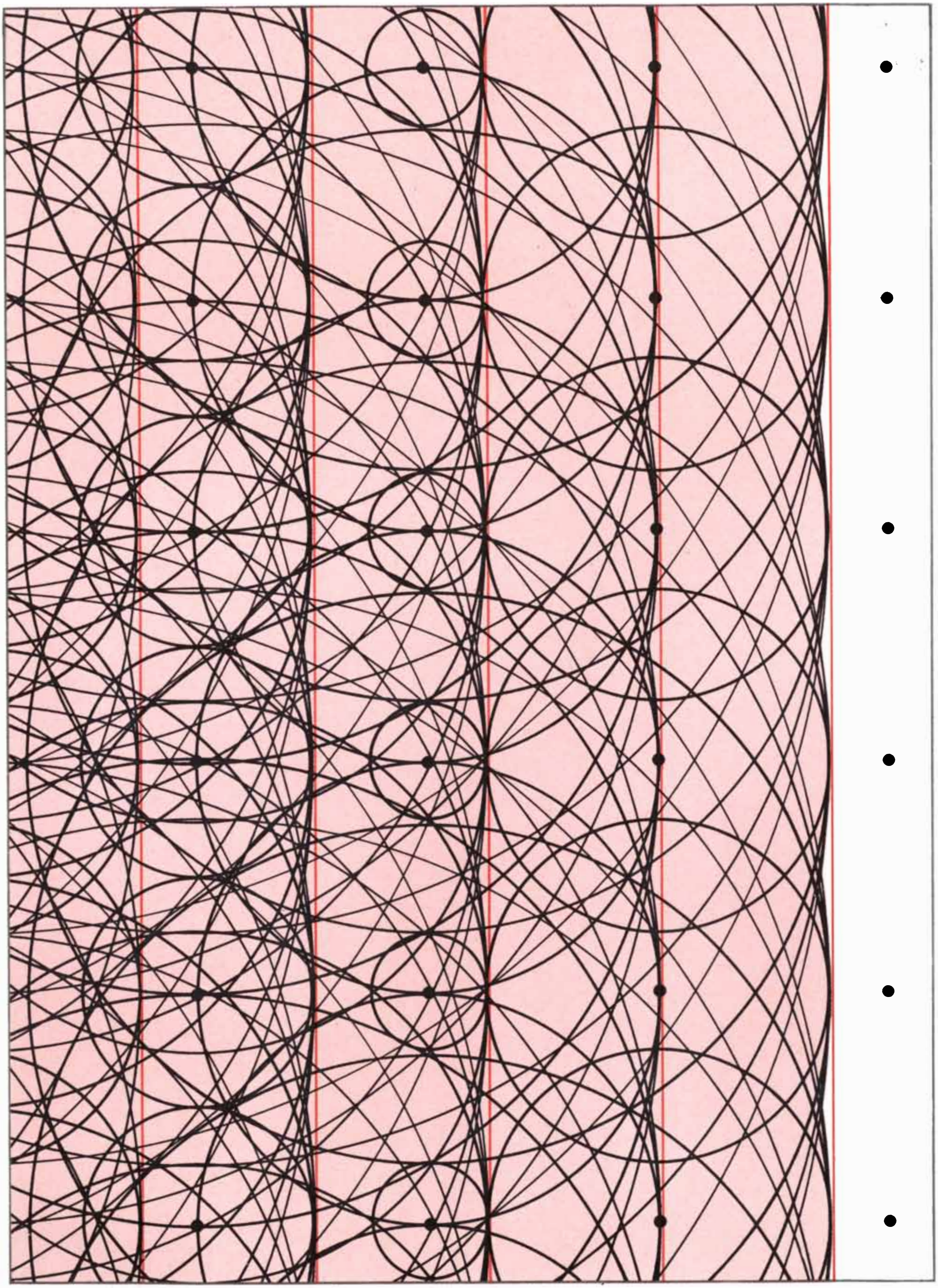
Now let us see what happens when light impinges on the surface of a liquid or a solid or a cloud droplet. Again we replace each atom by an oscillator. These oscillators vibrate under the influence of the incident light and emit light waves. In the bulk of the material all these light waves, apart from the weak incoherent scattering, add up to one strong refracted wave. This is not so, however, near the surface of the material. There is a thin layer of oscillators at the surface (about as deep as half a wavelength) for which the back radiation is not completely canceled by interference. The radiations backward of these oscillators add up to a "reflected" wave [*see illustration on page 67*].

What is the color of this reflected light if the incident light is white? One might perhaps conclude that it should be as blue as the sky, since it too comes from the reradiation of oscillators and we have learned that the intensity of this reradiation is proportional to the fourth power of the frequency. Actually it is as white as the incident light. The intensity of the reflected light with respect to the incident light in water, glass or crystals is practically independent of the frequency.

The explanation is that the reflected wave is a coherent composite of many individual reradiations. The oscillators, since they are not randomly distributed, reradiate in unison. That by itself would not yet explain the difference; it would only tell us that the reradiated intensity is high. In a coherent radiation it is the amplitudes that add up and not the intensities. Hence N coherent oscillators give N^2 times the intensity of one individual radiation. It still would seem that the reradiation should be blue, inasmuch as the radiation intensity of each oscillator increases strongly with frequency. What happens, however, is that the



OSCILLATOR AMPLITUDE is a function of the ratio between the frequency of the driving force, ω, and the oscillator's resonance frequency, ω_0. This ratio, ω/ω_0, is expressed in the horizontal scale, which is logarithmic. The amplitude approaches a constant value (*left*) when the driving frequency is much below resonance. This is the situation when molecules of nitrogen and oxygen in the atmosphere are exposed to visible light. When the driving frequency is much above resonance, the amplitude decreases as the square of ω/ω_0.



REFRACTED WAVE IN CRYSTAL consists of a parallel series of plane waves (*dark color*) formed by the crests of many spherical waves (*black circles*). The spherical waves depicted here represent light reemitted by the atoms (*black dots*) in a crystal that is exposed to a light beam entering from the left. The refracted wave is traveling to the right. The situation in glass and water is similar.

number of oscillators acting in unison also depends on the frequency: the layer that gives rise to reflection is half a wavelength deep, and the area of the layer whose reflected light arrives in step, or with the same phase, at a given point in space is also proportional to the wavelength. (This area is known as the first Fresnel zone. The radiations from all other parts of the surface interfere with one another, so that they give no light at that point.) Hence the number N of oscillators producing light in unison is proportional to the square of the wavelength. The intensity of this light is proportional to N^2. The net effect is to cancel the fourth power of the frequency, because higher frequency means smaller wavelength and a smaller value of N. As a consequence the reflected-light intensity is independent of frequency. Therefore clouds are white: the incident sunlight is reflected at the surface of the water droplets without change in spectral composition.

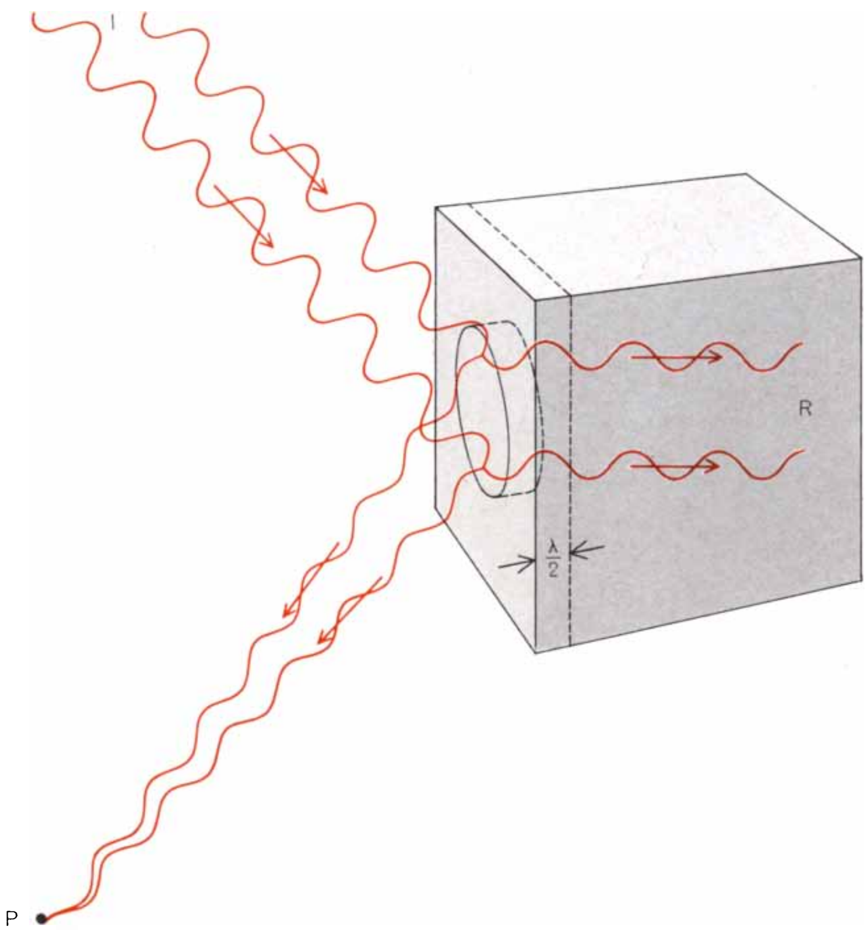
On the same basis we can understand the transparency of water, of glass and of crystals such as salt, sugar and quartz. If light impinges on these substances, it is partially reflected at the surface but without preference for any color. The rest of the light enters the substance and propagates as a refracted wave within it. Therefore these objects look colorless. Their outlines are nonetheless visible because of the reflection of the light at the surfaces.

Sometimes such objects may exhibit color under special circumstances. Reflection and refraction are only approximately independent of frequency. Both increase slightly at higher frequencies because such frequencies are a little closer to the natural resonance of the atom. Although these differences amount to only a few percent, they can become important if the details of refraction and reflection are critically involved in the way the light returns to the observer. Then, as in the case of a rainbow, these small differences may spread white light into its constituent colors.

Transparent substances with a large smooth surface reflect part of the incident light in a fixed direction according to the familiar laws of reflection. Therefore extended plane surfaces of colorless substances (windowpanes, water surfaces) can produce mirror images. If such colorless substances are in the form of small grains, each grain being larger than the wavelength of light, the substances appear white, like clouds. The incident white light is partially reflected in many directions, depending on the orientation of the grain surfaces. The light that penetrates the grains is again partially reflected at the inside surfaces, and after several reflections and refractions it comes back to the eye of the observer from various directions. Since none of these processes discriminates against any color, the returning light will be white and diffuse. This explains the color of snow, of salt and sugar in small grains and of white pills and powders: all consist of small crystals of molecules with resonances only in the infrared and in the ultraviolet. The whiteness of paper has the same origin. Paper consists of an irregular weave of transparent fibers [*see illustrations on next page*]. The molecules of the fibers also have no resonances in the visible region. The fibers reflect and refract light in the same way as fine grains of salt or snow.

If the grains are smaller than the wavelength of light, there are not enough oscillators in the grain to establish ordinary reflection and refraction. The situation is then more as it is in a gas of independent molecules, and the substance looks bluish. One can see this on a dry day when a cloud disappears. What often happens is simply that the droplets become smaller and smaller by evaporation until the cloud appears blue. The blue color of cigarette smoke is also evidence that the particles are smaller than the wavelength of visible light. The color of the sky above our cities is largely determined by the way sunlight is scattered by particles of smoke or dust, some larger than the wavelength of light, some smaller. That is why the city sky is a pale mixture of white and blue—far from the deep, rich blue that prevails where the air is clear.

Although water is transparent because



REFLECTION OF LIGHT from the surface of a solid or liquid involves only the oscillators (electrons) located in a small, pillbox-shaped volume at the surface of the material. When light (I) impinges on a smooth surface, part of the light proceeds into the material as a refracted wave (R) and part is reflected toward the observer (P). The radiation that makes up the reflected wave originates in a thin layer whose thickness is about half the wavelength of the incident light. The oscillators whose radiation adds up coherently at P are contained in a flat cylinder whose top surface is about λd in area, where λ is the wavelength of the light and d is the distance from the surface to the observer. This area is called the first Fresnel zone. For a spherical surface of radius R the area of the first Fresnel zone is equal to $\pi\lambda R$, provided that the distance to the observer is large compared with R.

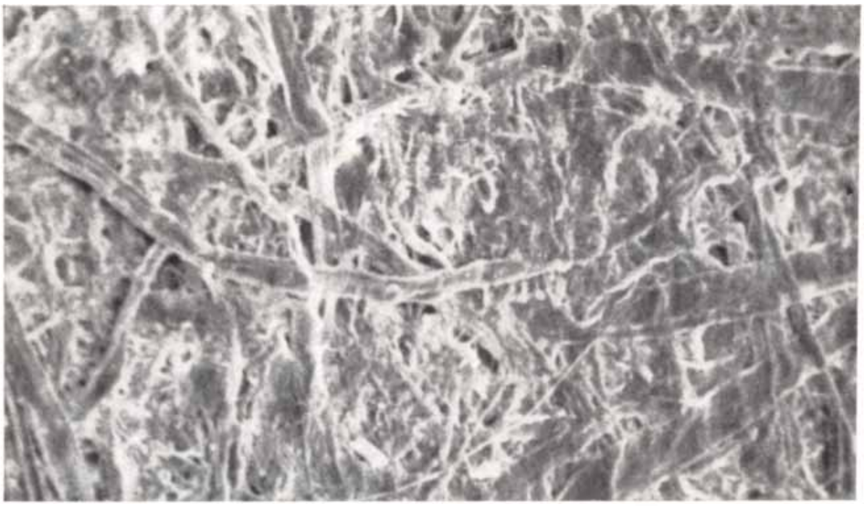
it has strong resonances only in the infrared and the ultraviolet, it does have a slight color of its own. This is not the wonderful deep blue one often sees on the surface of a lake or an ocean. That blue is the reflected color of the sky. The intrinsic color of water is a pale greenish blue that results from a weak absorption of red light. Because of its strong electric polarity the water molecule vibrates readily when it is exposed to infrared radiation. Indeed, its infrared resonances are so strong that they reach even into the visible red [*see top illustration on page 70*].

These resonances represent true absorptions of light because the energy of the light quantum absorbed is transformed into heat motion. The weak resonances in the visible red therefore cause a slight absorption of red light in water. Fifteen meters of water reduces red light to a quarter of its original intensity. Practically no red sunlight reaches a depth below 30 meters in the sea. At such depths everything looks green. Many deep-sea crustaceans are found to be red when they are raised to the surface. In their normal environment they appear black. The selection mechanisms of evolution could not distinguish between black and red under such conditions.

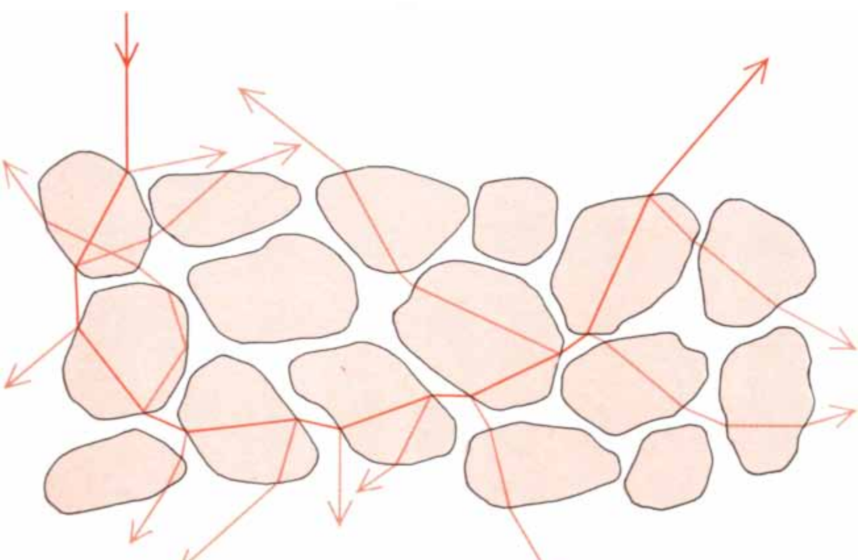
The greenish-blue color of water is different in kind from the blue color of the sky. It is a color produced by the preferential absorption of the red and not by the preferential reemission of the blue, as it is in the sky. One way to be convinced of this difference between air and water is to look at a white object under the surface of water: it looks bluish green. On the other hand, a snowy slope seen through many miles of air looks yellowish. In the first instance the red light was absorbed; in the second the blue light was scattered away.

Most of the colors we see around us are due to preferential absorption: the colors of leaves, flowers, birds, butterflies, rubies, emeralds and the whole gamut of paints and dyes. What accounts for the preferential absorption in such a diverse range of things and substances? Most atoms and molecules have resonances only in the infrared and the ultraviolet. In order to produce a resonance in the visible region the excitation energy must be between 1.5 and three electron volts. These are rather small values for electron excitations and large values for molecular vibrations. There are, however, atoms and molecules that do have excited states in that region. They are atoms with several electrons in incomplete shells and certain organic compounds: the dyestuffs. Such atoms can be excited by rearranging the electrons in the incomplete shell, which requires less energy than excitation to a higher shell. The dyestuffs are chain or ring molecules in which the electrons move freely along the chain or the ring. They are spread out, so to speak, over larger distances than electrons in ordinary atoms and molecules. The excited states in such a system are of lower energy than they are in atoms, because larger size gives rise to longer electron wavelengths, and this in turn is associated with lower frequency and thus lower excitation energy. Thousands of chemists have devoted their professional lives to the synthesis of organic molecules that have resonances in one part or another of the visible spectrum [*see illustration on opposite page*].

Although low-lying excited states give rise to resonance frequencies in the visible region, other conditions must be fulfilled before a molecule will serve as a dye. First, one must be sure that the light quantum is not simply reemitted after its absorption has lifted the molecule into the excited state. One wants the energy of the excited state to be transformed preferentially into heat motion. This will be the case if we deal with matter in



ORDINARY PAPER consists of a random mesh of translucent cellulose fibers. This 125-diameter magnification was made with a scanning electron microscope by Consolidated Papers, Inc. In such a micrograph the object appears to be tilted at an angle of 45 degrees.



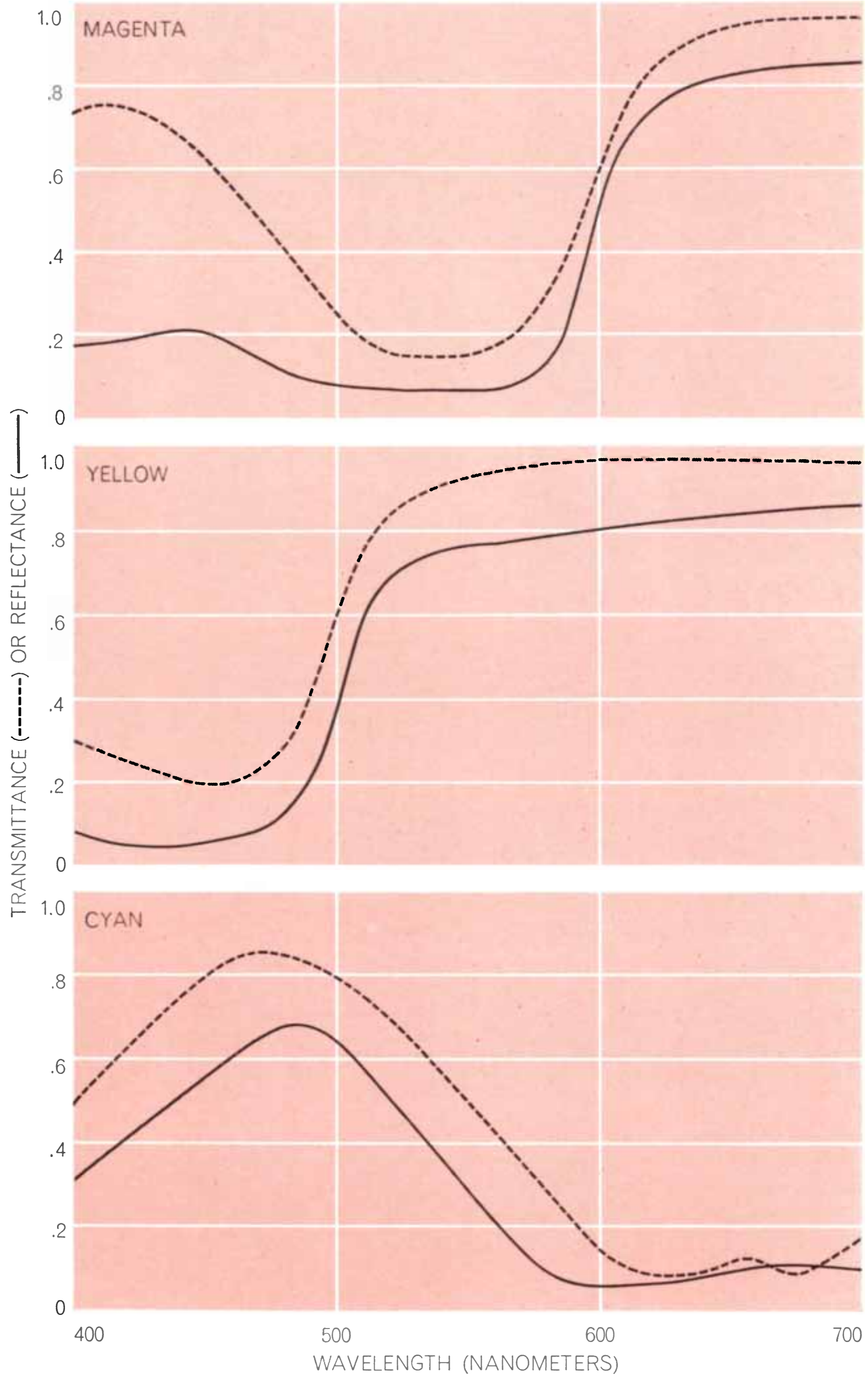
REFLECTION OF LIGHT FROM PAPER SURFACE involves many refractions and reflections as the rays of incident light perform a random walk through a mesh of translucent fibers, represented here in cross section. The multiple refractions of a single entering beam are traced in dark color; beams reflected from various surfaces are shown in light color.

bulk, liquid or solid. Under such circumstances reemission of light is very improbable. Second, the resonance frequencies must be spread over a broad interval. A dye with a narrow absorption band would reflect most wavelengths and thus look practically white. Here again matter in bulk contributes to the desired effect. In liquids and solids the energy levels of atoms or molecules are expanded into broad energy bands, with the result that resonances are spread over broad ranges of frequency. For example, a red dye absorbs light of all visible frequencies except the red. A green paint absorbs red and yellow as well as blue and violet. The absorption of a dye covers the visible spectrum with the exception of the actual color of the material. Some people may have wondered why a mixture of paint of all colors gives rise to a dirty black, although we are told that white is the sum of all colors. Colored paints function not by adding parts of the spectrum but by subtracting them. Hence a mixture of red, green and blue paints will absorb all wavelengths and look virtually black.

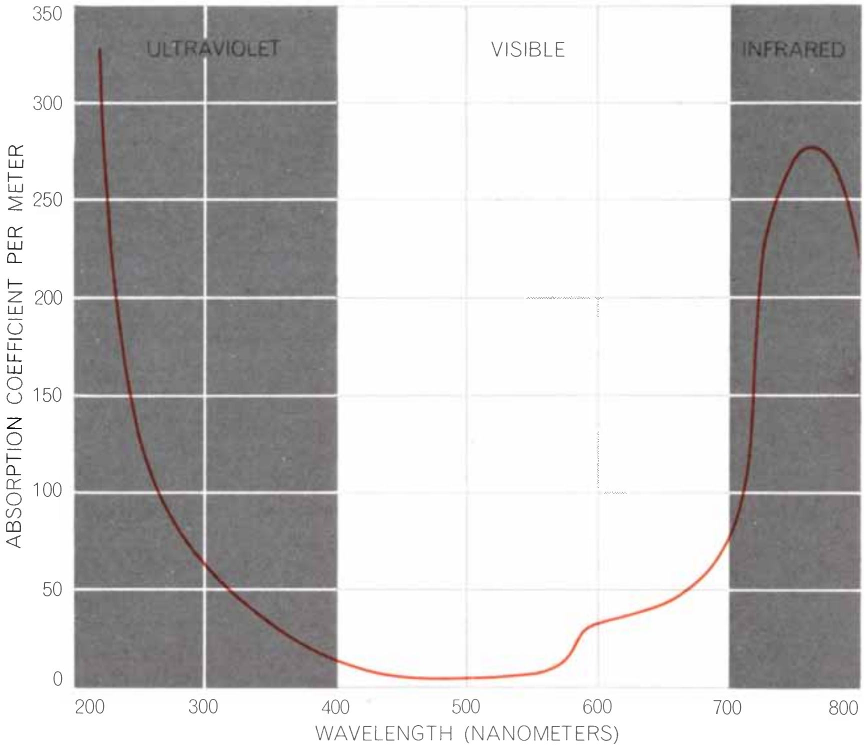
A simple and striking color effect is the one produced by a stained-glass window. The dyestuff is contained in the glass. When light falls on stained glass, it is partially reflected at the surface, just as it is by ordinary glass. Indeed, the reflection is a little stronger for those frequencies that are absorbed, because, as we saw earlier, the amplitude of vibration is larger when the frequency is in resonance with the system. This effect, however, is usually not very pronounced, since the main reflection comes from the oscillators with resonances in the ultraviolet, as it does in ordinary glass. The part of the light that penetrates the body of the glass—the refracted wave—is subjected to the absorbing effect of the dye. Accordingly only light of the frequency that is not absorbed will pass through the glass. That is why one obtains such impressive color effects when white light penetrates stained glass. The color of the glass is less strong when one looks at the side that is illuminated. The reflection from the surface is practically colorless; the principal color one sees is from light that has penetrated the glass and is reflected again by the second surface [*see bottom illustration on next page*].

A painted sheet of paper will serve as an example of ordinary painted objects. The paint causes the fibers of the paper to become impregnated with dye. When white light falls on paper, it is reflected and refracted many times before it comes back to our eyes. Whenever the light penetrates a fiber, the dye absorbs part of it: the fibers act as small pieces of stained glass. The best color effect is achieved when the reflecting power of the fiber is not too strong, so that most of the light enters the fiber. One remembers childhood experience with watercolors, which are most intense while the paper is still wet. The water reduces the difference in refraction between the fibers and the interstices, thereby reducing the reflection of the fiber surfaces.

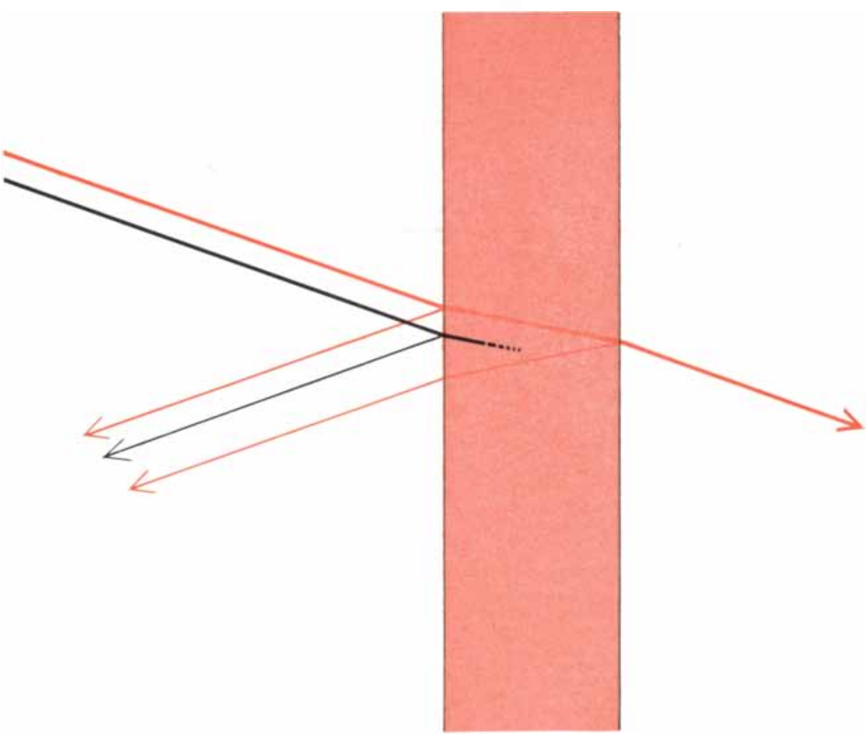
Glossy colored paper has a smooth surface. Its irregularities are small compared with the wavelength of light. The incident light is partially reflected without much preference for one color over another, but it is reflected by the smooth surface at a fixed angle according to the familiar laws of reflection. At any other



SPECTRAL CHARACTERISTICS of colored inks (*solid curves*) and of an optimum set of dyes for color film (*broken curves*) are plotted in these three panels. The inks and dyes are those represented in the illustration on page 62. There it can be seen that the dyes of color film can produce colors that are more highly saturated than those attainable with printing inks. The reason becomes clear in these curves: each of the color film dyes transmits more of the desired wavelengths than the corresponding printing ink is able to reflect.



LIGHT ABSORPTION BY WATER is negligible between 400 and 580 nanometers in the visible part of the spectrum. The absorption increases in the orange and red region and rises steeply in the near infrared. Absorption is also strong in the ultraviolet. The absorption is caused by resonances of the water molecule in response to various wavelengths.



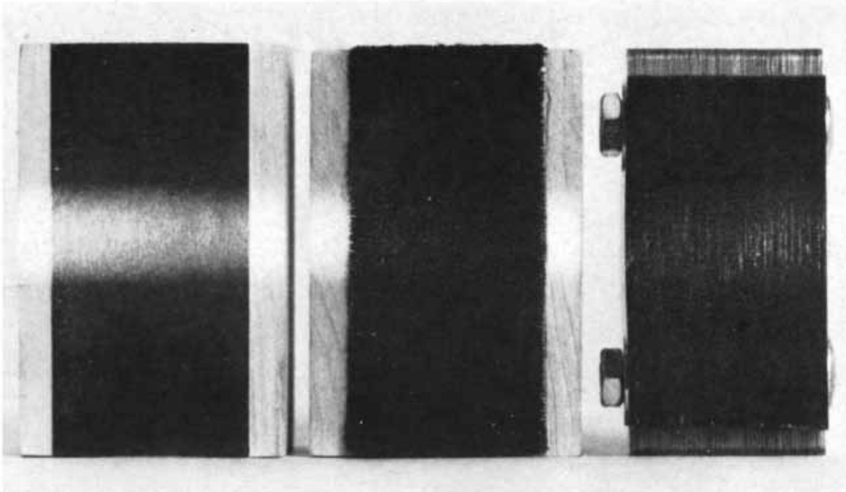
COLOR OF STAINED GLASS depends on which wavelengths the glass absorbs. Here it is assumed that the glass absorbs the shorter wavelengths so that primarily red light is transmitted. Thus blue light, represented here by black, enters the glass and is absorbed; it is also partially reflected. Red light is reflected from the rear surface as well as from the front, so that the total reflected light is predominantly red. Thus red stained glass looks red by reflected as well as by transmitted light; the transmitted color is purer, however.

angle most of the light that reaches the eye will have made several passages through the fibers before leaving the paper. That is why the color of the light is clear and deep: it is free of any uncolored direct reflection. Sometimes glossy paper demonstrates the fact that being in resonance implies larger amplitudes and therefore stronger reflection. One often notices an increased reflection of the deeply colored parts of a glossy picture, but only when the dye is deposited in the uppermost layer. Examine the colored illustrations in this article.

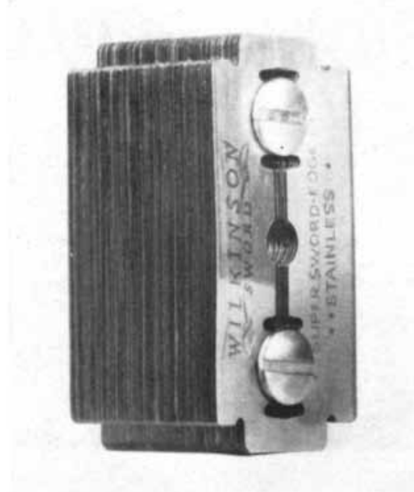
Objects are black when there is absorption for all visible frequencies. Well-known examples are graphite and tar. Black objects do not absorb all light that falls on them. There is always some reflection at the surface. Think of the reflection of the polished surface of a black shoe. A dull black surface reflects as strongly as a polished one but the reflected rays are distributed in all directions. A black surface with very low reflectivity can be produced by placing a few hundred razor blades in a stack. When the edges of the blades are viewed end on, they appear to be nearly dead black even though they are highly polished [*see illustrations on opposite page*]. The explanation is that light is trapped between the closely spaced edges and is absorbed after being reflected many times.

The most beautiful colors of all—the colors of plants, trees and flowers—are based on the same principle of preferential absorption. The cells of plants are filled with dyes: chlorophyll in green leaves and blades of grass, other dyestuffs in the petals of flowers. White light that falls on plants is reflected and refracted by the cells; a large part of the light enters the cells, in the same way it does the fibers of paper. When it returns to the eye, all the colors but one or two are strongly reduced by absorption. Only green light escapes from chlorophyll-containing cells, only red light from the petals of red flowers.

We now turn to the visual appearance of metals. A metal is characterized by the fact that within the confines of the material there are many electrons—the conduction electrons—extending over many atomic diameters. These electrons are most important for the optical properties of metals. There is one, two or sometimes three electrons per atom among the conduction electrons. The rest of the atomic electrons remain bound to the atoms. The conduction electrons can be regarded as an electron gas that penetrates the crystal lattice



REFLECTIVITY OF "BLACK" OBJECTS can vary considerably. The light-absorption capability of three black surfaces is demonstrated above by allowing a bright, uniform band of light to fall on a piece of paper coated with black ink (*left*), a piece of black velvet (*middle*) and the ends of a tightly bolted stack of razor blades (*right*). Even though the edges of the razor blades are highly polished, they tend to absorb light rather than reflect it.



RAZOR-BLADE LIGHT TRAP consists of some two hundred blades bolted together. Light that enters the wedges between adjacent blades is reflected so many times that most of it is absorbed before it can escape.

without much hindrance. The reason for this quasi-free motion lies in the wave nature of the electron. Although it is true that an electron wave is scattered by each of the metal atoms, the regular arrangement of atoms in the lattice makes the scattered waves interfere in a definite way: the waves all add up to one undisturbed wave in the forward direction. The corresponding electron motion is therefore the motion of a free particle. This is a phenomenon closely related to the formation of a refracted wave when light penetrates a crystal.

The motion of the conduction electrons is not completely free, however. Thermal agitation of the crystal lattice and other lattice imperfections produce some scattering away from the main electron wave. This is closely analogous to the weak scattering of the refracted light wave in a crystal. The effect can be expressed as a kind of friction of the conduction electrons. It is the cause of the electrical resistance in metals. In the reaction of electrons to visible light, however, friction does not play an important role; we are allowed to consider the electrons as freely moving.

What is the behavior of a free electron under the influence of light? It performs vibrations of the same frequency as the frequency of the driving force but of opposite phase. When the force is moving in one direction, the electron moves in the other one. It is the same kind of movement an oscillator performs when the driving frequency is much higher than its resonance frequency. A free electron in plain sunlight performs vibrations with an amplitude about 10 times larger than the amplitude of electrons in water and in crystals, or several times 10^{-17} meter.

What happens when light impinges on a metallic surface? The answer is, very much the same as happens when light strikes the surface of a liquid or a crystal, but there is one important difference. Since the resonance frequencies of a liquid or a crystal are higher than the frequency of light, they vibrate in phase with the light. In a metal, however, the electrons vibrate in *opposite* phase. Under these conditions a refracted light wave cannot be propagated if the density of electrons and the amplitude of their vibration is above a certain limit. The limit can be expressed in terms of the "plasma frequency" ω_p, which is given by the equation $\omega_p = (Ne^2/m)^{\frac{1}{2}}$, where N is the number of electrons per cubic centimeter and m is the electron mass. This frequency usually is in the ultraviolet. Whenever the light frequency is less than ω_p, as it always is for visible light, no refracted wave can develop in the medium; there are too many electrons inside moving in phase opposite to the light.

Since no light energy can propagate into the material, all energy of the incoming light must go into the reflected wave. Just as with water or glass, the reflected light wave is produced in a thin layer at the surface of the metal, a layer no thicker than the wavelength of the light. A more exact calculation shows that in a metal this thickness is equal to the wavelength corresponding to the plasma frequency divided by 2π. This value is less than 10^{-7} meter. Unlike the wave reflected from water and glass, however, the wave reflected from a metal surface has almost the full intensity of the incoming wave, apart from small energy losses due to the friction of the vibrating electrons in the surface. This is why "white" metals such as silver and aluminum are so shiny: they reflect almost all visible light regardless of its frequency. Smooth surfaces of these metals therefore are ideal mirrors.

In colored metals such as copper or gold there are additional losses apart from the electron friction. These losses come from absorption by electrons other than the conduction electrons. Each atom in a metal is surrounded by shells of those electrons that remain with the atoms after the conduction electrons have detached themselves and formed the gas of free electrons. The resonance frequencies of the remaining electrons are usually in the ultraviolet and thus do not contribute to any color. In copper and gold, however, the bound electrons are part of an incomplete shell and do have resonances in the blue-violet that lead to absorption. As a result copper and gold have a reddish-yellow appearance.

Many color phenomena have not been treated here: the color of thin films, of fluorescent materials, of light emitted by flames, of electric discharges as produced in neon tubes and many others. We have taken up only the most common features of colored objects in order to provide some insight into the optical processes that occur on the surface of things when they are illuminated by light and seen by our eyes.

How Light Is Analyzed

By separating light into its constituents the spectroscopist learns what kinds of matter are in the source. With modern techniques such as Fourier spectroscopy highly informative spectra can be obtained

by Pierre Connes

The efforts of ancient philosophers to analyze matter began with an intuitive but basically sound concept: Matter can be separated into its elementary constituents. The concept that light might be analyzed was much less obvious. Men looked at rainbows for millenniums without devising any kind of rational explanation for them. Even when René Descartes noted that the colors of a rainbow were like those produced by a prism, he was giving an analogy and not an explanation.

It was Isaac Newton who formulated the basic concept: Light from ordinary sources is complex. By "complex" he meant that such light can be analyzed into colors and that conversely the colors can be used to synthesize light. An optician should be allowed to rank this concept with Newton's discovery of gravitation.

Here I shall describe the rise of instrumental spectroscopy, which is the technique of analyzing light. From other articles in this issue it will be evident to the reader that much of the information we get about the physical world is carried by light and that analyzing light is highly rewarding. Spectroscopy is the first tool of astrophysics; the analysis of the light from planets, stars and galaxies is the means of determining what they are made of. Spectroscopy thus provides the best evidence for our belief in the homogeneity of the universe. At the same time spectroscopic analysis is used in every chemical plant to follow the progress of reactions.

In short, the complexity of light is today an exceptionally valuable source of information. To Newton and his contemporaries, however, the complexity of light was only a nuisance. Newton had been led to study the subject of light by the need to improve optical instruments. The images produced by lenses were then extremely poor. The worst defect was the persistence of strange colored edges that nobody was able to explain. It was clear that the colored edges arose within the instruments; indeed, the colors were to some extent responsible for the skepticism that greeted many of the early discoveries made with telescopes and microscopes. Newton provided the explanation and, believing (wrongly) the defect could not be cured, he invented the reflecting telescope, which was achromatic, or free of color.

By the 18th century the technique of building optical instruments had been greatly improved. Achromatic lenses were developed for telescopes. The technique of photometry, by which the intensity of light is measured, had grown out of the work of the French physicist and mathematician Pierre Bouguer, who measured and compared the intensity of the light from the sun and the moon. As a result of these developments all the tools needed for the evolution of spectroscopy were in hand. Strangely enough, however, no progress was made beyond Newton's crude division of visible light into seven colors. Apparently nobody conceived of a need to improve the analysis of light.

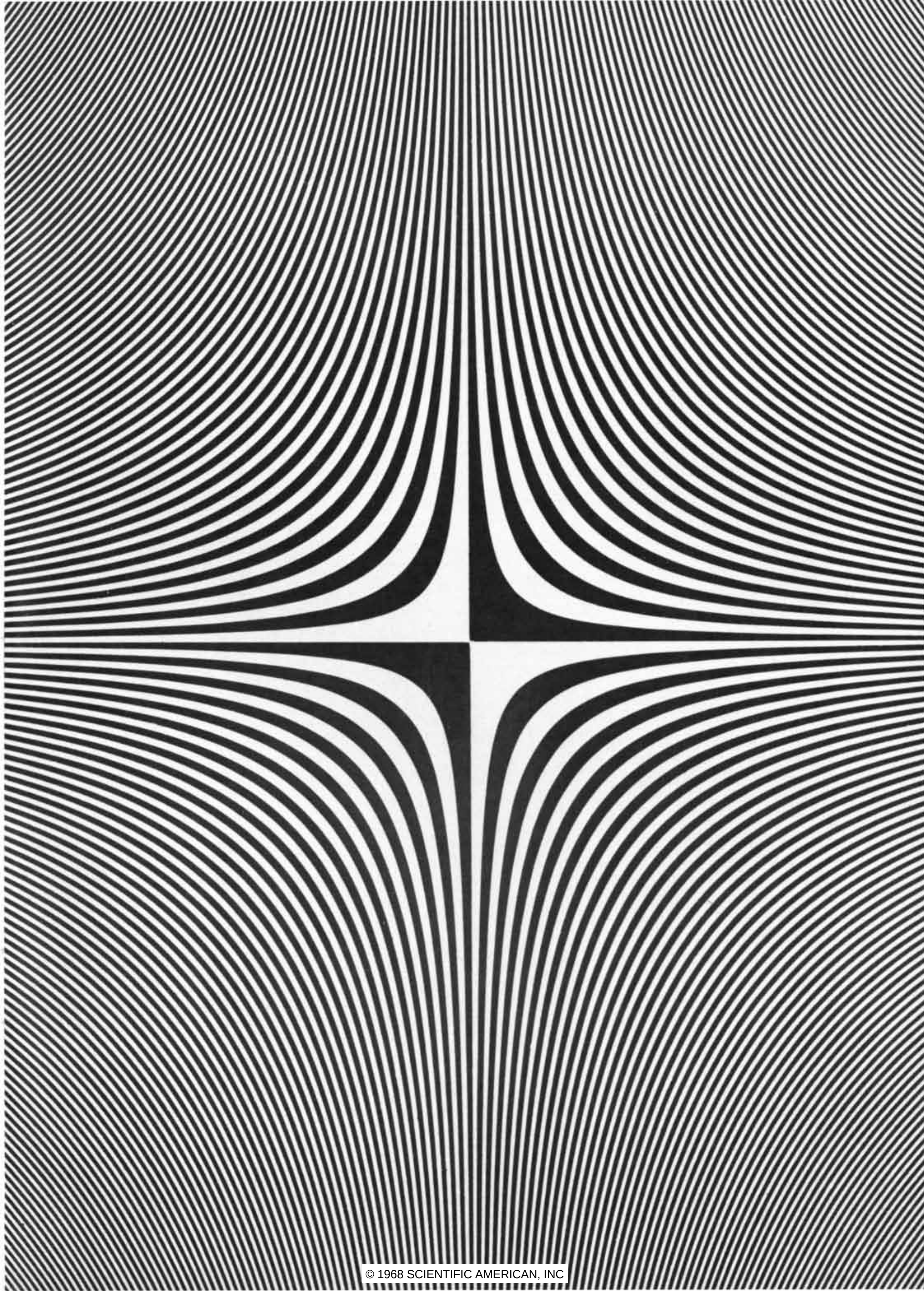
The change in outlook came in the first year of the 19th century, when the English astronomer Sir William Herschel became interested in the distribution of radiant heat according to color in light from the sun. In 1800 he investigated the matter by placing several thermometers across a solar spectrum that had been dispersed by a prism in the same way that Newton had dispersed sunlight. In modern terms Herschel built the first spectrometer equipped with a thermal receiver. (It is noteworthy that thermometers, which were crude but adequate for the experiment, had been available for more than a century.)

With this experiment Herschel made the unexpected discovery of invisible but heat-carrying radiation beyond the red end of the visible spectrum—in the region that has since been named the infrared. Obviously it was worth looking at the region beyond the other end of the visible spectrum, but the amount of heat carried by solar ultraviolet radiation happened to be too weak for Herschel's thermometer. He had nonetheless shown the way, and only a year later Johann Wilhelm Ritter of Germany and William Hyde Wollaston of England did detect ultraviolet rays by virtue of the fact that they blackened crystals of silver chloride just as well as visible light did. Eventually experiments showed that both infrared and ultraviolet rays could also be refracted, reflected and polarized.

What was then clearly needed was a finer analysis; today it would be called an increase in resolving power. From the early 19th century to the present the improvement of resolving power has been the first aim of spectroscopists. As we shall see, each large advance has invariably paid off in new discoveries.

The first step was taken by Joseph Fraunhofer, a highly skilled Bavarian optician, between 1815 and 1825. By a simple but adept use of lenses and slits he was able to produce a "pure" solar spectrum in which light from a given col-

GIRARD GRID on the opposite page was devised recently by André Girard of the French Office of Aeronautical Research to analyze light by a technique that is explained in the bottom illustration on page 81. A pair of grids replace the input and output slits of a grating spectrometer and create a high-luminosity means of directly scanning a spectrum of light.



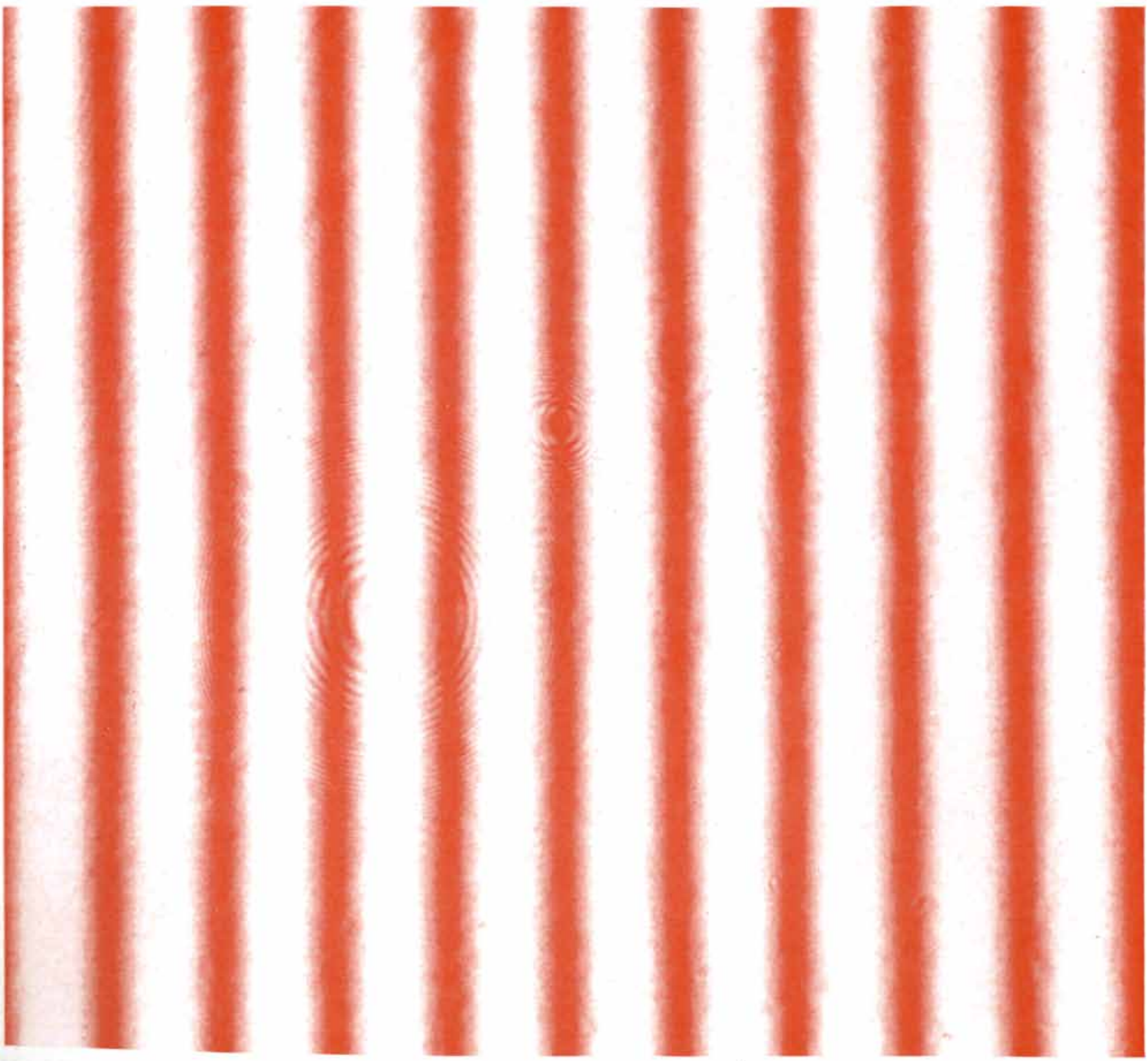
or did not fade gradually into other colors. The spectrum showed many sharp dark lines that ever since have been called Fraunhofer lines.

Fraunhofer also took the second step toward finer resolving power. He built a new tool, the diffraction grating, which far exceeded prisms in its ability to disperse light [*see top illustration on page 77*]. The invention of the grating was made possible only by the upheaval that had taken place in optics. Mostly as a consequence of the work of Augustin Jean Fresnel of France, the Newton emission theory of light was being replaced by the wave theory originally put forward by Newton's contemporary Christiaan Huygens.

This is not the place to discuss light theories; indeed, so far we have seen the analysis of light progressing quite independently of theory. The working of a diffraction grating, however, can only be understood in the context of wave theory. Moreover, Fresnel, in bringing about the acceptance of wave theory, had substituted for the subjective concept of color a precisely measurable quantity: wavelength. (His own measurements of wavelength were not accurate because he worked only with ordinary white light that had been more or less crudely filtered.)

Fraunhofer accomplished two important things with his diffraction grating. First, he was able to isolate within the light emitted by a sodium flame a pair of lines that appeared to be monochromatic, meaning that they represented light that could not be decomposed further by increasing the dispersion. (This result was only apparent; the resolving power was still insufficient to break the sodium line down further.) Second, Fraunhofer made the first accurate measurements of wavelength, obtaining figures that do not differ from modern ones by more than a tenth of 1 percent.

It took until the middle of the 19th century to achieve a complete explanation of the dark lines in the spectra obtained by Fraunhofer. The significance of the achievement was that it demonstrated that the lines corresponded to def-



INTERFERENCE FRINGES were photographed as they appeared in an interferometer of the Michelson type illuminated by light from a helium-neon laser at a wavelength of 6,328 angstroms, equivalent to the color in which the photograph is printed. The small ring patterns are attributable to the laser. Fringes yield information about wavelength of the light and thus about the source.

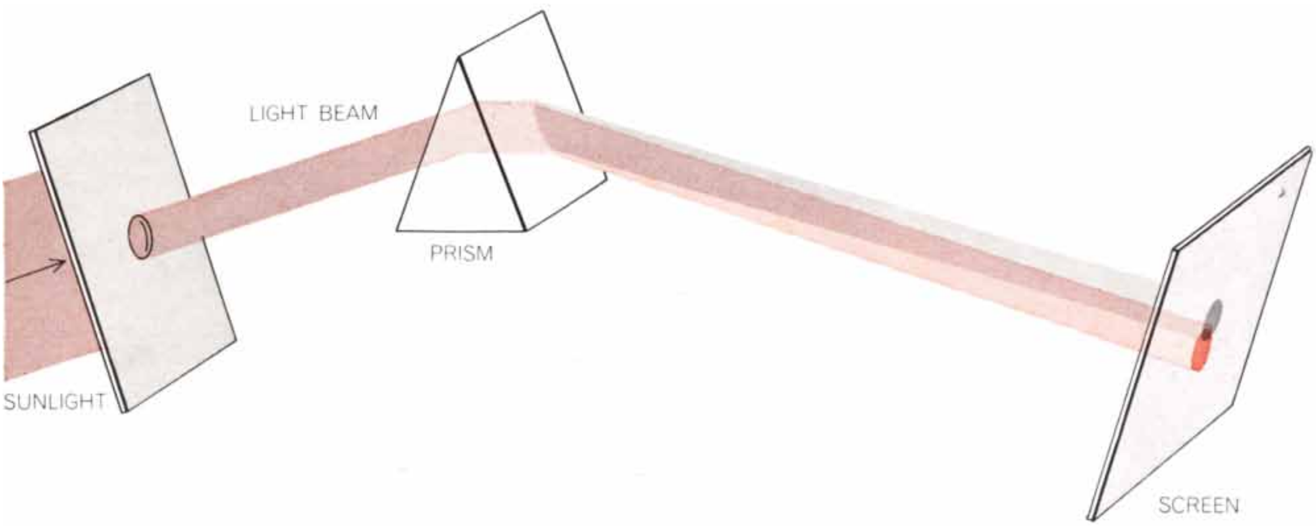
inite elements in the source of light. Each element gave rise to a characteristic pattern of lines—a fingerprint, as it were.

When this relation became clear, the missing incentive to develop spectroscopy was at last found. Now in the laboratory the spectroscope could be used instead of tedious chemical analysis to detect elements in trace amounts and to provide a quantitative estimate of abundance. In astronomy the spectroscope could be applied to solve the problem that had been declared unsolvable only a few years earlier by the philosopher Auguste Comte: the identification of the matter in stars.

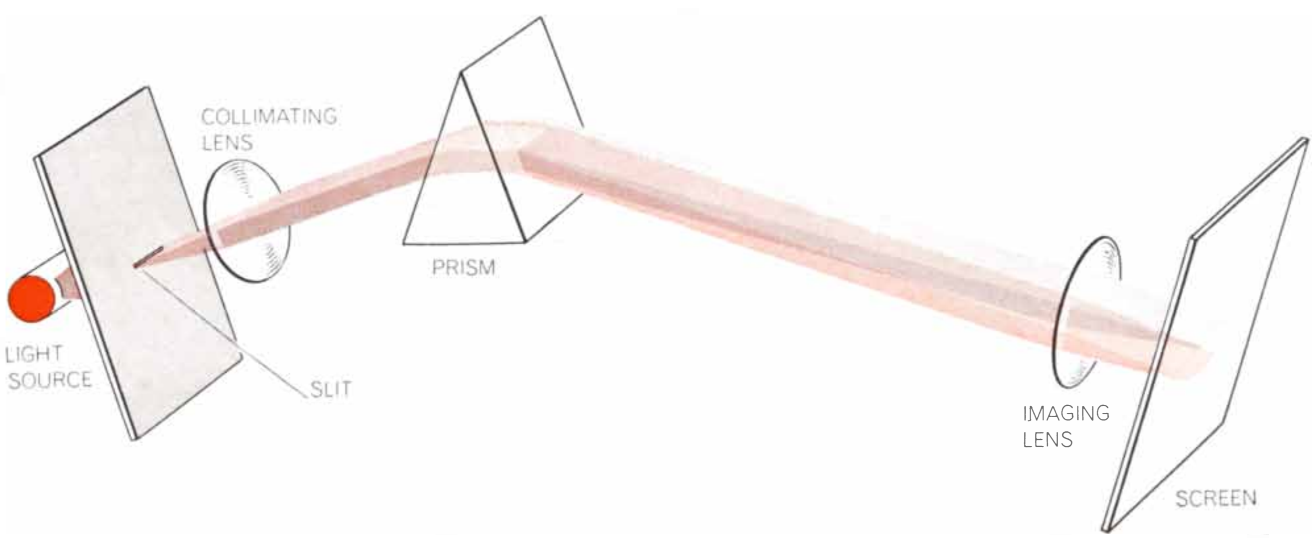
It is possible to mention only a few of the workers who contributed thereafter to instrumental spectroscopy. In Germany, Robert Bunsen and Gustav Kirchhoff brought the prism spectroscope to a high degree of perfection. As methods of casting and polishing glass improved, however, it became clear that resolving power could not be increased indefinitely by merely improving existing techniques. Lord Rayleigh showed that the limitation was a fundamental one: Because of diffraction—the spreading of a beam that takes place when light goes through a finite aperture—even a perfect prism cannot resolve two lines whose difference in wavelength is less than a certain amount. (This difference is now known as the Rayleigh limit.)

The resolving power—defined as the ratio of the mean wavelength of two lines to the minimum resolvable difference—is proportional to the total thickness of the glass. One cannot increase resolving power indefinitely by using thicker glass, however, because any substance that disperses light also absorbs it. Beyond a certain thickness nothing is to be gained.

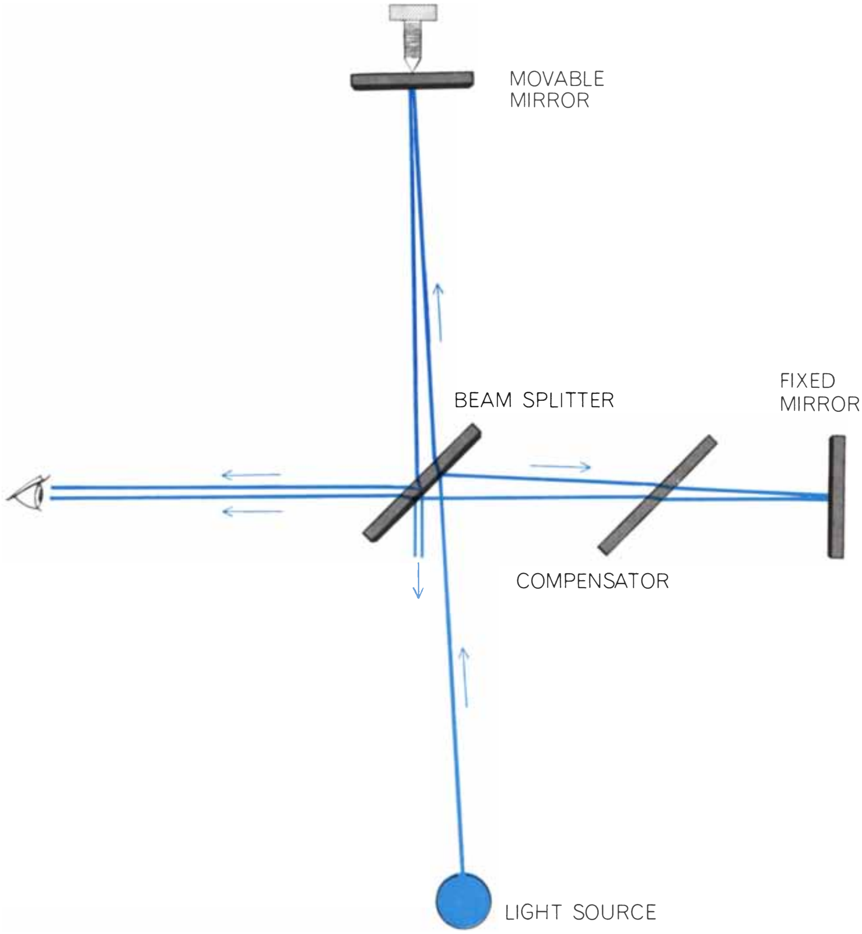
The resolving power of gratings is also related to their size, which in principle can be increased without limit. Ruling a large grating is the most difficult mechanical operation known, however, and progress has been very slow. One of the most notable contributors was Anders Angström, a Swedish physicist who made such remarkably accurate



FIRST STEP in analyzing light was made by Isaac Newton in 1666. Through a small hole in a window shutter he admitted a beam of sunlight to a darkened room and directed the beam through a prism. Because light of different colors is refracted, or bent, at different angles in passing through a prism, the constituent colors of the sunlight appeared like a rainbow on the wall opposite the window. Newton then used another prism to reunite the colors. With these experiments he demonstrated the composition of white light.



SHARPER SEPARATION of the components of white light was achieved early in the 19th century by the Bavarian optician Joseph Fraunhofer. He passed light through a slit. A collimating lens made the light parallel and directed it into a prism. Each color emerged from the prism in a different direction. A second lens converted the pattern into distinctly separated lines on the screen.



MICHELSON INTERFEROMETER, devised by A. A. Michelson of the U.S., split a beam of light into two beams with a half-reflecting glass plate (*center*). One beam went on to a movable mirror and the other one was deflected 90 degrees to a fixed mirror. The two beams were reconverged on the glass plate, producing constructive or destructive interference, visible as bright or dark fringes, as the movable mirror was adjusted. When white light is used, a compensator plate equalizes the lengths of the paths in glass of the two light beams.

measurements of wavelength that his name was given to a unit of length used for evaluating wavelengths. (One angstrom is a ten-millionth of a millimeter.) Toward the end of the century Henry Rowland of Johns Hopkins University produced gratings, and with them spectra, that nobody was able to duplicate during his lifetime—an achievement that is rare in the experimental sciences.

The beginning of the modern period is clearly marked by the work of A. A. Michelson of the U.S. Michelson was dissatisfied with the limitations of gratings and devised a radically different method of spectroscopy. His vehicle was an optical instrument that he invented in 1880 and named the interferometer. For this instrument he received the seventh Nobel prize in physics and the first Nobel prize to be awarded to an American. (Among the many uses Michelson found for his versatile tool was the ether-drift experiment that established his reputation with the general public. The experiment was designed to determine the velocity of the earth through the "ether" that many scholars, believing electromagnetic radiation could not be transmitted through a vacuum, thought filled the voids in the universe. The experiment, which involved measuring the speed of light, ultimately showed that there is no ether.)

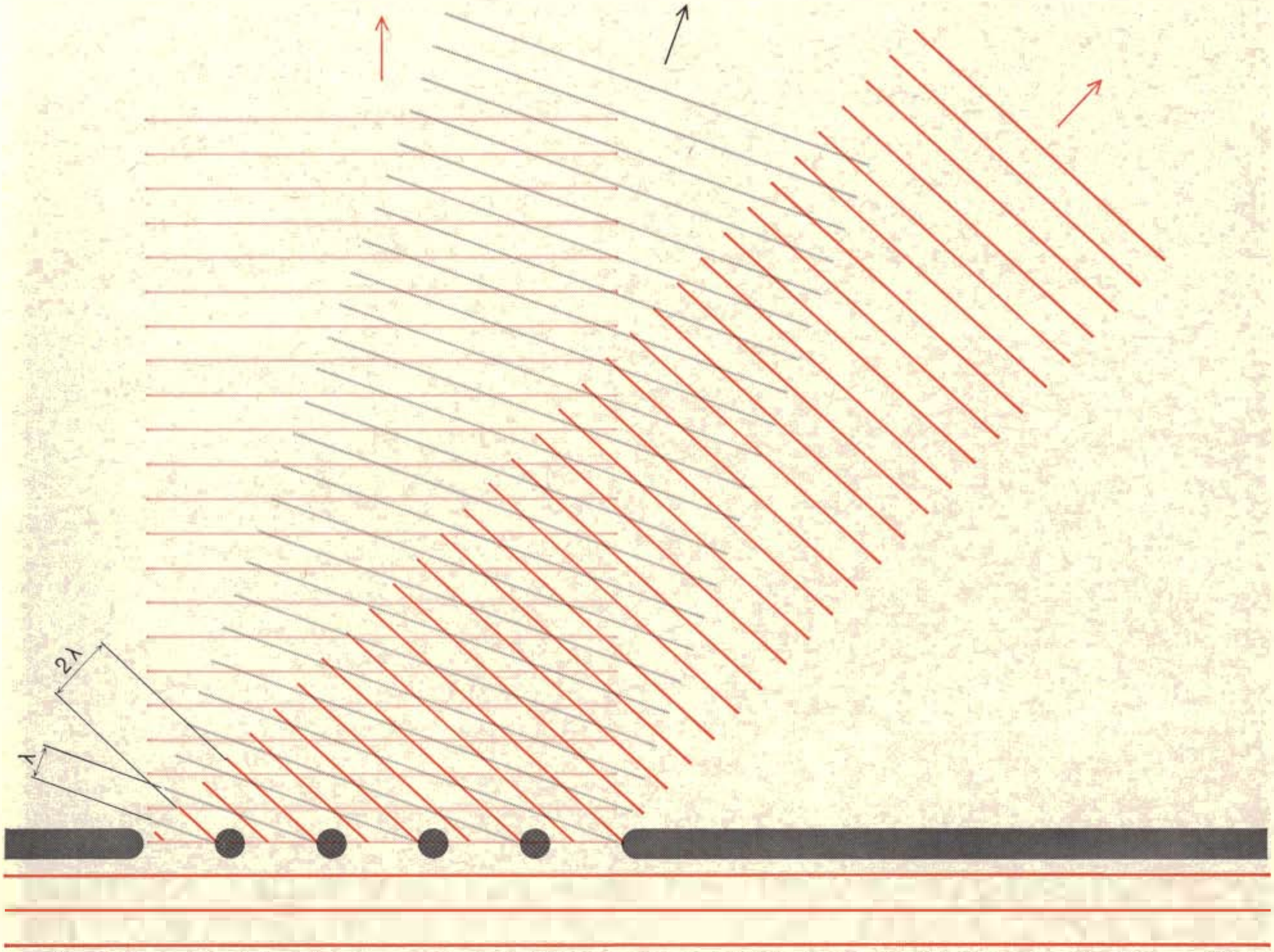
A Michelson interferometer works quite differently from a prism or a grating. The role of a prism or a grating is to disperse light, that is, to separate the different spectral elements into different directions so that they can be individually measured. Michelson reasoned that such spatial separation is not basic to spectroscopy and can be dispensed with. The interferometer makes no use of dispersion. In Michelson's interferometer light is split into two beams by a half-reflecting glass plate, follows two paths of unequal length and is recombined on the beam-splitting plate [*see illustration at left*]. The light waves of the two beams interfere with each other. If the two component beams are in phase, or in step, the recombined beam is bright; if they are out of phase, the recombined beam is dark. The two situations are respectively termed constructive and destructive interference. If the difference in the length of the two paths varies from one part of the beam to another, there will be constructive interference in some places and destructive interference in others. To the observer the result appears as the series of bright and dark lines called interference fringes. The spacing between fringes is proportional to the wavelength of light.

A recording of the intensity output of the interferometer while the path difference is varied in a uniform manner is called an interferogram. It is utterly unlike a direct recording of the source spectrum. The spectrum can be reconstructed from the interferogram, however, by applying the mathematical operation known as the Fourier transform. (Baron Jean Baptiste Joseph Fourier, a French mathematician of the early 19th century, applied his findings to several physical problems but never dreamed about their possible bearing on spectroscopy.) The interferogram can be said to contain all the needed information about the spectrum in a coded form.

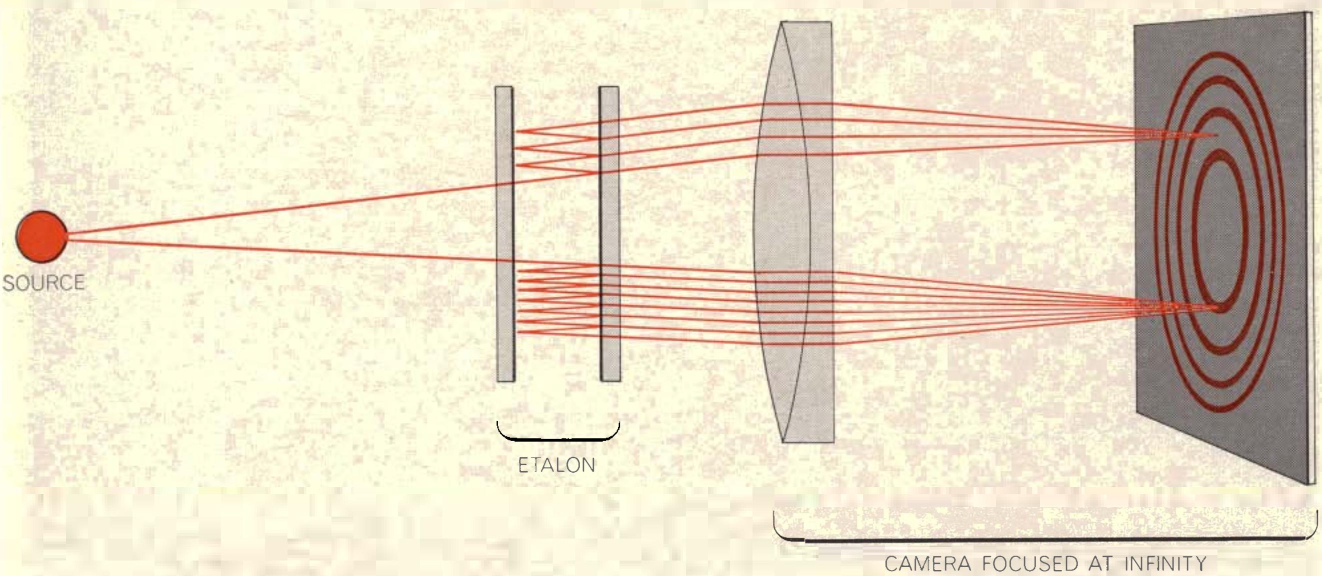
The extreme elegance of Michelson's method arises from the fact that resolving power is no longer related to the path length within an absorbing medium or to the width of the ruled surface of a grating. It is purely a function of the path difference between the two beams. The path difference can be increased almost without limit, not only in theory but also in practice.

Today we can record interference fringes. Michelson, however, had to rely on his eyes. Moreover, performing a Fourier transform is easier said than done: the interferogram is an experimentally determined curve and does not fit any simple analytical formula. The decoding can be done by numerical computation. The basic rules are simple and the whole process can be broken down into elementary arithmetic operations, but their number can be enormous if the resolving power is high and the spectral range is an extended one.

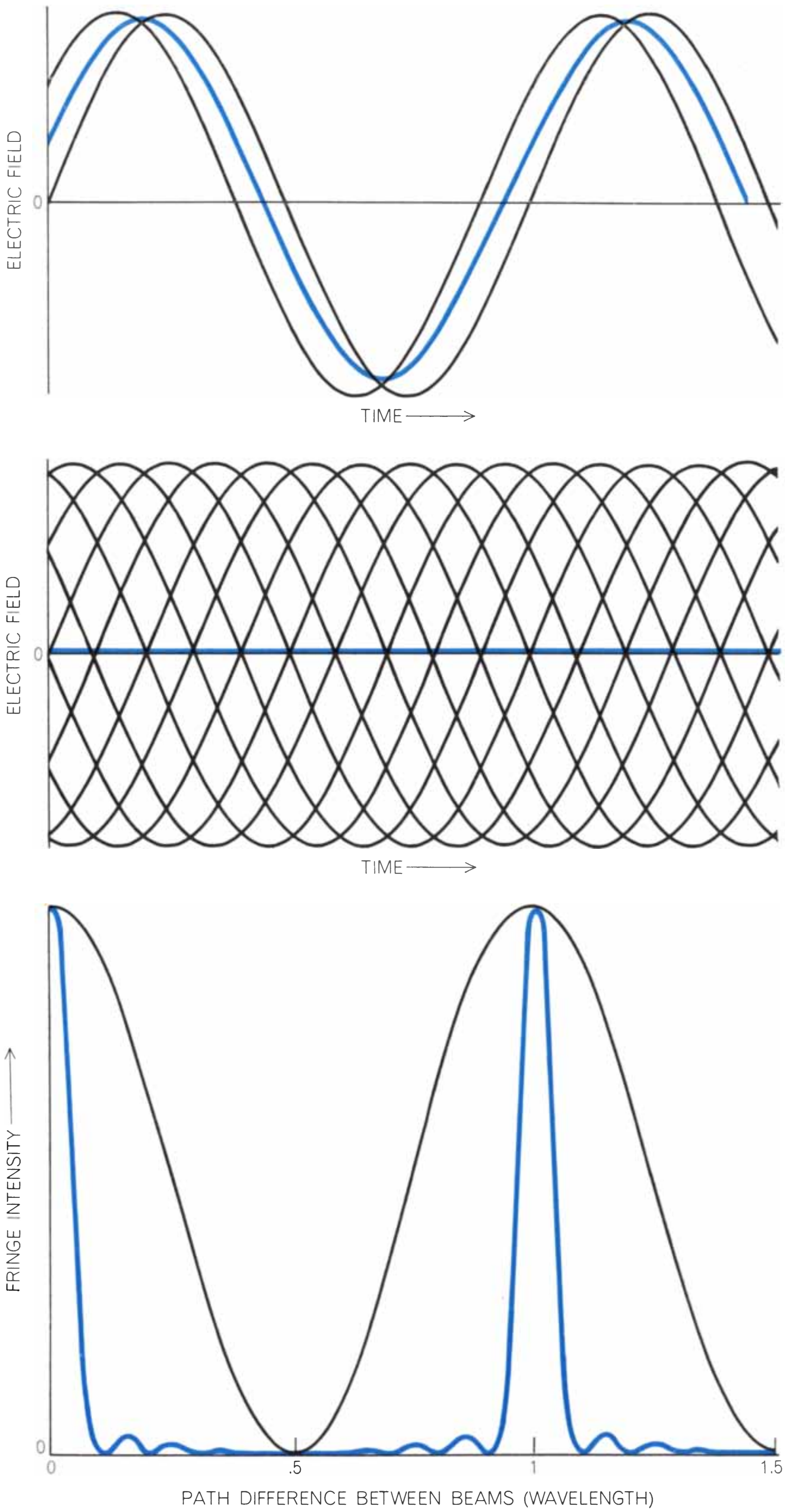
Because of these difficulties Michelson did not attempt to use his method in the general case, that is, for extended, complex and unknown spectra. He restricted himself to the study of just one apparently monochromatic line. The curve he plotted was not the interfero-



DIFFRACTION GRATING devised by Fraunhofer consisted of many fine, parallel wires. Four wires are shown here in cross section. Part of the light travels straight through (*light color*). For each wavelength, some light will be deflected in each of several other directions. The angle through which it is deflected is determined by the requirement that the light through each opening should travel an integral number of wavelengths farther than light through an adjacent opening. Here a first-order beam (*gray*) and a second-order beam (*dark color*) are shown. Since the angle depends on the wavelength, the colors of the light are separated.



FABRY-PEROT INTERFEROMETER was invented in 1897 by the French opticians Charles Fabry and Alfred Perot. It consists of two highly reflecting parallel plates called an etalon. When light waves reflected between the plates interfere destructively (*top*), canceling each other out, darkness appears on the screen. When the waves interfere constructively (*bottom*), reinforcing each other, the point of focus is bright. The result is a ring pattern such as the one on the cover of this issue. Unlike the Michelson interferometer, in which two beams interfere, the Fabry-Perot interferometer combines a large number of parallel beams of decreasing intensity.



APPEARANCE OF FRINGES is compared for three devices. If in a two-beam interferometer two beams of equal amplitude are combined after paths differing in length by a tenth of the wavelength (*top*), the resulting amplitude (*color*) is nearly the same as if the two paths had been the same length. If in a multiple-beam device 10 equal-amplitude waves are each delayed a tenth of a wavelength from the preceding one (*middle*), the resulting wave (*color*) has zero amplitude. At bottom is the intensity resulting when two beams (*black*) or 10 beams (*color*) are interfered as a function of the path difference between successive beams. Multiple-beam devices, such as a Fabry-Perot interferometer, produce the sharpest fringes.

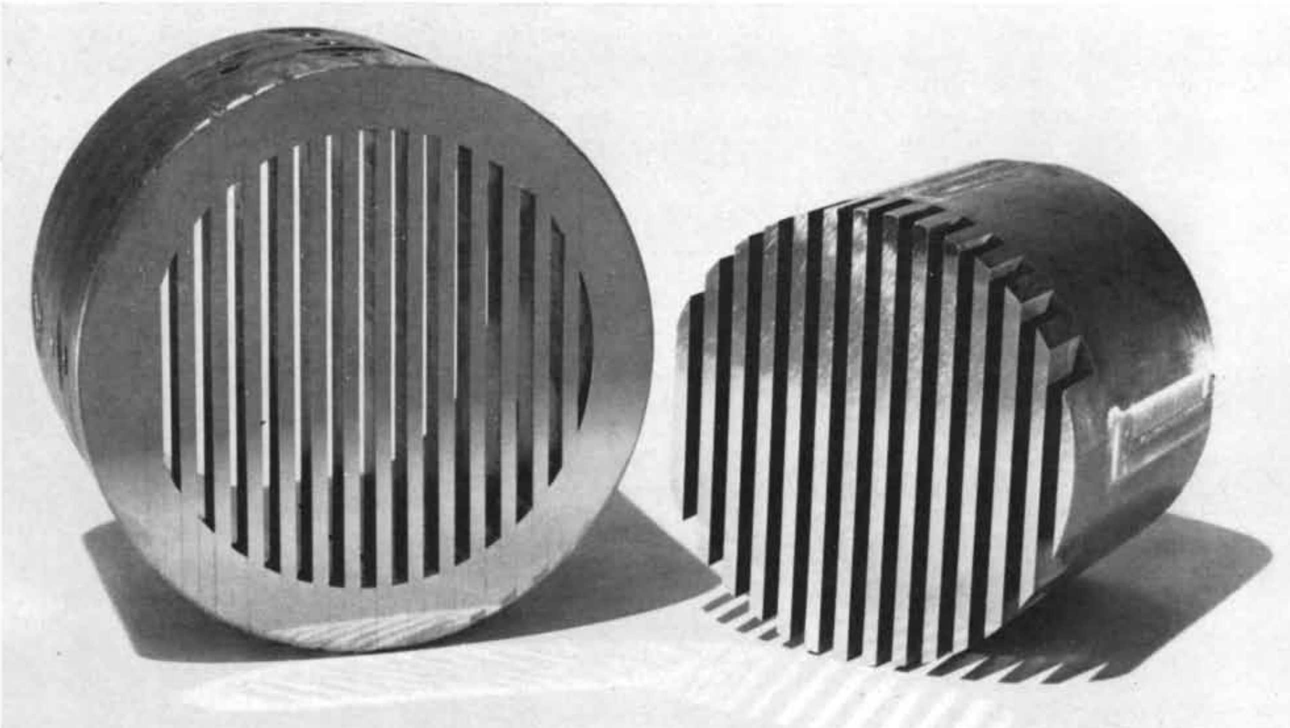
gram itself but the fringe-visibility curve, which is a smoothed-out version of the interferogram. The curve enabled him to discriminate among certain assumed spectra, but he could not unambiguously define the true spectral distributions. As a result his computed spectra show errors when they are checked with modern results.

Michelson's errors, however, are trivial compared with the importance of the discoveries he made. One was that lines believed to be monochromatic in actuality had several different components. This splitting is called the hyperfine structure of optical lines, and it yields information about the structure of atomic nuclei. Second, Michelson showed that a line that has been split as much as possible exhibits a continuous distribution of frequency, or energy. A "monochromatic" line thus has to be regarded as a theoretical concept with no physical existence, although today lasers come closer than any other source of light to generating such lines.

The interferometer could also be used to measure the wavelength of sharp spectral lines. This part of Michelson's work ultimately led to the adoption (in 1960) of an optical line as the primary standard of length. The reason is simply that wavelengths can now be measured more accurately than the length of any material body.

Another form of interferometer was invented in 1897 and applied to spectroscopy by the French optician Charles Fabry and his collaborator Alfred Perot. It is extremely simple—just two plane-parallel plates with highly reflecting surfaces [*see bottom illustration on preceding page*]. The Michelson type of interferometer has two equal beams; the Fabry-Perot interferometer has an infinite number with decreasing intensity. The fringe pattern of a Fabry-Perot interferometer is quite different from one generated by a Michelson interferometer, and it makes possible a direct recording of the spectrum. A Fourier transform of the experimental data is not needed, and there is no ambiguity of interpretation.

For these reasons the Fabry-Perot interferometer was widely taken up for high-resolution spectroscopy. The Michelson fringe-visibility method, although it still holds a place of honor in all textbooks, is used in only a few cases. Nonetheless, the Fabry-Perot arrangement does have limitations. Its very simplicity makes it impossible for it to approximate theoretical performance. The two surfaces have to be polished



LAMELLAR GRATING devised by John D. Strong of the University of Massachusetts consists of two sets of strip mirrors that can be moved with respect to each other. Here the two sets are shown separately. When they are assembled, they create an interferometer that is like Michelson's in producing only two beams but differs from a Michelson interferometer in requiring no beam splitter.

glass or quartz, and even when they are made with all possible care, they show small residual ripples. The reflecting surfaces are coated with evaporated layers of metals or dielectrics that cannot be made perfectly uniform. Finally, the plates and the spacers that are supposed to keep them parallel are subject to flexion and thermal expansion.

The best the present state of the art can provide is an accuracy of the order of a hundredth of a visible-light wavelength. This means in turn that at best the peaks cannot be made sharper than a hundredth of their spacing. The spectrum to be studied cannot then contain more than about 50 separate lines, and even this is a highly optimistic figure. No order-of-magnitude improvements are in sight.

We now have to introduce a few modern concepts that dominate the recent evolution of spectroscopy. Direct recording of spectra with photomultipliers and photoconductive or thermal receivers has come into play. Spectra on photographic plates are scanned by densitometers. Electronic amplifiers can expand traces from weak lines without limit—one just has to turn a knob! It soon becomes obvious, however, that mere amplification is useless. When the spectral curve is sufficiently blown up, it always shows the meaningless fluctuations called noise. The important consideration thus becomes signal-to-noise ratio; it is the one basic limitation to the accuracy of photometric measurements.

Signal-to-noise ratio depends on several factors. The first is the monochromatic brightness of the source. Even when the source is a terrestrial one, this factor is not completely under the spectroscopist's control. For instance, putting more electric power into the gaseous-discharge sources used for studying atomic emission spectra broadens their emission lines, which cannot be tolerated.

The second factor is the "receiver noise equivalent power": the light power that, if it impinged on the receiver, would give rise to the same output as the output of the receiver operating in the dark. From the far ultraviolet to the far infrared detectors are now available that operate close to the fundamental limitations imposed by thermodynamic and quantum-mechanical laws. Hence large improvements in detectors can no longer be expected.

The third factor is the recording time. Unfortunately signal-to-noise ratio increases only as the square root of the total time during which energy is collected. The price for obtaining improved signal-to-noise ratios by this means is therefore very high. In all practical cases the recording time is limited, and one can only try not to waste any of it.

The fourth factor is the resolving power. When a spectrum is divided into more and more separate portions, the energy per portion unavoidably goes down. For a continuous spectrum—all other factors being held constant—the energy and the signal-to-noise ratio are inversely proportional to the resolving power.

The spectroscopist has a measure of control only over the recording time and the resolving power. A requirement for high resolving power forces him to longer recording time. The theoretical maximum resolving power of a slit instrument, which is limited by diffraction, may become irrelevant; with a weak light flux the practical resolving power, which is limited by the available energy, is much lower than the theoretical limit. This practical resolving power can be improved only by increasing the light-gathering capacity of the instrument, that is, the size of the beam that can be fed through the spectrometer. Such a move means increasing the size of the disperser, and practical limits are again soon in view.

The Fabry-Perot interferometer represents a marked improvement over slit devices in light-gathering power. The reason is that it needs no sharp slits to record a spectrum. The interference filters now commonly used to isolate a narrow band of optical wavelengths are simply thin, low-resolution Fabry-Perot interferometers.

An altogether different way of producing spectra was proposed in 1950 by Peter B. Fellgett, who was then working at the University of Cambridge. He reasoned as follows. All spectrometers, which scan a spectrum bit by bit, waste most of the available light, whereas spectrographs, which record a spectrum photographically, do not. The reason is that the receiver behind the output slit in a spectrometer is a single-channel device: it can gather information about only one spectral element at a time, unlike the photographic plate, which contains a large number of individual detectors (the silver grains in the emulsion).

Fellgett concluded that the waste of light in a spectrometer could be eliminated if information about all spectral elements were fed through the receiver at the same time. (In the language of communications technology the receiver would be said to be multiplexed.) He looked around for ways to achieve the necessary encoding of the spectrum.

Although several approaches seemed to be feasible, the most promising one was Fourier spectroscopy, which had to be discovered anew because everyone had forgotten that Michelson had (in a rather obscure paper, to be sure) given all the essentials. The method had never been made to work; as I said earlier, Michelson in his experiments had used only the smoothed-out fringe-visibility curve and not the complete interferogram curve. As a matter of fact he could hardly have done more than he did, given the state of instrumentation at the time and the lack of high-speed automatic computers to work out the necessary Fourier transforms.

Multiplexing can be achieved with the two-beam interferometer because there is no dispersion and all the light is being utilized all the time. The gain to be expected, compared with the scanning of a spectrum, is greatest for extended spectral ranges and is manifest even at low resolving power. (These are circumstances Michelson never dreamed of; he applied the Fourier technique only to high-resolution spectrograms covering a narrow range.) Multiplexing has proved most useful in the infrared, for reasons that have to do with the different types of detector. Fellgett's idea received little notice at the time, and many technical difficulties had to be solved before skeptics could be convinced by actual results.

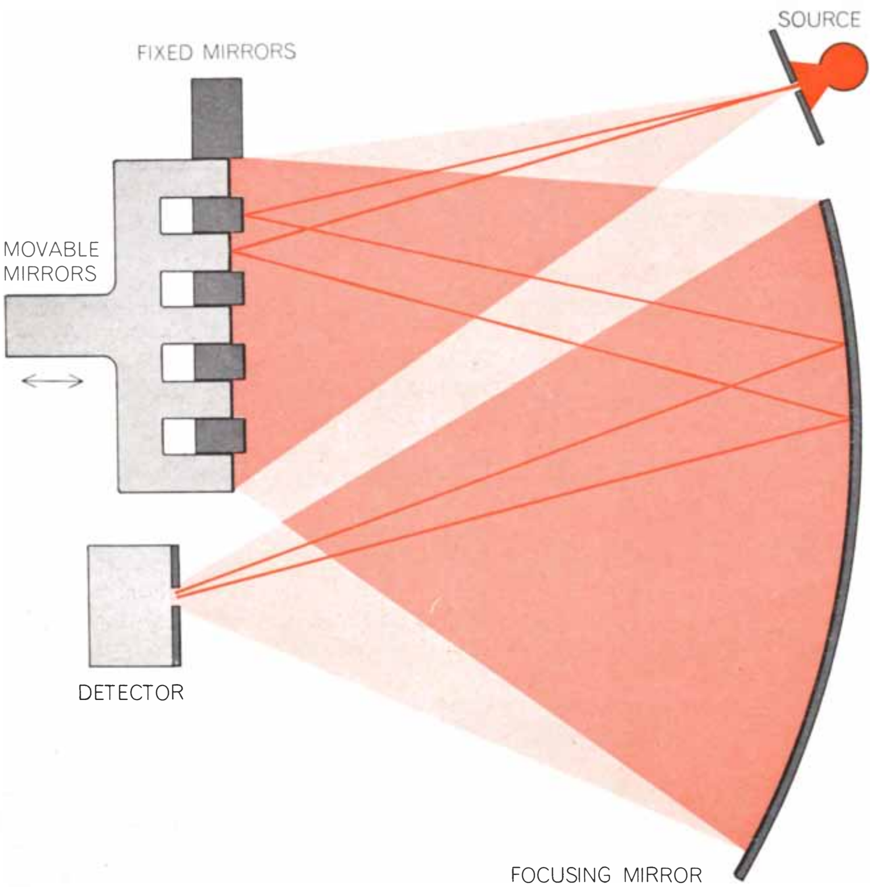
In France, at the Bellevue Laboratories of the National Center for Scientific Research, Pierre Jacquinot also rediscovered Fourier spectroscopy, but from a different viewpoint. He had greatly contributed to the improvement of Fabry-Perot interferometer spectroscopy, which means that he was well aware of its limitations and was looking for ways of overcoming them. He found that the spectral range could be increased by using only two beams and unscrambling the data later by Fourier analysis. Jacquinot set his disciples, of whom I am one, to work in that direction.

The first spectra recorded by Fellgett, which were spectra of cool stars in the near infrared, had very low resolving power, but the results were encouraging because the objects are so faint. Other early workers in the Fourier field (around 1955) were Lawrence Mertz of Harvard University, John D. Strong and George Vanasse of Johns Hopkins and H. A. Gebbie of the British National Physical Laboratory. Strong, Vanasse and Gebbie initiated the use of the technique in the far infrared.

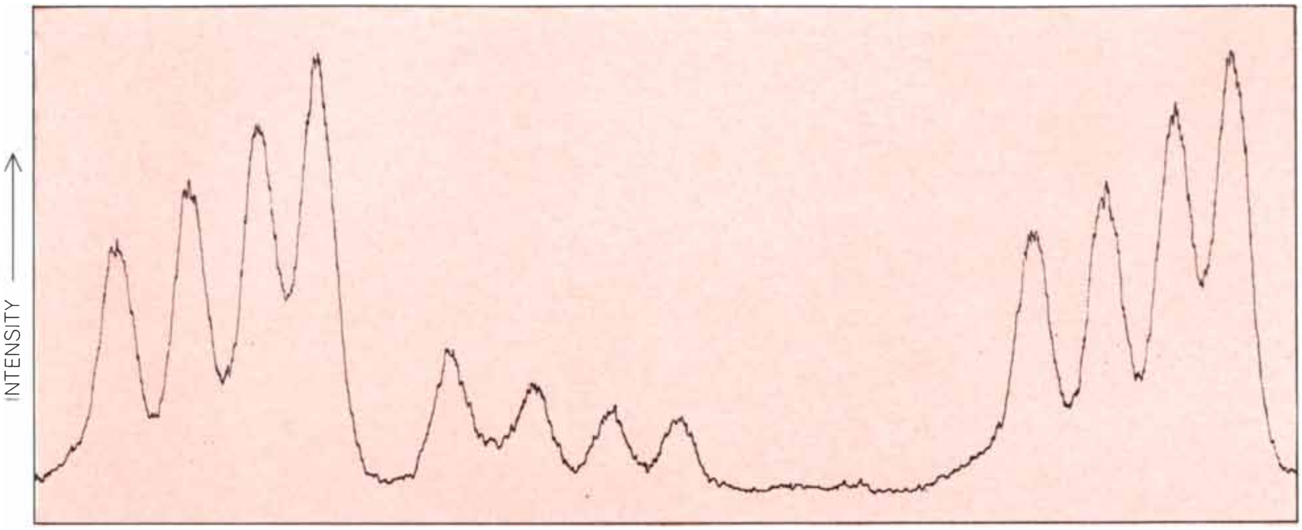
During the past 10 years the contributors to Fourier spectroscopy have become numerous. At an international conference on instrumental spectroscopy at Bellevue two years ago more than half of the papers dealt with Fourier spectroscopy. We shall indicate only the general trends. Most of the work has been done in the far infrared (wavelengths greater than about 50 microns), where the use of the method is now so common that commercial Fourier spectrometers are available. This is no accident; the accuracy required in the construction of the interferometer is less when the wavelength is greater. Moreover, the energy available in that range is very low, so that the results given by scanning spectrometers are comparatively poor and easy to improve on.

Fourier spectroscopy is also sometimes employed because of advantages we have said nothing about since they are not fundamental—which does not mean they are negligible. Two-beam interferometers, in particular those developed by Mertz, can be made very small and light. They lend themselves well to spectroscopic observations from aircraft, balloons, artificial satellites and deep-space probes.

Much effort is being devoted to the



OPERATION of lamellar grating is indicated. The detector records the zero-order diffraction beam. If path lengths (*colored lines*) of light reflected from movable mirrors and from fixed mirrors differ by half a wavelength, the beam will be dark at the detector. As one set of mirrors is moved at a constant rate with respect to the other one, the light of each color will fluctuate at detector with frequency inversely proportional to wavelength.

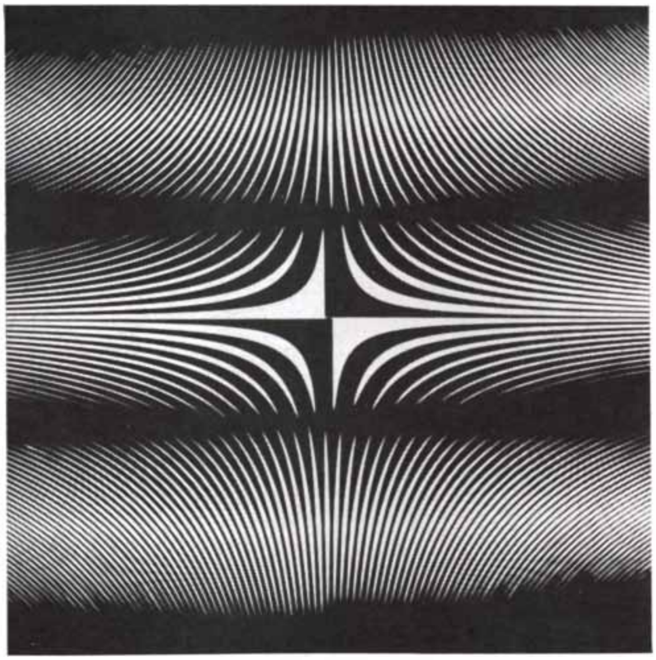


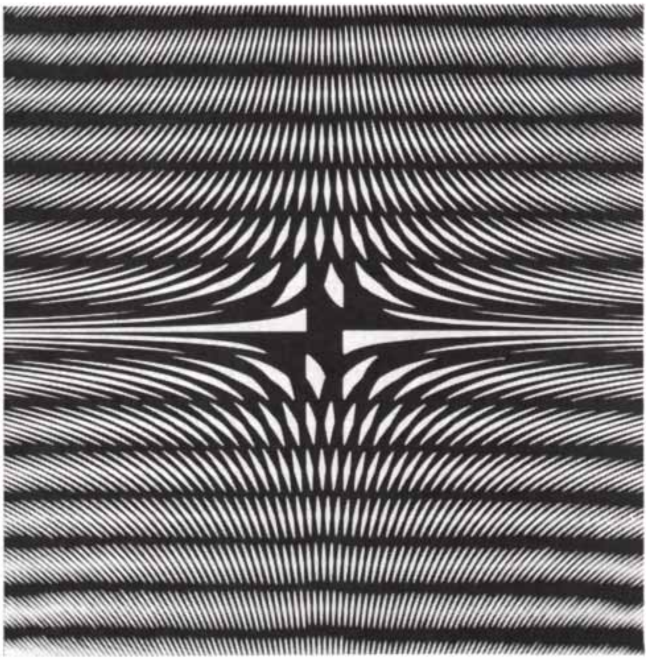
FABRY-PEROT RECORDING was made by a photometer that scanned across a Fabry-Perot ring pattern. The four peaks at left show four clearly resolved components of one blue line of terbium, which is a rare earth. The four lower peaks show four components of another line, and then the first pattern is repeated. Separation of the first two peaks at left is .01 angstrom. The small ripples are caused by noise in the detector. Such noise sets an ultimate limit on the accuracy of measurements that can be made of light intensity.

still difficult problems of computing the Fourier transform. Several types of special-purpose computers have been built. Some operate in real time: they actually plot the spectrum while the interferogram is being recorded. The main tool, however, is still the general-purpose computer. Striking advances have recently been made in the art of programming Fourier transforms, and optical spectroscopy will be the main beneficiary of these advances.

The reader may have guessed that the author, being a confirmed Fourier spectroscopist, is about to discuss his own contribution. (To choose to devote more space to one's own work than to Newton's is disturbing, to say the least, but one should understand that this huge distortion is a perspective effect and make the proper correction.) At Bellevue we have been from the start aiming at very high resolving power in the visible or the near infrared, because this is what the theoreticians in the group were asking for. (They deal mostly with the hyperfine structure of atomic energy levels.)

Briefly summarized, the difficulties were connected with the high accuracy required for both intensity and path-difference measurements in the interferogram. Errors in path difference distort the computed spectrum in the same way that imperfections in the construction of a slit spectrometer do. For in-





MOIRÉ PATTERNS are produced with Girard grids such as the one shown on page 73. For each frequency of light the spectrometer will form an image of the input grid on the output grid. If one grid is oscillated slightly, the output of light will be modulated by the varying overlap of the image and the output grid. The modulation is greatest when the output grid exactly lines up with the input grid. The overlapping images located a short distance apart, which correspond to different colors, can be separately discriminated.

stance, a grating ruled with periodic errors produces ghosts, or spurious lines. Similarly, if the device that measures the displacement of the interferometer carriage is afflicted with a periodic error, the Fourier-computed spectrum will also exhibit ghosts, and of much greater intensity. That is why the requirements for mechanical accuracy are even more stringent in a Fourier interferometer than in the ruling engine used to make gratings.

Errors in intensity produce additional noise in the spectrum. The difficulty is greatest in the very circumstances where the largest gain from multiplexing is sought. The problem is particularly severe when the intensity of the source fluctuates rapidly, which is what happens with all astronomical sources because of air turbulence.

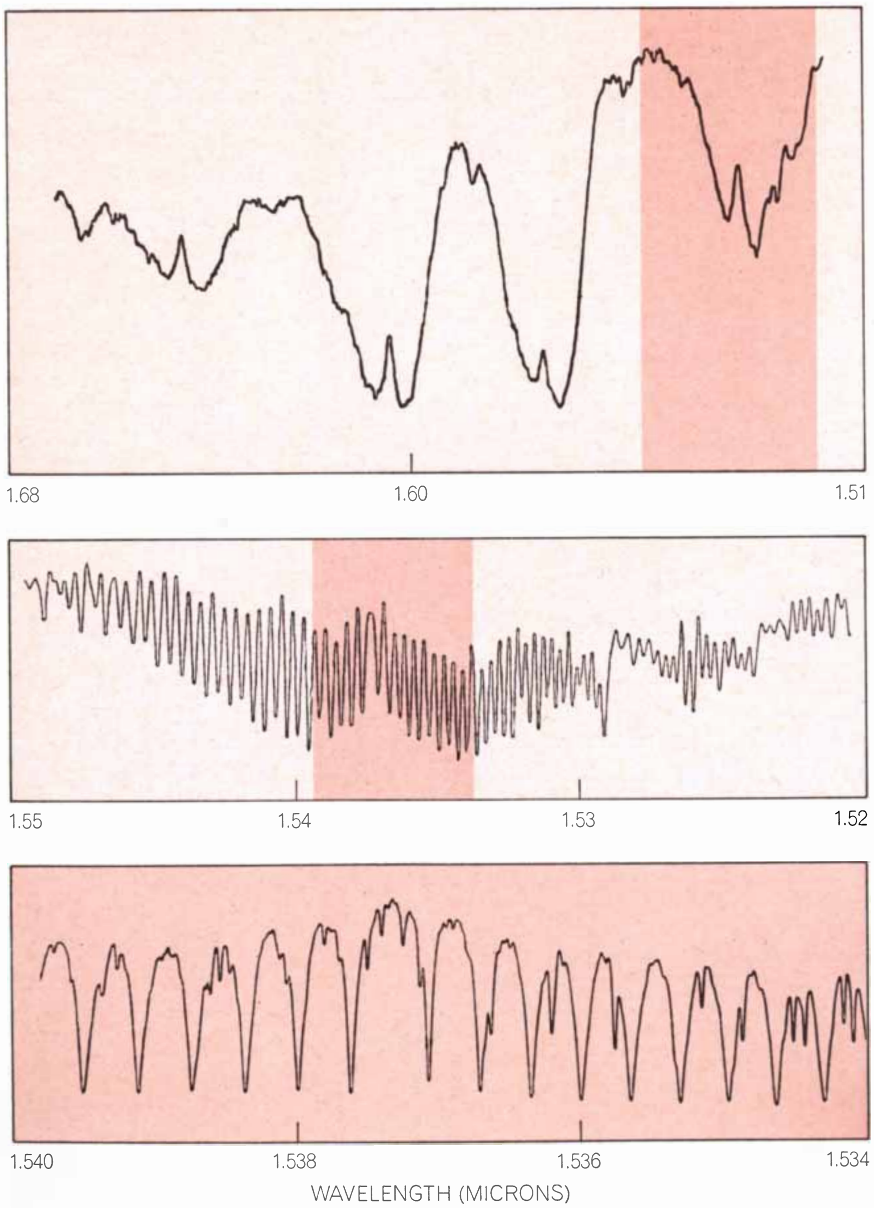
These problems have now been solved, but the steps are too technical to warrant description here. They involve sophisticated electronics and servo-control devices and also the development of new computer programs to extend the number of interferogram samples that can be transformed. This latter part of the work is the responsibility of Janine Connes, the author's wife, at the Numerical Computation Center of the Meudon Observatory.

Applications are progressing in two directions. Spectra of laboratory sources have been recorded (in collaboration with Jacques Pinard) that clearly exceed those given by the best gratings in resolving power and those given by Fabry-Perot interferometers in spectral range. Greater accuracy in determining wavelengths is being achieved, together with more freedom from ghosts and stray light.

The improvement is perhaps even more striking for infrared astronomical spectra because the energy from the sources is low and the observing time is sharply limited. In a program executed jointly with the Jet Propulsion Laboratory of the California Institute of Technology, where the author spent a year, spectra of Venus, Mars, Jupiter and a dozen red stars have been recorded. They show an improvement in resolving power by a factor of 100 or more compared with the best spectra previously obtained [*see illustration at left*]. The near-infrared spectrum of Mars and Venus is now known more accurately than the spectrum of the sun was a few years ago. Three new trace gases (hydrochloric acid, hydrofluoric acid and carbon monoxide) have been found in the atmosphere of Venus. Very large infrared telescopes will soon be specially built for multiplex spectroscopy.

Making predictions about the future of this both old and young method is obviously risky. One cannot be far wrong, however, in stressing the importance of having nonoptical techniques intrude on what has so far been the purely optical approach to light analysis. Opticians have to acknowledge that the tools of their trade progress very slowly. The methods by which lenses are polished today do not differ markedly from those of Galileo or Newton. Mirrors and glass plates used by Michelson or Fabry could be incorporated quite satisfactorily in the latest interferometers.

On the other hand, the elaborate, fully transistorized servo system I built three years ago for my astronomical measurements has today only one possible future—providing parts for my son to play with. The immediate question is whether the new all-integrated-circuited servo now being completed will produce anything before it becomes obsolete. The time is long past when experimenters could afford to let technical improvements lie idle for 100 years.



SPECTRA OF VENUS have improved greatly with improved techniques. At top is a curve covering part of the near-infrared spectrum of the planet's atmosphere; it was obtained in 1962 with a grating spectrometer. The area in darker color is covered in the middle spectrogram, obtained by the author in 1964 with multiplex spectroscopy. It gives more detail of one of the four carbon dioxide bands of the top spectrogram. Author's later results (*bottom*) show with even higher resolution the part of the middle spectrogram that is in darker color. Little dips between major ones are partly due to less abundant isotopes of carbon and oxygen.

In hope of doing each other some good

Kodak

Commercial note

It is our belief that there is money to be made in electroplated plastics. We sell polypropylene of electroplating grade. Established companies in a position to evaluate and act on pertinent technical information should request it from Eastman Chemical Products, Inc., Kingsport, Tenn. 37662 (Subsidiary of Eastman Kodak Company).

Water below

Three cheers for the U. S. Geological Survey and one cheer more for its Water Resources Division!

More acclaim than commonly bestowed is deserved by those who labor under interdisciplinary yoke to strike forth restorative waters from beneath parched land. In hope both of the general welfare and of a more specific welfare for those of us who deal in photographic goods and services do we point to the Survey's recent work with aerial color photography. The sense of it:

1) High aloft, cameras record the patterns in the big picture.

2) Down on the ground the elements of the patterns that differ in color are studied—why they differ, why they differ between simulatory color systems and systems which purposely distort color rendition in a way to extend man's color sense into the infrared.

3) Often as not, the differences turn out to be botanical.

4) Plant species distribute themselves to reflect their different adaptation to moisture, salinity, and geochemical conditions. Even species set out by the hand of man can exhibit subtle differences in vigor so caused and perceptible only from aloft, as patterns.

5) Hydrologists interpret the patterns to advise where and how to strike.

A hydrologist who has written on this work and might be tempted into correspondence is William J. Schneider, U. S. Geological Survey, Washington, D.C. 20242.

Below the water

The lady in the picture has been married to one of the two gentlemen for the three decades he has been with us. He is a physicist who quantifies response of photographic materials to light. His colleague's skill lies in using photographic materials as a professional illustrator. Both men neglected to state years ago on their applications for employment that they wanted to work under water.

The trio find themselves in a happy position. What they would do anyway for enjoyment turns out to be useful to customers of Kodak.* They love to be under water, and they love trying to see how good pictures they can take under water. For this pastime the fellows enjoy two special advantages: 1) long-term inside knowledge of films and their behavior; 2) intimate daily access to the mightiest known aggregation of technical photographic facilities. Too expensive for most customers would be the experiments they have done with processing variations on color film, with underwater grey scales, color charts, resolving power arrays. Changes in contrast, color balance, density scale, graininess, sharpness, and tone rendition have thus been shown—at Kodak's expense, not the customer's—to have different implications under water not just for the beauty of the results but with respect to the threshold between losing useful information or surfacing with it.

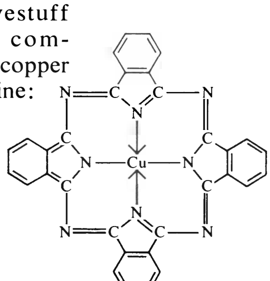
*Usefulness to customers is the most reliable route to success in business, we find.

One outcome is the conclusion that there is an underwater advantage in the increased contrast obtainable in KODAK High Speed EKTACHROME Film by "pushing" it in Process E-4 to much higher than normal speed. (This can be conveniently arranged simply by the extra purchase of a KODAK Special Processing Envelope ESP-1 when Kodak processing is arranged with the dealer.)

After delivering this opinion at an ocean engineering symposium, our finmen planned to proceed to the Bahamas to get going on an underwater Kodak Colorama, such as are displayed in gigantic proportions in New York's Grand Central Station and more modestly elsewhere. They just might bring it off.

Rings of rings

On the morning of November 25, 1935, the New York *Times* reported somewhat belatedly the discovery of the first new blue pigment in a century. Though the report gave it only a commercial dyestuff name, the compound was copper phthalocyanine:



It is now clear that several hundred thousand additional phthalocyanine compounds can be synthesized if wanted. A whole book could be written on the subject and has been.* Study of the same compound that the *Times* announced as a dyestuff gives insight into mechanisms common to semiconductors and the cytochrome respiratory enzymes. Nickel phthalocyanine gets into quite a different field of inquiry by catalyzing the air oxidation of saturated fatty acid esters, which are not particularly prone to oxidation. Phthalocyanines are semiconductive, photoconductive, photosensitizing, fluorescent, luminescent. They make good chemical jigs in which to hold metals for neutron irradiation. Inks that ushered in good full-color printing depend on them.

Phthalocyanines do not occur in nature, but more complex elaborations of its ring-of-rings structure do. The hemin that makes us red-blooded is such a structure, and so is the green chlorophyll that lets light support life. With an earlier view of magic, Merlin would have loved to get his hands on this blood-related stuff. With iron phthalocyanine he could have catalyzed the oxidation of Luminol (EASTMAN 3606) to give a crimson glow clearly visible in broad daylight without having to withdraw to a cave.

*"Phthalocyanine Compounds", by Moser and Thomas, Reinhold, New York, 1963.

The nearly 6,000 EASTMAN *Organic Chemicals for laboratory use might all be phthalocyanines and still give no assurance of serving all interests. We therefore officially list only a modest number of "non-commercial" ones, offer on a tentative basis a dozen or so additional phthalocyanines and the related octaphenylporphyrazines, and invite expressions of need for any of the other hundreds of thousands. Communicate with Distillation Products Industries, Rochester, N.Y. 14603 (Division of Eastman Kodak Company).*

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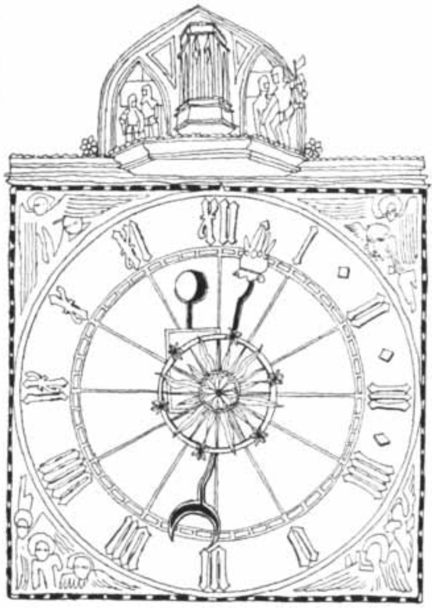
SCIENCE AND



From CERN to Serpukhov

Ten tons of electronic equipment supplied by the European Organization for Nuclear Research (CERN) were recently flown from Geneva to Moscow for use in conjunction with the 70-billion-electron-volt accelerator at Serpukhov, 60 miles south of the Russian capital. It was the first shipment ever made of Western equipment to the U.S.S.R. for joint experimental use by Western and Russian workers. The accelerator at Serpukhov, where the equipment will be installed, is now the world's largest. It began operating at full beam energy 11 months ago.

Under an agreement signed in mid-1967 CERN undertook to supply a fast ejection system to guide the accelerated protons out of the synchrotron into an experimental hall and radio-frequency separators to sort out various kinds of high-energy particles for use in experiments. In return the Soviet Institute of High Energy Physics agreed to welcome CERN physicists in groups of about six at a time to work at Serpukhov for periods of three to six months.

The first CERN-Serpukhov team will soon begin a "yield experiment," which will measure the number of subnuclear particles of different types that are created when a target is struck by the 70-BeV proton beam. It will provide data essential for planning future experiments. A second experiment of the East-West team will be the measurement of total cross sections in collisions between the newly created particles and stationary protons.

Meanwhile CERN's plan to build a 300-BeV accelerator at a cost of $350 million was set back sharply by the decision of the British government to withdraw its support. The British were scheduled to supply about a quarter of the construction and future operating funds. The government decided that the big machine would absorb too much of the nation's limited research and development budget. The other CERN partners hope that it will still be possible to build a somewhat smaller and less costly machine.

Ring around a Proton

A dream of high-energy physicists is to find some way to accelerate protons to enormous energies without having to build synchrotrons of ever larger diameter and cost. In a recent issue of *Nature* J. D. Lawson of the Rutherford Laboratory in Chilton, England, describes a Russian proposal for a machine that would accelerate ringlike clouds of electrons within which a few protons would be trapped by electrostatic forces. The proposal was intensively discussed at a symposium held last winter at the Lawrence Radiation Laboratory of the University of California at Berkeley.

The idea of accelerating a compact bunch of electrons containing a few embedded protons was evidently first proposed in 1951 by R. B. R-S-Harvie. He pointed out that the energy of the few protons would exceed the energy of the electrons by a factor of about 1,800, which is the amount by which a proton's rest mass exceeds the mass of an electron. Thus if the electrons could be accelerated to a billion electron volts (1 BeV), the protons would be given an energy of some 1,800 BeV, or some 25 times the energy now achieved by the world's largest proton accelerator (*see above*). Harvie was unable, however, to suggest a way of holding the electrons together against the large repulsive forces they would exert.

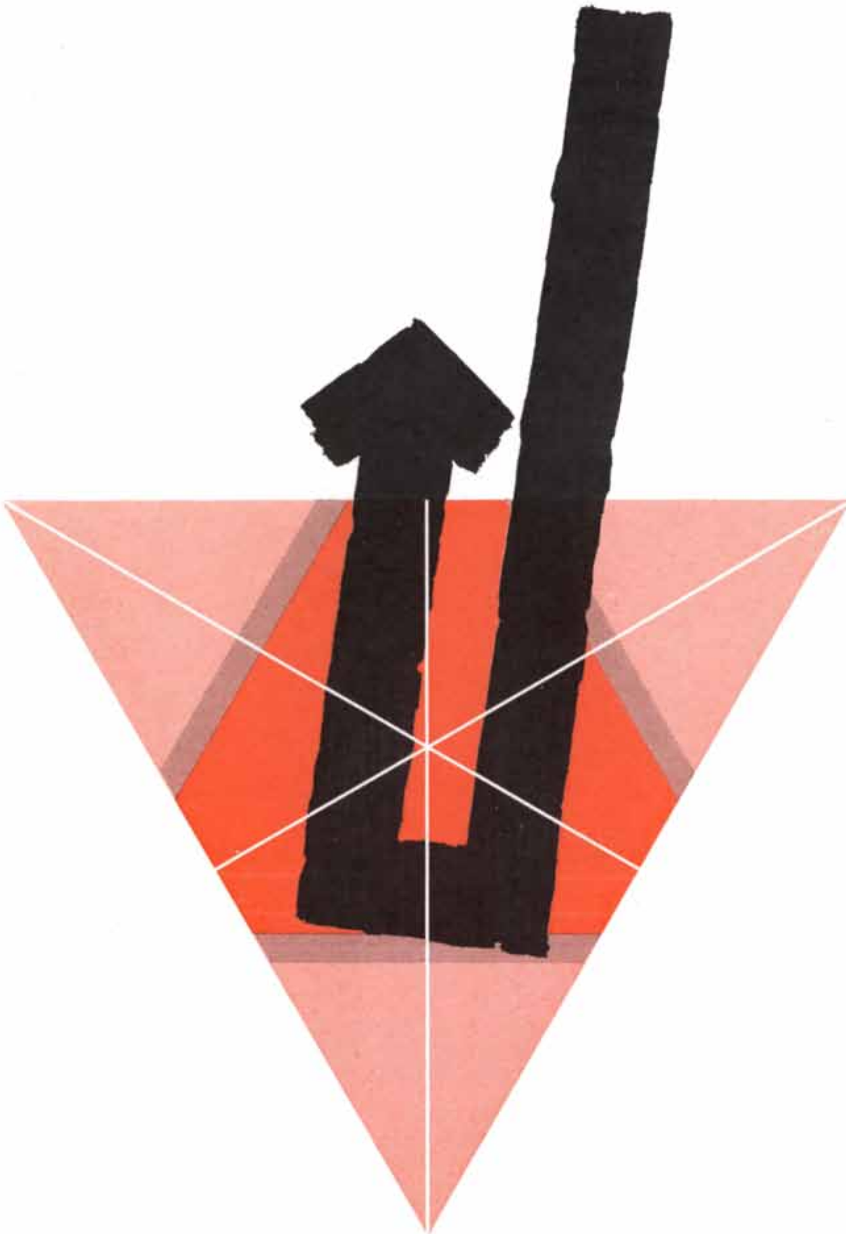
A Russian group headed by V. P. Sarantsev conceived a way around this problem. It proposes using a ring of electrons within which the electrons would travel at velocities near the speed of light. The mutual repulsion of electrons would be much reduced by the magnetic field produced by the current in the ring. The magnetic field would form "hoops" around the ring and tend to confine the electrons. The Russian group has been conducting its feasibility studies for some time, and no one has yet found any flaws in the concept. It is conceded, however, that development of a practicable machine might involve difficulties comparable to those encountered in the attempt to control nuclear fusion.

What Is Death?

The traditional criteria for death are cessation of respiration and heart action, but modern medical technology can keep a patient breathing and his blood circulating long after his brain has died. Now a special Harvard University committee has recommended that brain death, or irreversible coma, be considered a definition of death and has drawn up a set of guidelines for determining when there is no discernible activity of the central nervous system. The 13-man committee, drawn from the faculties of medicine, public health, law, arts and sciences and divinity, was headed by Henry K. Beecher of the Harvard Medical School. Its report was published in the *Journal of the American Medical Association.*

According to the committee a permanently nonfunctioning brain is characterized by certain clinical signs. One is unreceptiveness and unresponsiveness of the patient to any external stimuli or inner needs. Another is lack of any spontaneous muscular movement or any unassisted breathing—or effort to breathe—over a period of at least an hour. Finally, there are no reflexes: the pupil of the eye is fixed and dilated even in the presence of a bright light, there is no swallowing or yawning and usually no stretch reflex. These clinical signs constitute primary evidence of brain death; electroencephalograms should be considered secondary because they may show spurious waves. A "flat" brain-wave pattern, according to the report, constitutes confirmation of brain death.

The final determination of death through irreversible coma should be made only when the clinical and encephalographic tests have been repeated at least 24 hours after the initial tests. The determination should be made by the physician in charge; it is "unsound



and undesirable" to have the family make the decision. Then the family should be informed. "At this point death is to be declared and *then* the respirator turned off." The decision, the committee noted, "should be made by physicians not involved in any later effort to transplant organs or tissue from the deceased individual."

Methadone Supported

Heroin addicts whose habit is switched to the drug methadone and who are given adequate support and counseling apparently stay off heroin, become self-supporting and demonstrate increasingly less antisocial behavior. These are the preliminary findings of a committee established under the auspices of the Columbia University School of Public Health and Administrative Medicine to evaluate the Methadone Maintenance Program, which has been conducted at several centers in New York City for about four years under the direction of Vincent P. Dole and Marie Nyswander. The program grew out of research at Rockefeller University in which Dole showed that addicts could be maintained on regular doses of methadone, a drug that had previously been used to ease the distress of withdrawal from heroin.

Patients in the Methadone Maintenance Program, who have been heroin addicts for an average of 10 years before admission, volunteer to be hospitalized for about six weeks, during which they are built up to a stabilizing dose of the drug. Thereafter, as outpatients, they are maintained on methadone, tested regularly for heroin or other drug usage, given psychological support and counseling on employment and education. The committee considered the cases of 544 men treated at two centers. At the time of admission only 28 percent of them were gainfully employed; 40 percent were receiving welfare support. Of those who have been in the program for more than two years, 85 percent are employed or in school; the proportion on welfare is down to 15 percent. None of the patients has become readdicted to heroin. There has been a steady decrease in the number of arrests. Although all the men continue to take methadone, periodic medical examinations have shown no toxic effects.

The committee concludes that "for those patients selected and treated as described, this program can be considered a success.... Those who remain in the program have, on the whole, become productive members of society." Since these patients are volunteers, older than the average addict and perhaps more highly motivated, the program's results should not be generalized to the total addict population. The committee suggests a number of new lines of research to establish the general applicability of the method and to assess long-term results.

Alaskan Oil

A deposit of petroleum and natural gas that may prove to be the largest ever found in the U.S. has been discovered on the northern coast of Alaska. A consulting firm in Dallas has reported that the discovery "could develop into a field with recoverable reserves of some five to 10 billion barrels of oil, which would rate it as one of the largest petroleum accumulations known to the world today." The famous East Texas oil field, which is the largest source of petroleum previously discovered in the U.S., had original reserves estimated at five billion barrels.

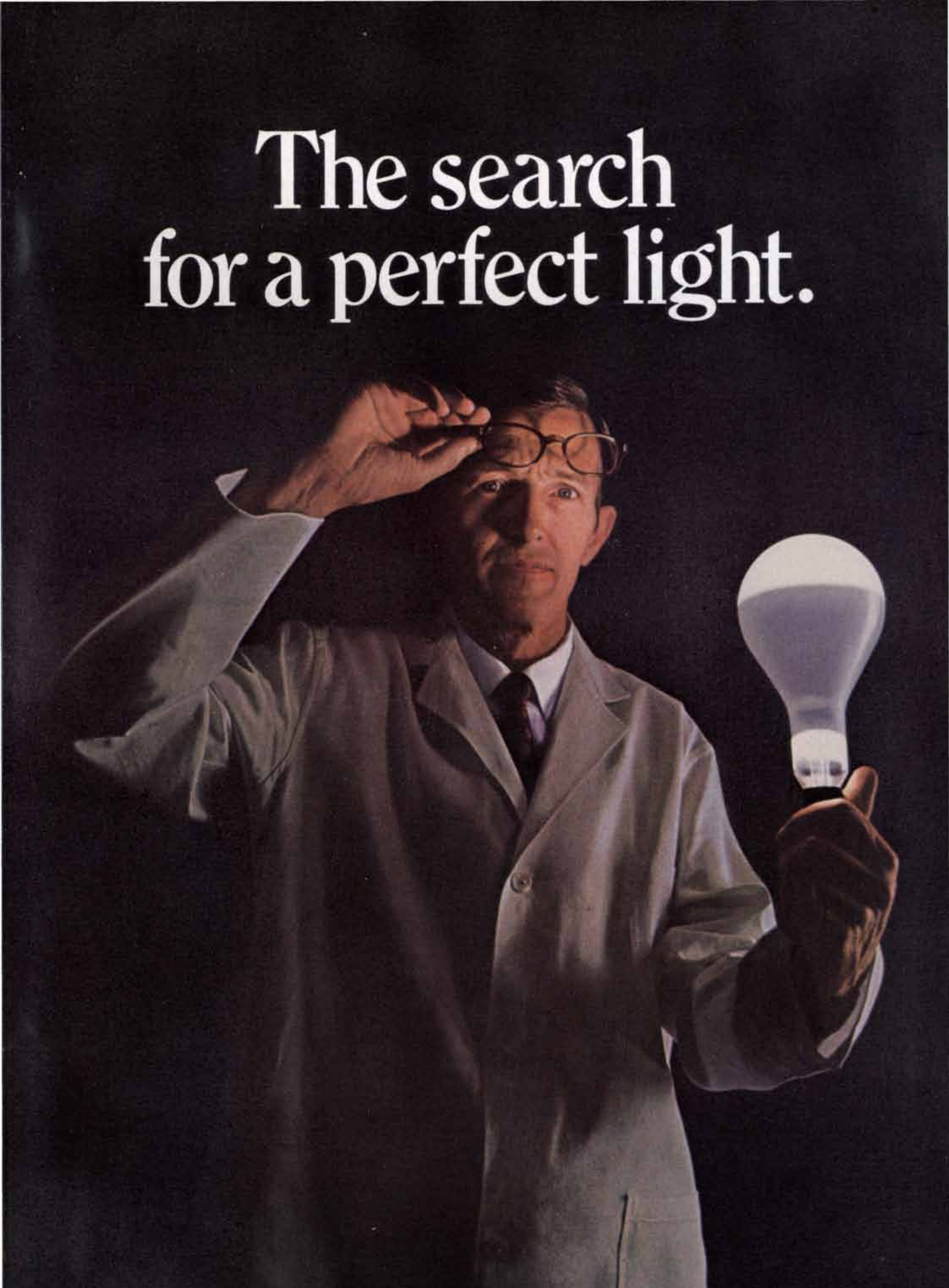
The Alaskan discovery was announced by the Atlantic Richfield Company and the Humble Oil & Refining Company, which each have a half-interest in the field. The field is in the Prudhoe Bay region of the Arctic slope, the northward declivity from the Endicott Mountains and the Philip Smith Mountains to the Beaufort Sea. Because the site is in a remote area, large-scale facilities will be needed to convey the oil and gas to warm-weather ports 900 miles away. The two companies have estimated that commercial development of the field will take at least three years.

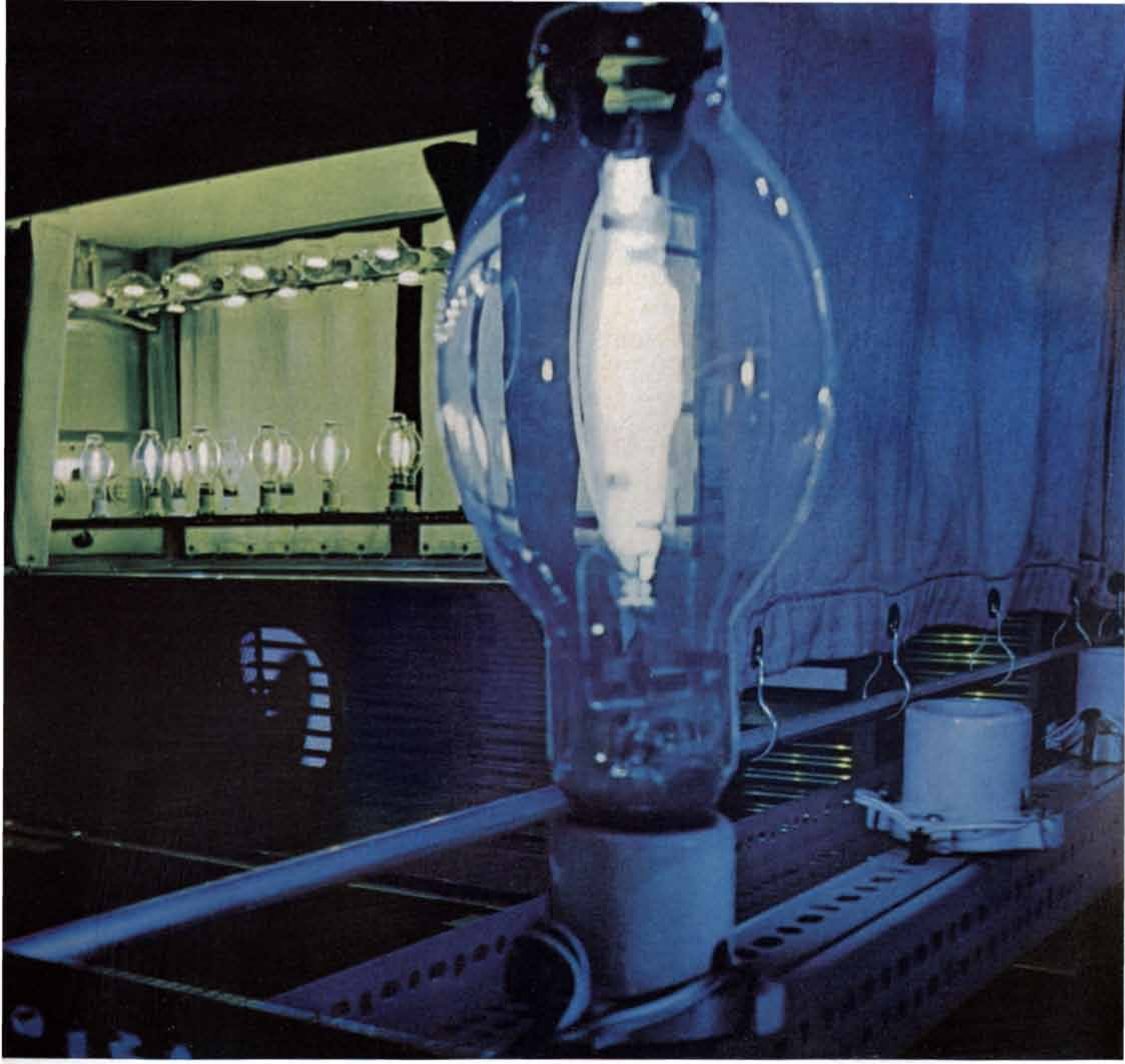
Where Proteins Start

The synthesis of proteins takes place on particles called ribosomes, which consist of two subunits of unequal size. Christine Guthrie and Masayasu Nomura of the University of Wisconsin have recently described in *Nature* a distinctive role for the smaller subunit. It is the place where protein synthesis starts. Surprisingly, moreover, the smaller subunit is not bound to the larger subunit when the synthesis begins.

It had long been known that ribosomes could be dissociated into two subunits, which were identified as 30S and 50S because of their sedimentation properties. What seemed puzzling was why there should be two subunits—why not a single particle? One could guess that the subunits might have different roles, but no one knew what they might be.

The puzzle was not clarified by the discovery, about two years ago, that in


The search
for a perfect light.



lit and thinned-down to about an inch because you don't need yards and yards of bulky cables. Light can be built into walls, doors, stairs, domes, or any other parts of a building. Because of its flexibility, it can be woven into draperies and built into furniture. There's even the possibility that electroluminescent screens could perform the function of cathode-ray tubes. If so, we may see the day when a color TV set will be thin enough to be hung on a wall like an oil painting.

But so much for the future. Here's more of what we've done lately. We've developed one of the whitest, brightest, most natural looking lamps in the lighting industry . . . the Metalarc lamp. It's the closest anyone has ever come to duplicating natural sunlight. We found that combining mercury with sodium oxide and scandium oxide could achieve the same characteristics of the sun in terms of color temperature. Mercury being heavy in the blue and the green, and the oxides being heavy in the red, orange, and yellow.

From this we got our Metalarc white light which is being used wherever the sun can't be. From stadiums for night sporting events to underground passages for men at work.

But even though our Metalarc is the best light under the sun for turning night into day, we're not satisfied. We still go on our endless search climbing the infinite ladder of perfection.

The closer we get to the top, the further we have to go. Maybe nothing we've made so far can replace the sun. But some day, who knows?

SYLVANIA

bacteria, at least, the synthesis of protein chains is initiated by a particular amino acid, formyl methionine, which is carried to the ribosome by a specific "transfer" RNA known as $t\mathrm{RNA}_F$. The selection of this and subsequent amino acids is directed by "messenger" RNA held by the ribosome. It was also observed, in later experiments, that bacterial cells contain free subunits of 30S and 50S and that indeed there was an exchange of these subunits during protein synthesis.

By careful experiments in which the two kinds of subunit were distinctively labeled with heavy isotopes, Guthrie and Nomura demonstrated that ribosomes dissociate into subunits before any formyl methionine is bound to either one of them. They then proved conclusively that protein synthesis starts when a 30S unit combines with a strand of messenger RNA and with a molecule of $t\mathrm{RNA}_F$ bound to formyl methionine. This complex then joins up with a 50S subunit and protein synthesis proceeds to completion.

Through a Lenslet Brightly

The renewed interest in the optics of three-dimensional imaging techniques brought about by the spectacularly successful marriage of holography and the laser (see "Applications of Laser Light," by Donald R. Herriott, page 140) has led to the revival of another old idea in photographic optics known as lenslet photography or integral photography. Invented by Gabriel Lippmann of France in 1908, the technique is based on the use of thousands of small spherical lenses ("lenslets") to produce a three-dimensional image comparable to the one obtained by the holographic method. Potential applications of integral photography are being explored at the Bell Telephone Laboratories by a group under the direction of Robert J. Collier, who describes the technique in a recent issue of *Physics Today*.

In integral photography incoherent light reflected from a subject is focused by each one of an array of tiny lenslets onto a photographic plate placed behind the plane of the lenslets and close to their back focal plane. The image formed by each lenslet is a complete picture of the subject seen from a unique aspect. After the photographic plate is exposed to record an array of bright point images of each point on the subject, an accurate positive image, consisting of an array of transparent spots on an opaque background, is made. The developed plate is then replaced in the back focal plane in register with the original lenslet array and is illuminated from the rear with diffuse incoherent light. Each transparent point image emits a spherical wave that emerges from the front of the lenslet as a narrow beam whose direction corresponds to the direction of the incoming beam during exposure. The beams from all the lenslets converge to form an array of bright spots at the original positions of points on the subject. The term "integral photography" derives from the integration of all these tiny point images to form the final three-dimensional image. In effect the array of tiny lenslets samples the directions of light coming from any given point on the subject and plots the intensity of each sample in unique positions with respect to the optic axis of the entire lenslet array.

Collier points out that because integral photography requires only incoherent light, it is applicable to the recording of three-dimensional images in situations where the subjects are moving and hence are not suitable for most kinds of holography. Such subjects include the interior of furnaces, jets and plasmas and the surfaces of cathode ray tubes and living organisms. Collier also foresees possible applications of lenslet photography in three-dimensional portraits, posters, road signs and perhaps television close-up displays.

Reversible Retardation

What is a mental retardate? Thirty years ago two University of Iowa psychologists who had studied a group of physically healthy but mentally retarded children reported that after the children had been moved from an orphanage to a different environment, they had progressed to normal intelligence, as measured by their IQ score. The mental retardation had disappeared. At the time of these reports psychologists tended to think IQ was fixed by heredity, and the findings of Harold M. Skeels and Marie Skodak were essentially ignored. With the passing of time their work attracted more attention, ultimately helping to inspire preschool programs such as Project Head Start, designed to prevent mental retardation. Recently the Joseph P. Kennedy Jr. Foundation made separate awards of $20,000 to Skeels and Miss Skodak in recognition of their early research.

Skeels's investigations were begun after he noted a pronounced spurt in the mental growth of two young children from an Iowa orphanage. Having been classified as imbeciles, they were living (space not being available elsewhere) in a home for feebleminded women. There the children received more affection, attention and opportunities for play than they had had at the orphanage. Skeels arranged to have 11 other mentally retarded orphans under three years old placed in the institution for feebleminded women. Over a two-year period the IQ scores of all the children moved upward; with two exceptions each child gained more than 15 IQ points. In contrast, 12 children who remained at the orphanage and whose IQ's were initially at the "normal and dull average" level, showed an intellectual loss with time. Indeed, their average loss of 26 points was nearly equal to the retarded children's average gain of 27 points.

The related findings of Miss Skodak were based on a study of 100 orphans who had been adopted at an early age. Their IQ score was generally higher than what would have been expected on the basis of their actual parentage and was close to the score of their adoptive parents.

Skeels and Miss Skodak have followed the development of the children they originally studied. Twenty years later the "retardates," no longer in institutions, were married or self-supporting; their educational and occupational achievement levels compared favorably with averages taken from the U.S. Census.

High-Speed Sewage

Recent experiments in Texas have shown that the flow of liquid through sewer pipes can be speeded up by more than 50 percent if small amounts of synthetic organic polymers known as flocculants are added to the liquid. The experiments, carried out in six-inch pipes at a test site, were conducted by the Western Corporation for the Federal Water Pollution Control Administration. At the Federal agency's request the city of Cleveland will soon test the polymers in brick sewers as large as five and a half feet in diameter.

The polymers cause small particulate matter to coagulate into larger masses termed flocs. The liquid is thereby made less sludgy. Flocculant polymers have already been used with good results in a number of sewage-treatment processes that involve the separation of solids from water. The flocculation makes possible a much more rapid separation than can be achieved with unflocculated liquids. If the process proves to increase the flow significantly in municipal sewage pipes, it will not only increase the capacity of the pipes but also make pumping easier and help to keep the pipes clean.

Thomas Harriot (1560-1621)

Woodcarving by William Ransom
Photographed by Max Yavno

"Before awarding all the prizes for discoveries and inventions in mathematics, philosophy and natural science to claimants throughout the wide Republic of Letters, let modest Hariot be heard and examined. Let his papers and all his credentials be laid out before the high court of science, not in the light of to-day, but contemporaneously with those of Tycho, Kepler, Galileo, Snell, Vieta and Descartes. Hariot himself has claimed nothing, but Justice and Historical Truth are bound to assign him a niche appropriate to his merits."[1]

[1]Henry Stevens, *Thomas Hariot and His Associates*, Privately Printed, London, 1900.

INTERACTIONS OF DIVERSE DISCIPLINES

Of the 800 members of the professional staff of Planning Research Corporation, 188 pursue the discipline to which Harriot made some of his greatest contributions: mathematics. Twenty-nine other disciplines are represented on the Planning Research professional staff. Here, the classical sciences, philosophy, engineering, and mathematics *interact* on multi-disciplined teams with the new behavioral and management sciences, economics, and the computer sciences. An appropriate combination of these disciplines can find the answer (by analysis, not by judgment) to the technical, economic, or social problem you want solved.

Approximately half of Planning Research Corporation's present contract work is in general problem solving. Projects range from market analysis and planning for industry . . . to the management of natural resources and the care of human resources for state governments and the Federal Government . . . to problems in the exploration of space.

Executives in government and industry are invited to write or call Mr. Stuart A. Krieger, Executive Vice President, for further information on Planning Research Corporation's capabilities. There is no obligation.

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Better communication is critical to the growth of developing nations

Pakistan is one example. The requirement for more adequate, more reliable communication across the 1200 miles separating East and West Pakistan, as well as the mountainous terrain between Pakistan and other nations of Europe and Asia, has become a major concern.

Sanders undertook total systems responsibility for designing and installing a communications network to link the two segments of the country and provide extensive worldwide communications.

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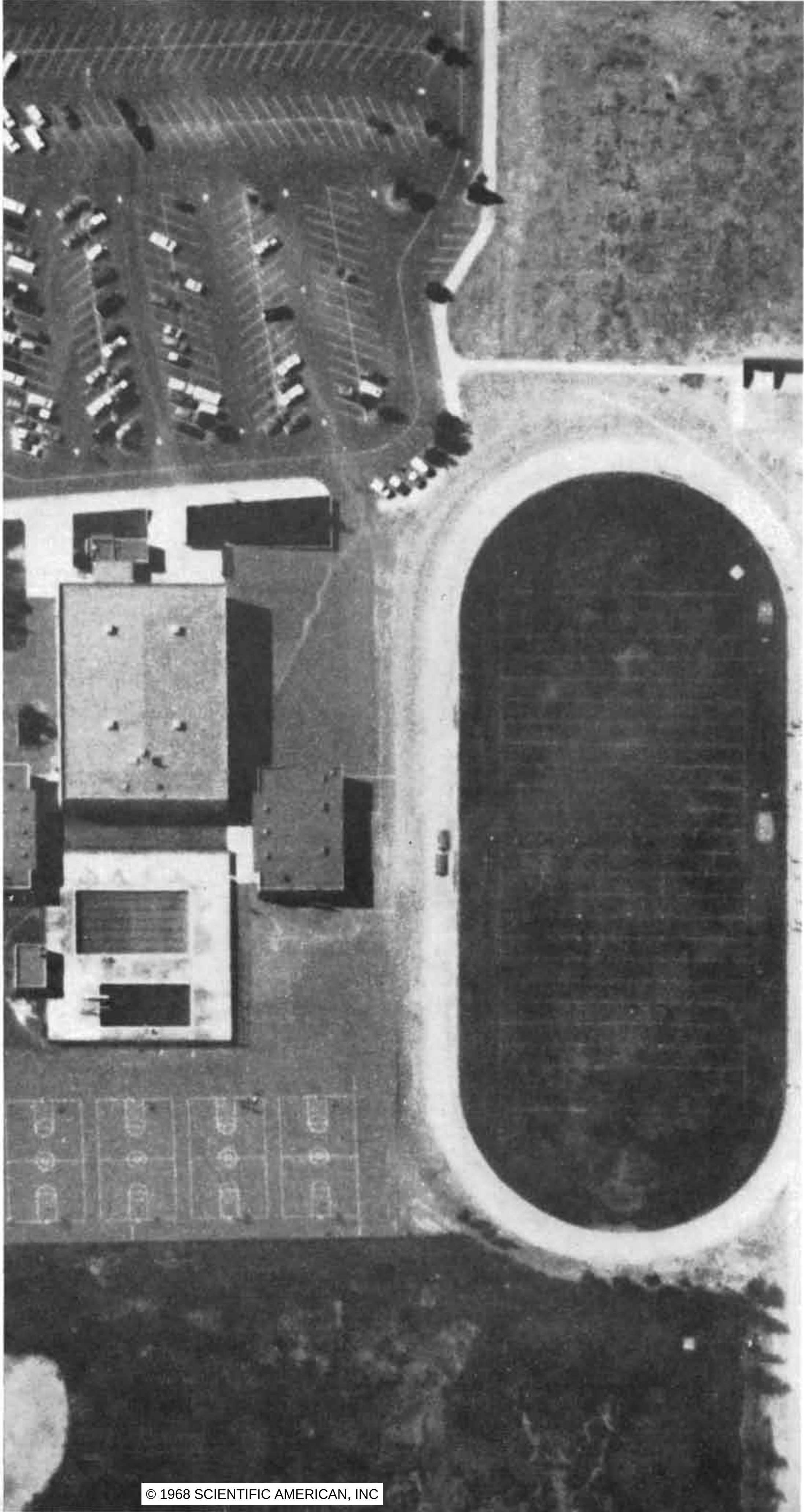


How Images Are Formed

New procedures based on wave theory and executed by computers have supplemented the traditional techniques of ray optics. The result is a major advance in the quality of lenses and the images they form

by F. Dow Smith

Because light wavelengths are short light can convey a remarkable quantity of information. The fidelity with which this information is ultimately presented in an image depends on the physical characteristics of the optical system that forms the image. In recent years optical technology has made dramatic advances; aerospace photography from very high altitudes and photomicrographic techniques for producing integrated circuits are just two applications of the remarkable optical systems that are now being developed. The new technology is based on a comprehensive new discipline of image formation that combines traditional geometric optics with the wave and diffraction theory of modern physical optics, and brings to bear new mathematical routines executed by high-speed computers.

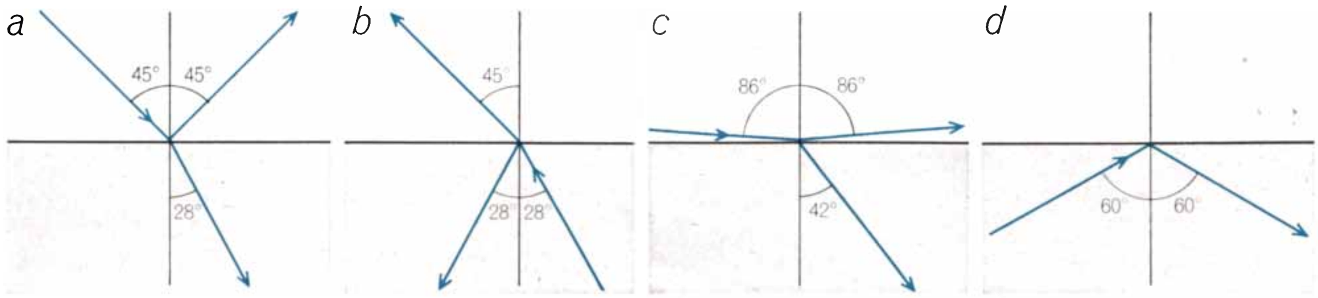
The behavior of light was one of the first aspects of the physical world to be observed and investigated by the ancient philosophers. They learned by experiment that rays of light striking a surface at an angle are reflected at precisely the same angle. A general law of refraction—the change in angle of a ray passing from one transparent medium into another—was more elusive, although about A.D. 150 Ptolemy was able to measure the bending of a beam of light as it passed from air into water or glass (and in the opposite direction). Johannes Kepler found that when light struck a glass surface nearly perpendicularly the angles of incidence and refraction were in the ratio of 3 : 2. Finally in 1621 the Dutch mathematician Willebrord Snel (not Snell, as it is commonly given) found the correct relation for all angles of incidence, including large ones. At about the same time René Descartes derived the correct mathematical expression. Isaac Newton showed that the angle of refraction also depended on the color of the incident light. Thus the simple geometrical relation was established: the sines of the angles of incidence and refraction are inversely proportional to the indexes of refraction of the two mediums. For light of any color the index of refraction of a medium is inversely proportional to the speed of that light in that medium. Snell's law, as this relation is called in English-speaking countries, is a sufficient physical basis for all geometrical optics, the high development of which in the late 19th and early 20th century made possible great achievements in the design of complex lenses and optical instruments [*see illustrations on next page*].

HIGH INFORMATION CONTENT in an image is demonstrated by the photographs on the opposite page. The contact print is a strip from a portion of a negative exposed at a high altitude east of Los Angeles by an advanced Itek Corporation aerial camera. The scale is 1 : 36,000 (one inch equals 3,000 feet). The print covers about 7.5 square miles, ranging from Baldwin Park in the west (*top*) to Charter Oak in the east (*bottom*). A small segment of the contact print (*center, about four inches from the top*) was enlarged 25 diameters and the resulting print is reproduced here at a total enlargement of 31.5 diameters. The detail revealed in the enlargement includes the lane markers in the swimming pool, runners on the track and players on the football field.

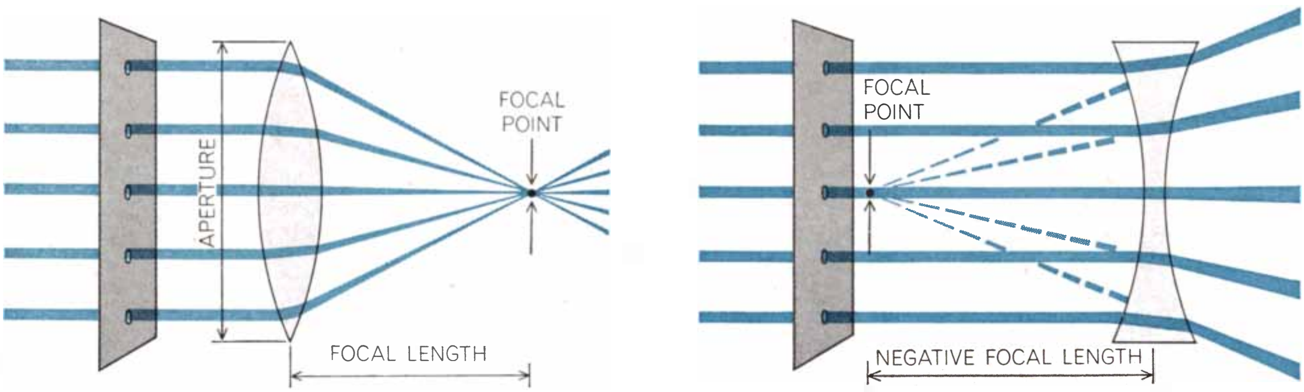
From the optical designer's point of view, a practical lens for a camera or other instrument consists of a set of refracting or reflective surfaces, usually spherical in form, arranged along a common axis. A lens "formula" consists of a set of numbers giving the thicknesses and spacing of the various elements and the indexes of refraction of the glasses of which they are made. The aim is to bring bundles of light rays from some "object point" to a single point, the image, and to do this simultaneously for many points and for light of many wavelengths.

It is not possible simply to solve a set of algebraic equations and come up with a complete lens formula. There are, however, formulas that express the general behavior of rays of light, particularly those close to the lens axis, the "paraxial" rays. These formulas show that all the rays typically do not come to the same focus and this results in image errors known as aberrations. It is not possible or indeed desirable to reduce all these errors to zero in a practical system. Instead the usual practice is to allow a specified amount of a certain aberration to occur and to cancel its effect by introducing an opposite error from a different kind of aberration. Formulas derived from aberration theory can be a general guide to lens design, but the formulas are approximate at best.

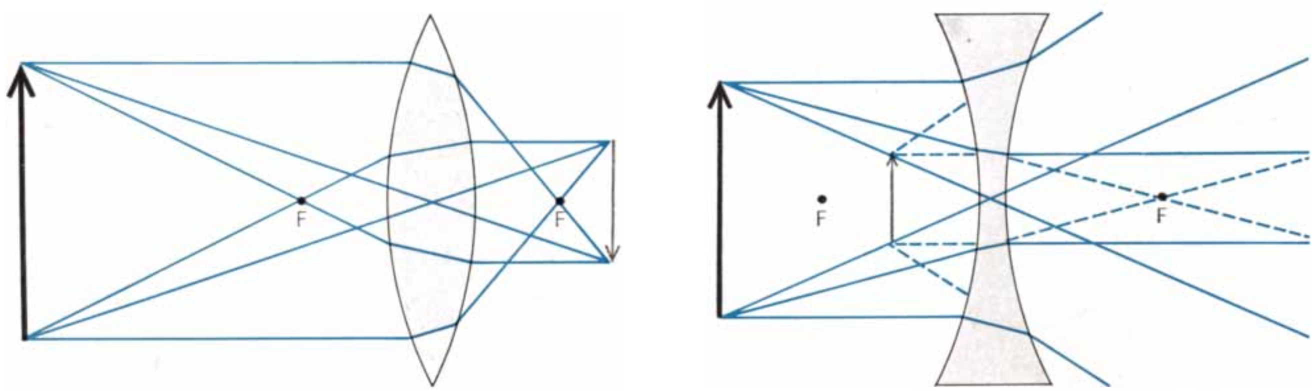
The classic and continuing method of lens design is therefore "ray-tracing," a trigonometric process by which an individual ray is traced through the lens. Its change in direction at each surface is computed by Snell's law. In this way the position at which each ray intersects the desired image plane can be determined. In the very early days these computations were done with logarithms to six or more decimal places; the process was laborious and only a few rays could be traced. Later the process was speeded up by the introduction of mechanical desk calculators. The designer would select a number of rays from one object point and determine where each intersected a plane near the image, and then do the same for other points in the field of view and for light of various wavelengths. After making a set of calcula-



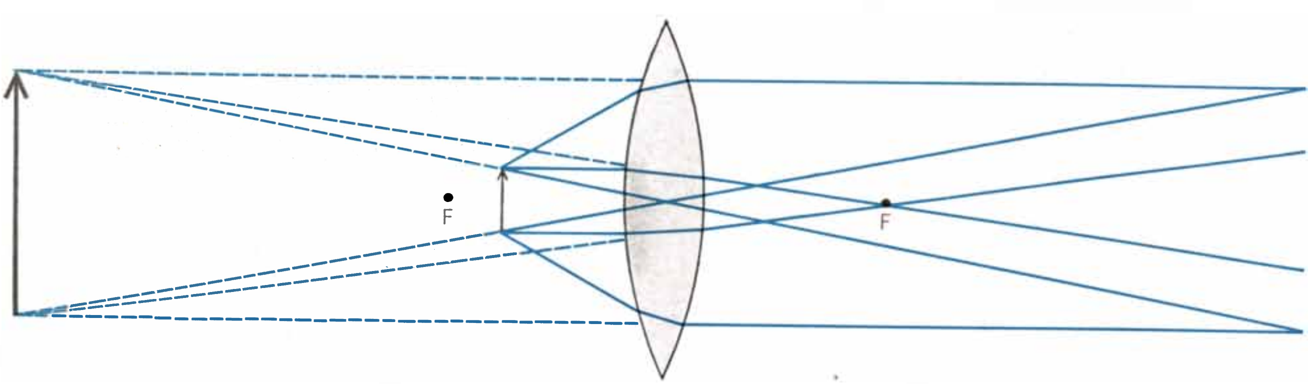
REFLECTION AND REFRACTION are shown for light passing from air (index of refraction 1) to glass (index 1.5). The angle of reflection equals the angle of incidence and the sines of the angles of incidence and refraction vary inversely with the indexes of refraction (*a*). Reversing the direction of light propagation does not change the angles (*b*). A grazing incident ray is refracted at a limiting angle (*c*). When the direction is reversed, at any larger angle a ray is totally reflected within the denser medium (*d*).



LENSES refract light rays. Parallel rays (pencils of light formed by holes in a screen) are converged to the focal point by a convex (positive) lens (*left*). Rays are diverged by a concave (negative) lens so as to seem to originate at the negative focal point (*right*).



RAYS from points on an object (*black arrows*), refracted by a lens, converge to establish corresponding points on an image (*gray arrows*). Parallel rays are refracted through the focal point; rays intersecting at the first focal point emerge parallel; rays through the center of a thin lens are not deviated. A convex lens forms a real image, as on film; a concave lens forms only a "virtual" one.



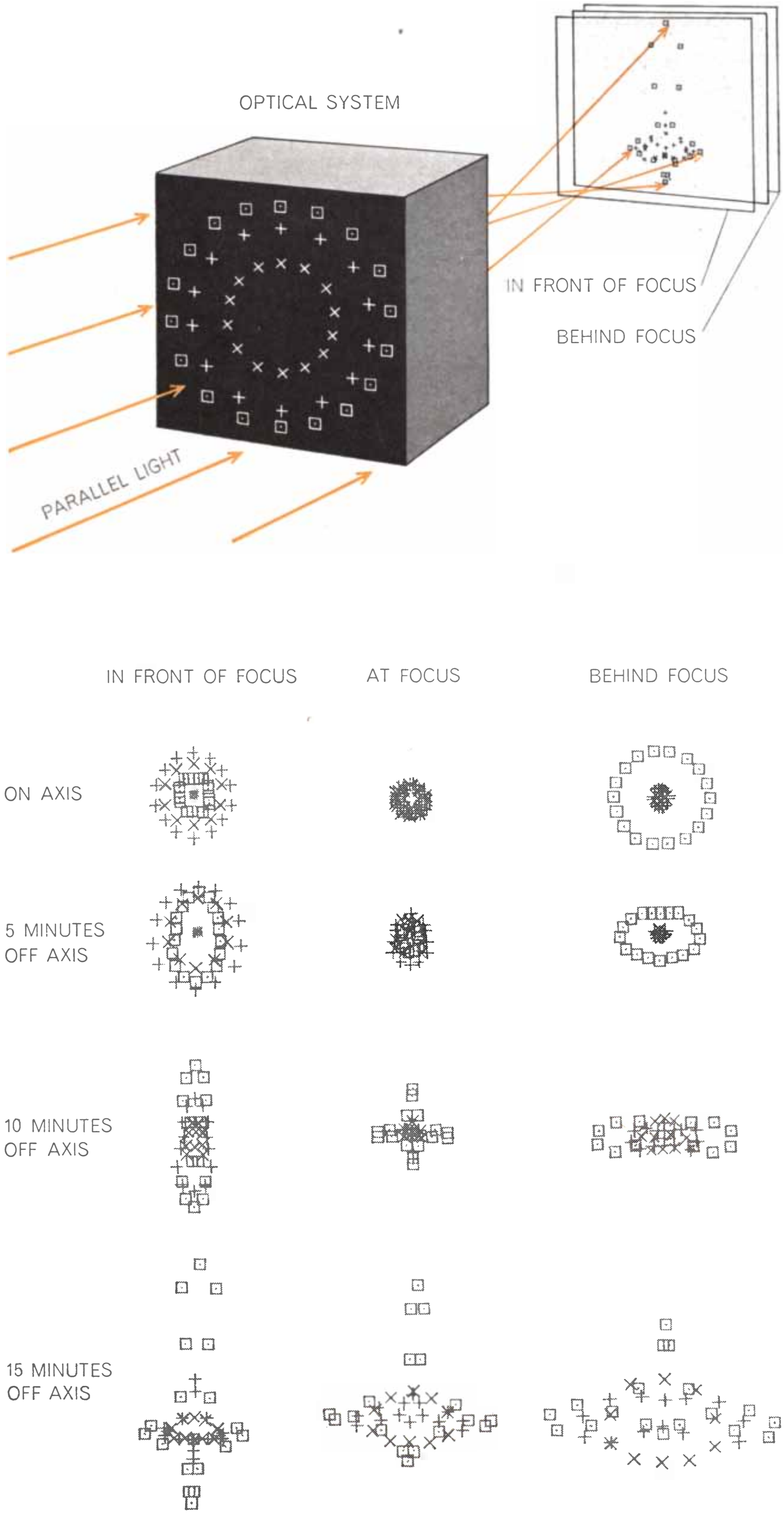
MAGNIFICATION can occur when an object is located inside the focal point of a converging lens, which forms a virtual, enlarged and upright image. In microscopes and telescopes the object to be magnified is an image that has been formed by an objective lens.

tions he would evaluate the resulting image, adjust his lens elements accordingly and do the calculations again.

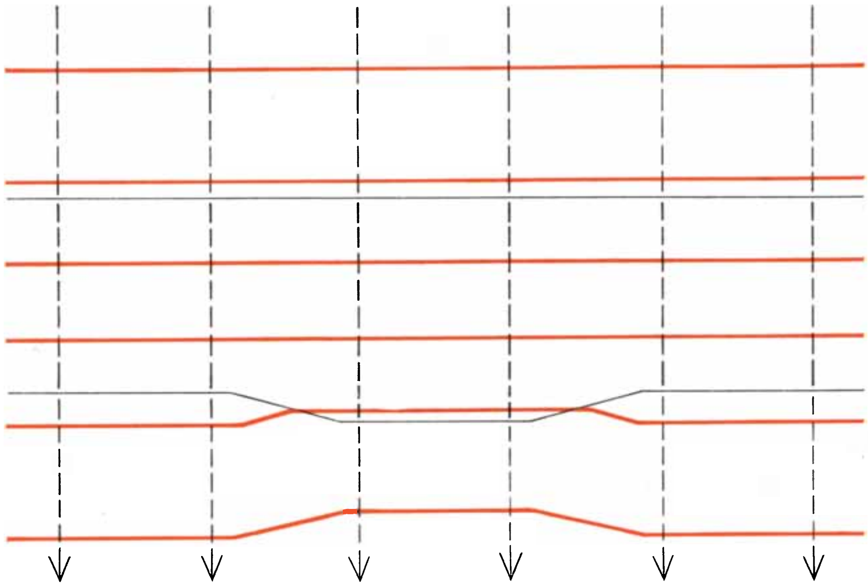
The design process was greatly accelerated with the advent of high-speed digital computers, which also made possible the development of a new pictorial tool, the spot diagram. With the computer a very large number of rays can be traced for a single object point. The interactions of these rays on the image surface provide a dot pattern that represents the image of that point [*see illustration at right*]. Such diagrams, determined geometrically, are good representations of the image when the aberration is large, but the better the lens, the less adequate they become. The reason is that diffraction effects (discussed in the opening article of this issue) become relatively more important as aberration effects are reduced. It is possible with a computer actually to calculate the diffraction image, but the procedure is cumbersome and not generally appropriate for engineering applications. The real importance of the computer in optics has been in the development of remarkable new processes of "automatic lens design," processes that are able to cope with the complexity of modern high-quality lenses that must perform near the physical limit set by diffraction.

The problem of the lens designer is essentially to adjust the variables of the lens formula so as to bring the quality of the image to some predetermined level. A lens may have as many as 10 or more elements, and so the number of variables affecting it (curvature, thickness, spacing and glass type of the elements) can add up to 50 or more. The number of variables defining image quality is also large because a number of different things must be considered for several different object points and for several different colors of light.

The designer usually begins by assuming an approximate lens configuration and then adjusts the elements in an orderly way, testing his results as he goes along, until he achieves the desired image quality. His problem has been compared to the situation of the explorer dropped without maps into the Himalayas and asked to find Mount Everest: he can always find a local peak by climbing upward, but he can never know it is the highest peak in the range until he descends into a valley and tries a new direction—and even then he has limited data on the basis of which to avoid another false ascent. Similarly, the designer, in his multidimensional space, can arrange for a suitably programmed com-



SPOT DIAGRAM was constructed by computer by D. H. Schulte to test his design for a 150-inch telescope. The diagram shows how the system would handle rays of parallel light entering its aperture (as from a distant point source) at many different points, each represented by a symbol in the schematic diagram (*top*). Ideally the image should be a point. In fact it varies from a good circle only about .25 second of arc (1/14,000 degree) in diameter (*spot at top center*) to more spread-out patterns as the image plane is moved (*columns*) and as the angle the rays make with the system's axis goes from zero to 1/4 degree (*rows*).

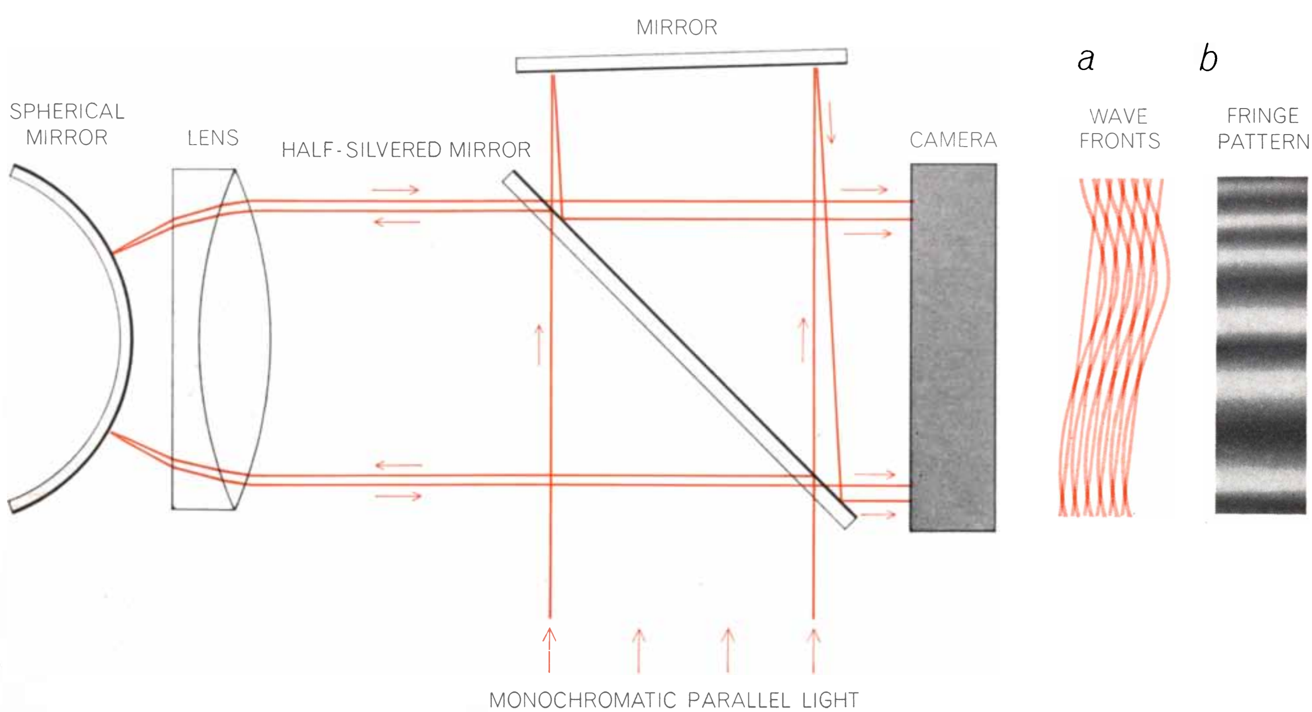


ERROR IN A LENS is manifested in the emerging wave front. In this diagram (with large vertical exaggeration) a straight-line wave front (*color*) formed by parallel light rays (*broken lines*) moves through a faulty piece of flat glass and is deformed from flatness by a bump.

puter to begin with the trial lens configuration and quickly adjust the variables to find the local optimum. If a suitable optimum is not achieved, the computer programs can move across the "valley" to a nearby "peak"—a slightly different lens design. If an adequate solution is not found nearby, however, the designer himself must take some action to move to a quite different region of the mountain range to find a new area of solution. The computer programs devised by a number of independent workers in different parts of the world to solve these problems are among the most complex ever developed. (Much of the complexity lies in the fact that these programs must produce not just a mathematically acceptable solution but one composed of practical lens elements that can be manufactured. Every designer remembers his frustrations with computer programs that produced lenses of negative thickness or other physically impossible—let alone undesirable—configurations.)

Automated lens design or not, the main problem remains of choosing the image-quality variables: the terms in which the optimum solution is to be described. That depends in turn on an analysis of the objects of which images are to be formed. In discussing ray-tracing I referred to object points, and one can indeed treat the image of an extended object as a superposition of images of individual points on the object. This is possible because one can assume that each point is an independent radiator of light and that the light from the various points has no phase relation, or coherence. If the object is illuminated by laser light, the radiation will be coherent, and that is something else again [see "Applications of Laser Light," by Donald R. Herriott, page 140].

If an object can be regarded as an array of independent point sources of light, then it is important to consider how a lens system forms an image of such a point source. The fact is that, for fundamental reasons arising from the wave nature of light, a geometrical point

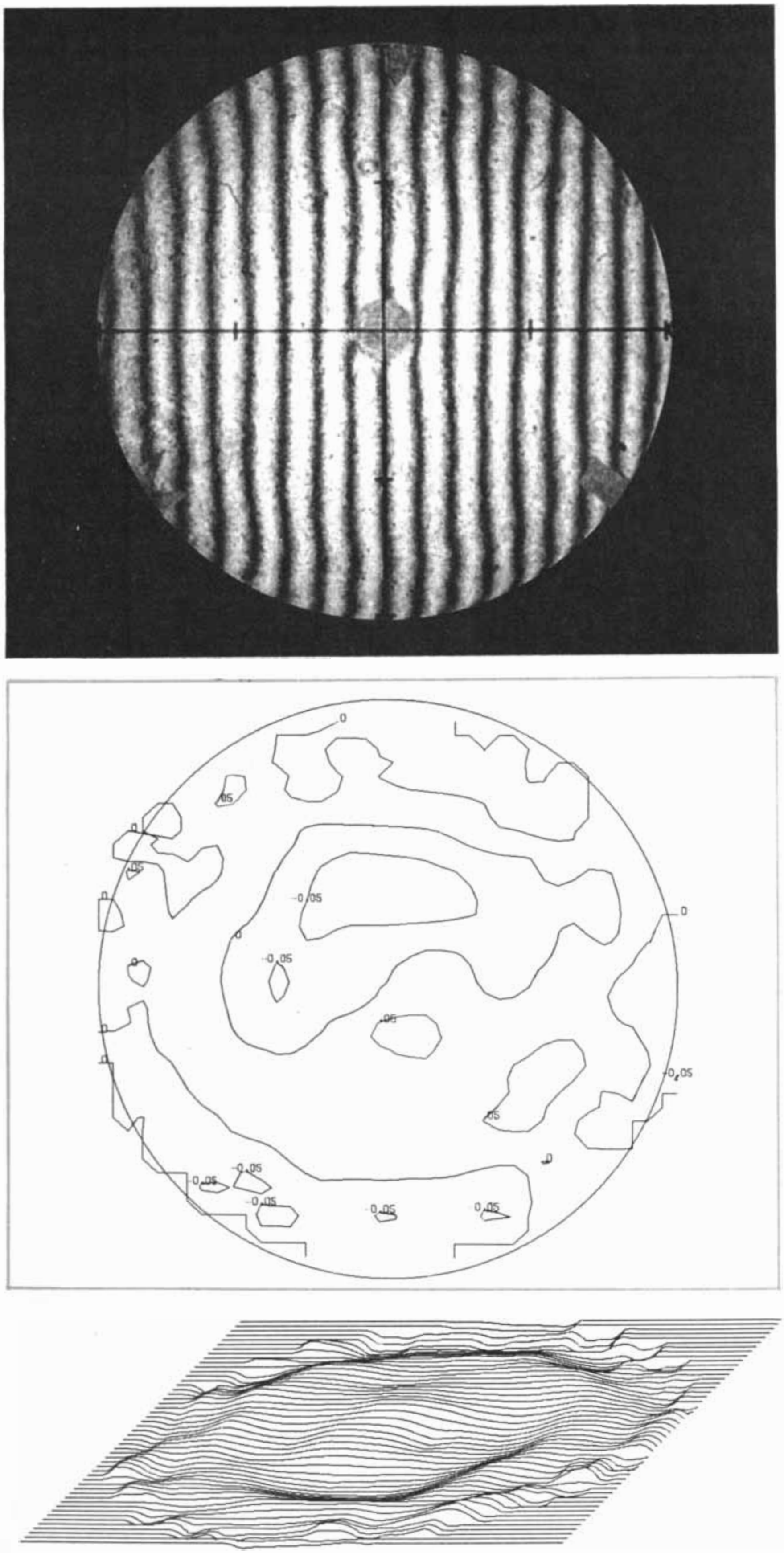


INTERFEROMETER is set up to measure the wave aberration, or error, in a lens or mirror by the Twyman method. Light deflected by the half-silvered mirror through the lens is reflected by the mirror. Any error in the lens or mirror will be manifested as a deviation from flatness in wave fronts returned by the lens-mirror combination to the beam splitter. When the light is recombined, perfect wave fronts from the flat mirror (*top*) and deformed ones from the test element interfere (*a*), forming fringes on film (*b*).

object cannot be imaged as a perfect point; at best it can form a diffraction pattern of a finite size. In the case of a circular aperture and an aberration-free lens, the pattern is the familiar one analyzed by the English astronomer George Biddell Airy in 1834: a central bright disk containing some 85 percent of the energy, surrounded by equally spaced and successively fainter rings [*see photograph at left on page 54*]. The diameter of the bright disk is a function of the wavelength of the light and the *f* number (the focal length divided by the aperture) of the lens. A perfect *f*/8 lens, for example, produces an Airy disk about eight microns (thousandths of a millimeter) in diameter. When the aberrations have been made very small, the spreading of each point of light by diffraction may become the main factor reducing the quality of the image, and must therefore be considered in the design of very good lenses.

The best way to do this is to regard each point object as the origin of a wave that enters the aperture of the lens system and is there converted into a wave emerging from the rear of the lens. Any error in the lens will be manifested as an error in the emerging wave front, as is most clearly seen in the case of a straight-line wave front moving through a flat piece of glass [*see top illustration on opposite page*]. In a lens the ideal emerging wave front is spherical, with its center of curvature at the image point (the focal point, in the case of a plane incident wave from a distant source). In a practical lens there will usually be errors in the sphericity of this emerging wave front. The errors are described by the wave aberration (*W*) of the lens, a function that gives, for each point in the emerging wave front, the linear separation (generally expressed in wavelengths) between the actual wave and some reference surface. A convenient reference is a sphere centered on the paraxial image, the image formed by rays near the axis of the lens [*see illustration on page 103*]. The concept of wave aberration is of such a fundamental nature that, as we shall see, it provides the most general single description of the optical performance of the lens. The importance of the concept was first recognized by Lord Rayleigh, who pointed out that reducing the wave aberration below a quarter of a wavelength often brought no practical improvement in the quality of the image.

The process of geometrical ray-tracing I described earlier can provide an exact determination of the shape of the emerging wave front since the wave



FRINGE PATTERN (*top*) is from a 50-inch mirror tested with a laser by a modified Twyman method. Several such patterns were automatically scanned and the resulting data were averaged by a computer to plot the contours (*middle*) and the perspective drawing (*bottom*) of the wave aberration. The "root mean square" aberration, or departure from a perfect wave front, is 1/34 wavelength, the maximum "peak to valley" distance 1/6 wavelength.

front is, at each point, perpendicular to the rays. Moreover, the wave-front shape is the traditional and correct starting point for calculating the diffraction pattern. Clearly, then, the wave front contains a full description of the image as it might be given by either geometrical or diffraction optics. What is even more important, the wave-front error of an actual lens or mirror can be measured, making it possible for the optician who is building the element to know the exact nature of the error in its surface and indeed giving him a map showing where the surface is too high and where it is too low. The wave front produced by a complete system can also be measured. The wave front thus connects the work of the designer of a system with the work of its builder.

For the designer the wave front provides the most convenient single criterion of lens performance and one that is preeminently suitable for computer programs. From the tentative design the values of the wave aberration W are determined with respect to a nearest-fitting reference sphere. The values are squared to eliminate negative numbers and averaged over the aperture, and the square root of this average is taken to yield the root-mean-square (RMS) wave aberration. This number turns out to be well correlated, in the case of high-quality images, with the overall quality of the image. Automatic design programs are often written to optimize the system specifically by adjusting for the minimum RMS wave aberration.

Although it is valid to consider an incoherently lighted object as an array of points to be examined one at a time, the designer often finds it better to evaluate the input to his system as an extended array of points in a particular pattern. Somewhat surprisingly, it is possible to analyze the complex, irregular pattern of light and dark that constitutes the surface of an object and predict how it will be formed into an image by a given optical system. The basis of the method is the "transfer function," which was developed as a theoretical concept over the past 20 years and has recently become available as a practical engineering tool now that certain difficult computational problems have been solved. The transfer function describes the ability of an optical system to form images of a particular class of extended objects: incoherently illuminated arrays of bars each of which has a sinusoidal variation in brightness. The point is that any physical scene can be regarded as a superposition of sinusoidal patterns (and can be analyzed into such patterns by the process of Fourier analysis), just as a complex musical sound can be treated as a superposition of sinusoidal tones. This being so, one ought to be able to consider the behavior of an optical system in imaging individual spatial-frequency components much as one describes the fidelity of a sound system in reproducing tones over its required range. The transfer function is analogous to the frequency-response curve of a sound system.

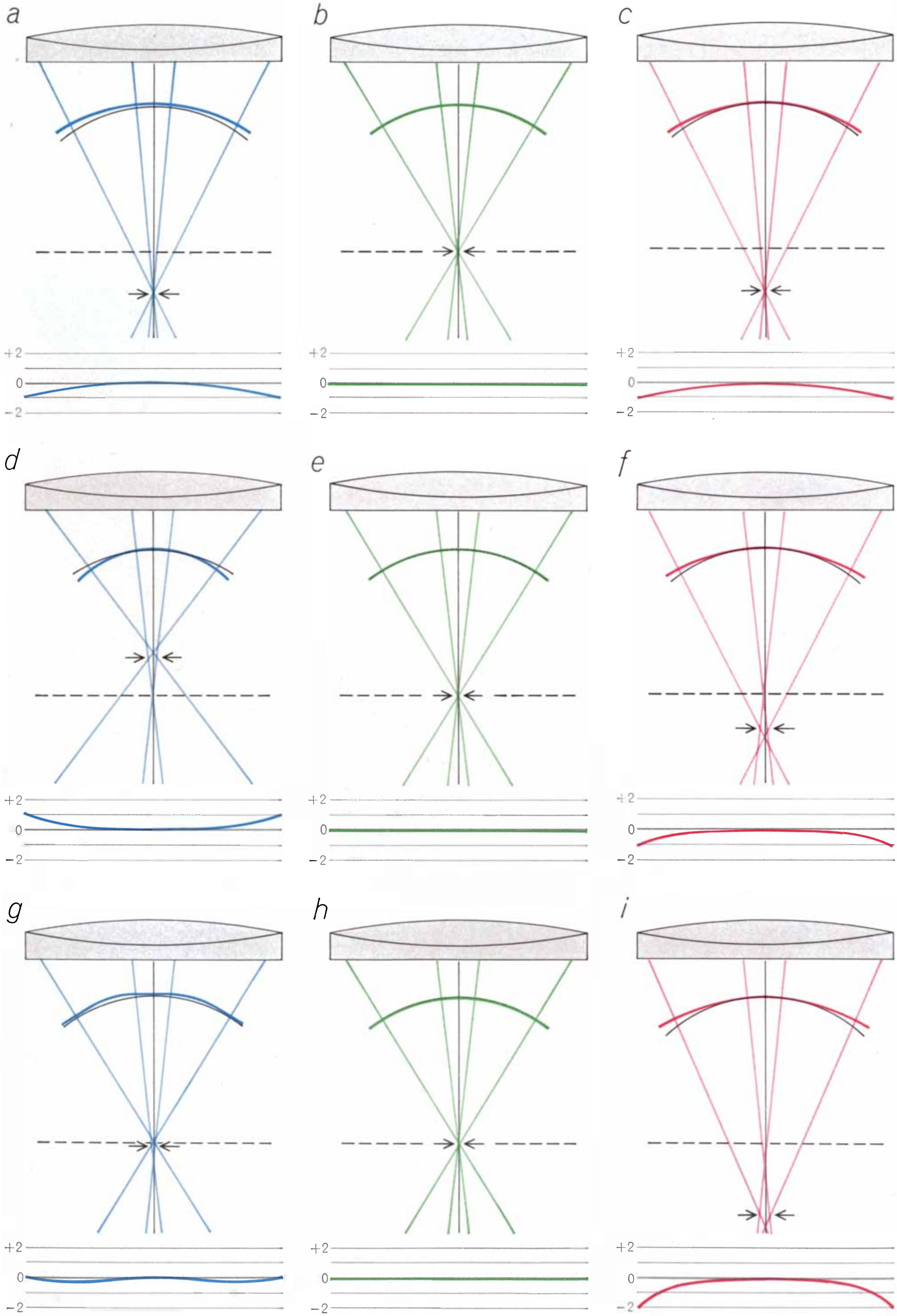
Any optical system, no matter what its aberrations, forms a sinusoidal image of a sinusoidal object. The image has the same spatial frequency as the object (multiplied by the system's constant magnification). That is, the system is linear. However, the image is not identical with the object because in any practical optical system there will be some loss of contrast: the light-to-dark ratio is reduced as some light spills from the light bands into the dark ones. The spillage increases as the bands are more closely spaced, so that the contrast eventually drops to zero. The ratio of the contrast of the image to that of the object, arbitrarily set at one for the limit of infinitely coarse bars, is the value of the transfer function at a particular spatial frequency. The transfer function is therefore a curve that gives the image contrast as a function of spatial frequency, usually expressed in cycles of light and dark per millimeter at the image plane [*see illustration on page 106*].

The transfer function provides a basis for predicting the performance of a single element or the overall performance of an optical system. For example, in an aerial camera the velocity of the vehicle usually causes a predictable amount of blurring in the image. The image motion can be described by a transfer function that, when multiplied by the function for the lens, gives an exact function for the combination of the two. The result can be combined with a transfer function for the photographic emulsion to predict the performance of the total system. (This last step is less exact because the emulsion's response is nonlinear; a sine-wave exposure does not always produce a sine-wave image in the emulsion.) Similarly, the transfer function can predict the image quality a lens will yield when it is combined with an electronic image detector such as a television camera tube.

The transfer function can be calculated from a description of the wave front, either from a computed wave front during the design stage or from an actual wave front measured in the laboratory. In the case of a perfect lens the computation is done rather easily. When the wave aberration is not zero, however, the calculation is complex and requires a large computer. Moreover, a number of similar calculations must be made for various orientations of the input sine-wave bars, since the optical system may respond to the different orientations quite differently.

A more powerful approach is to obtain the transfer function by first calculating the energy distribution in the image of a point source, that is, the extent to which light from a point source is spread out in the image. This procedure is possible because one can regard the point source as being composed equally of sinusoidal components with all possible wavelengths. Therefore if the image is decomposed into its sinusoidal components by a spatial Fourier analysis, the result is the transfer function. Recently Robert R. Shannon and his associates at the Itek Corporation, notably Steven H. Lerman and William A. Minnick, have worked out a practical system for making these computations through advanced programming methods. Their work used a new theoretical approach to the diffraction calculation of point images from wave-front data developed in England by Harold H. Hopkins, now at the University of Reading. The necessary Fourier decomposition had only recently been made practical for digital computers by a method of fast Fourier transformations that was introduced by James W. Cooley of the International Business Machines Corporation and John W. Tukey of Princeton University. Richard L. Mitchell, then at the Aerospace Corporation, developed a computer program with which

ABERRATIONS can be controlled by combining them. In a hypothetical example (*opposite page*) one lens has been fully corrected for simple chromatic aberration but its combined focus for red and blue light is still different from the focus for green (*a, b, c*). Another lens (*d, e, f*) has spherical aberration that varies with the color of the light. Combining the errors in the two lenses makes a lens with improved performance in blue light (*g, h, i*). In each diagram the marginal and paraxial rays are shown in color and their wave front (*color*) is compared with a perfectly spherical reference wave front (*black*); the broken line is the desired image plane and the arrows mark the best image attained by each lens. The curves below the diagrams give the wave aberration *W* of each lens in wavelengths.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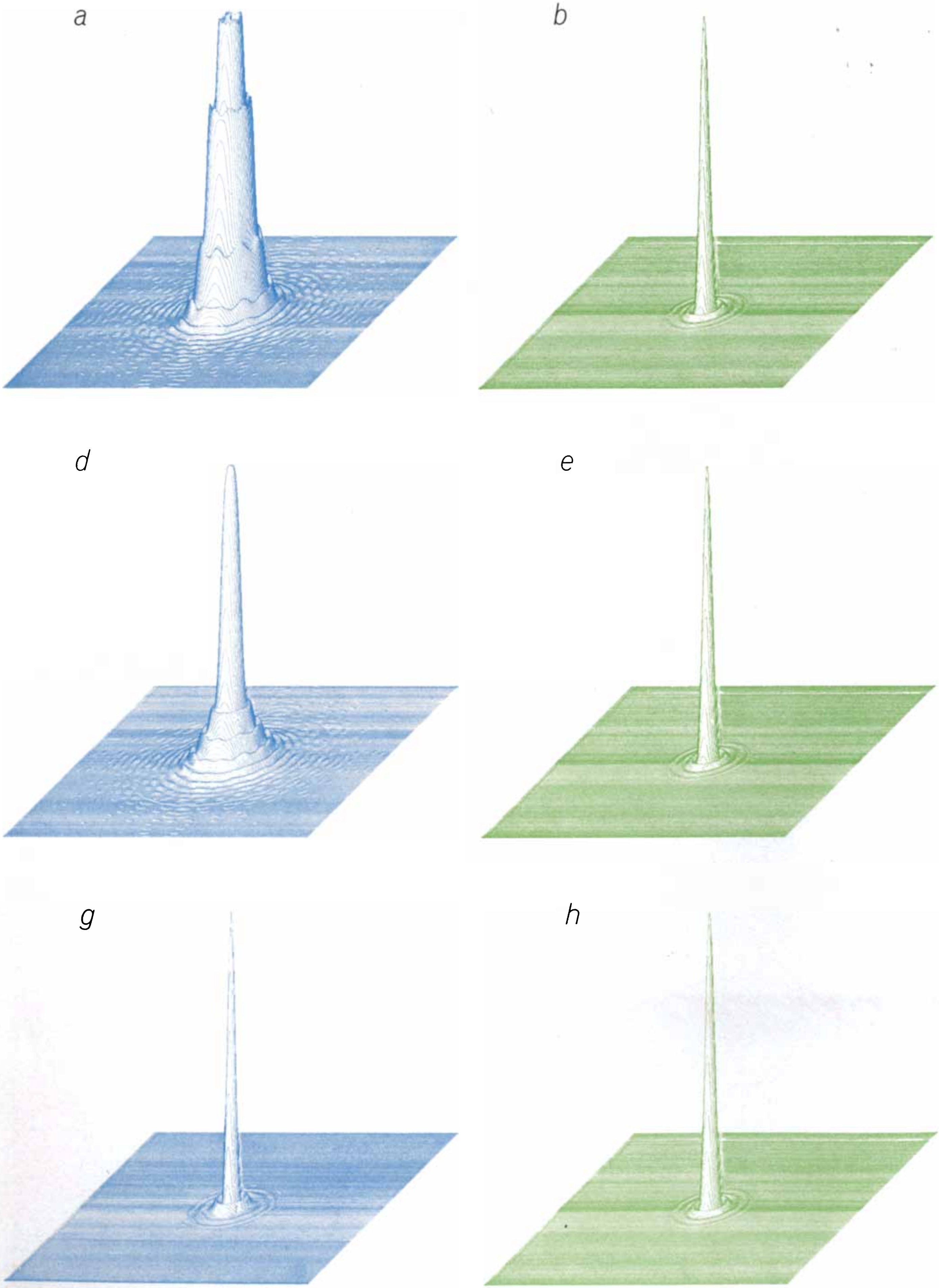
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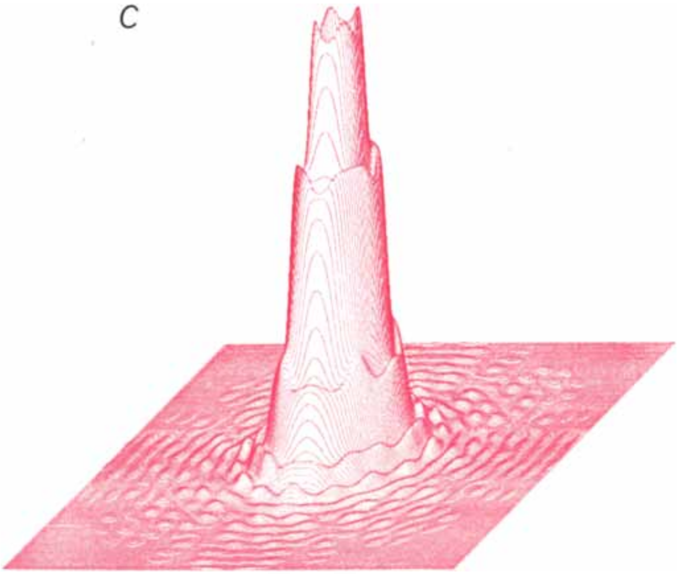

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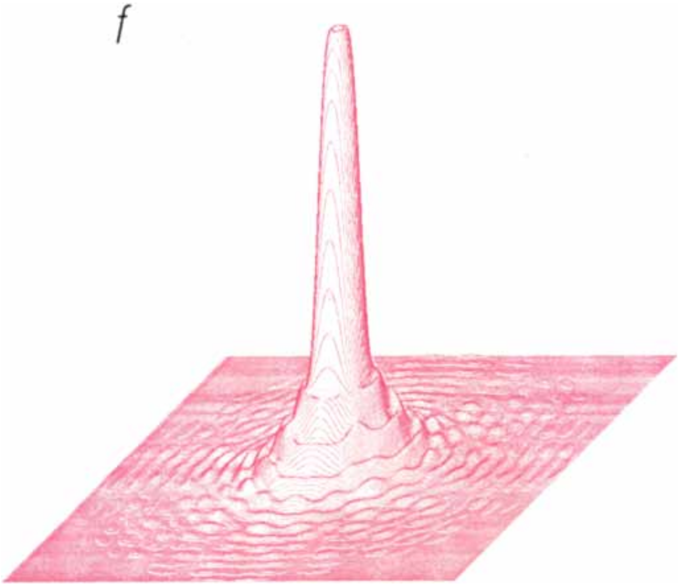

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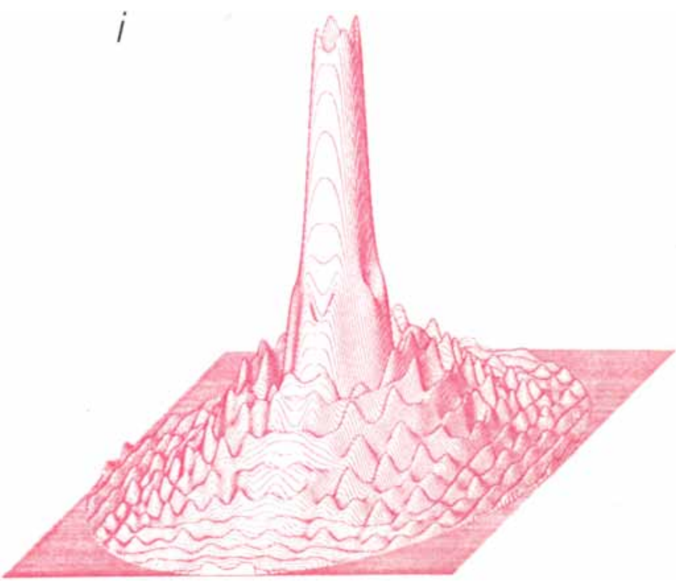


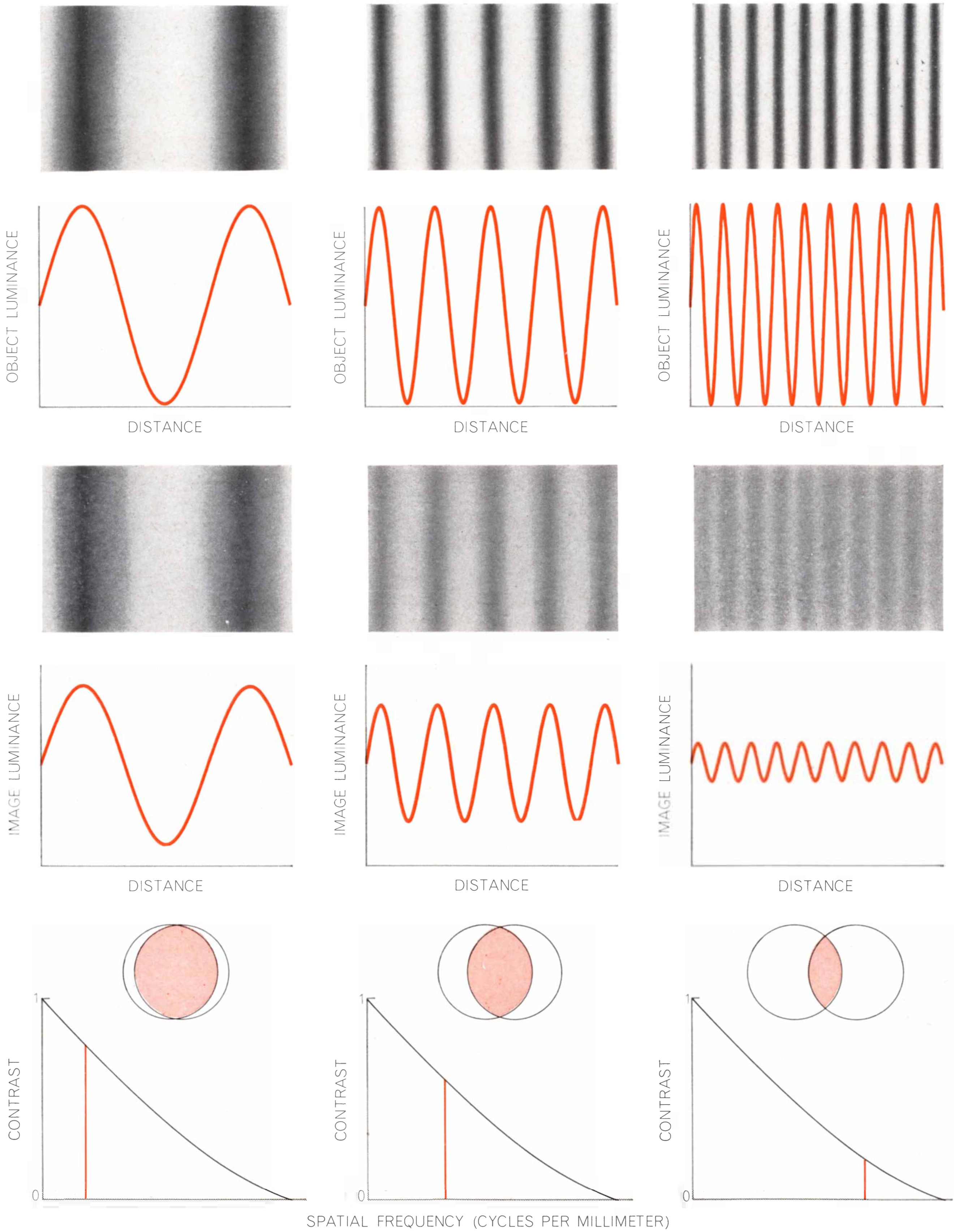
energy distribution and transfer function results can be automatically plotted in perspective [*see illustrations on these two pages and at top of page 108*].

As I pointed out earlier, one of the great advantages of the new methods of optical designing is that they enable the designer of a lens and the man who must evaluate its performance to speak the same language—wave-front language. It is the laser that has made practical the actual measurement of wave-front aberrations for a wide range of lenses, but the basic procedure was worked out in England more than 40 years ago by F. Twyman, who devised a modification of the Michelson interferometer [see "How Light Is Analyzed," by Pierre Connes, page 72]. In the Twyman procedure light from a monochromatic source is divided by a half-reflecting mirror, with one part going to the lens under test and the other to a precisely flat optical surface. When the light beams are recombined, the resulting interference between the two produces a fringe pattern directly related to the wave aberration *W*. The pattern is interpreted as the contour lines on a topographic map are, except that the contour interval is half a wavelength instead of many feet. (The factor of one-half arises because the light passes twice through the lens being tested.)

Prior to the introduction of the laser, this method suffered from several limitations. Since the two interferometer beams must be in phase to produce useful interference, the two light paths cannot differ by more than the length of a single train of waves emitted by the light source, a few centimeters in the case of a pure mercury arc. Moreover, the test set-up must be kept vibration-free through the required exposure time, which was particularly difficult in the case of large lenses and mirrors. The laser solved both problems. Continuous gas lasers provide coherence lengths of many feet and sufficient power to allow fast recording of fringe patterns and thus minimize vibration effects.

A basic limitation of the interferom-

PERFORMANCE of each lens-light combination diagrammed on page 103 is represented visually in computer-plotted graphs of the distribution of energy in point images (*left*), each a three-dimensional graph of light intensity (*vertical*) against distance in the image plane. A slender peak means a good image (*b, e, g, h*). The large aberration of the third lens in red light is evident (*i*). (Small, asymmetrically distributed irregularities are artifacts of computer process.)

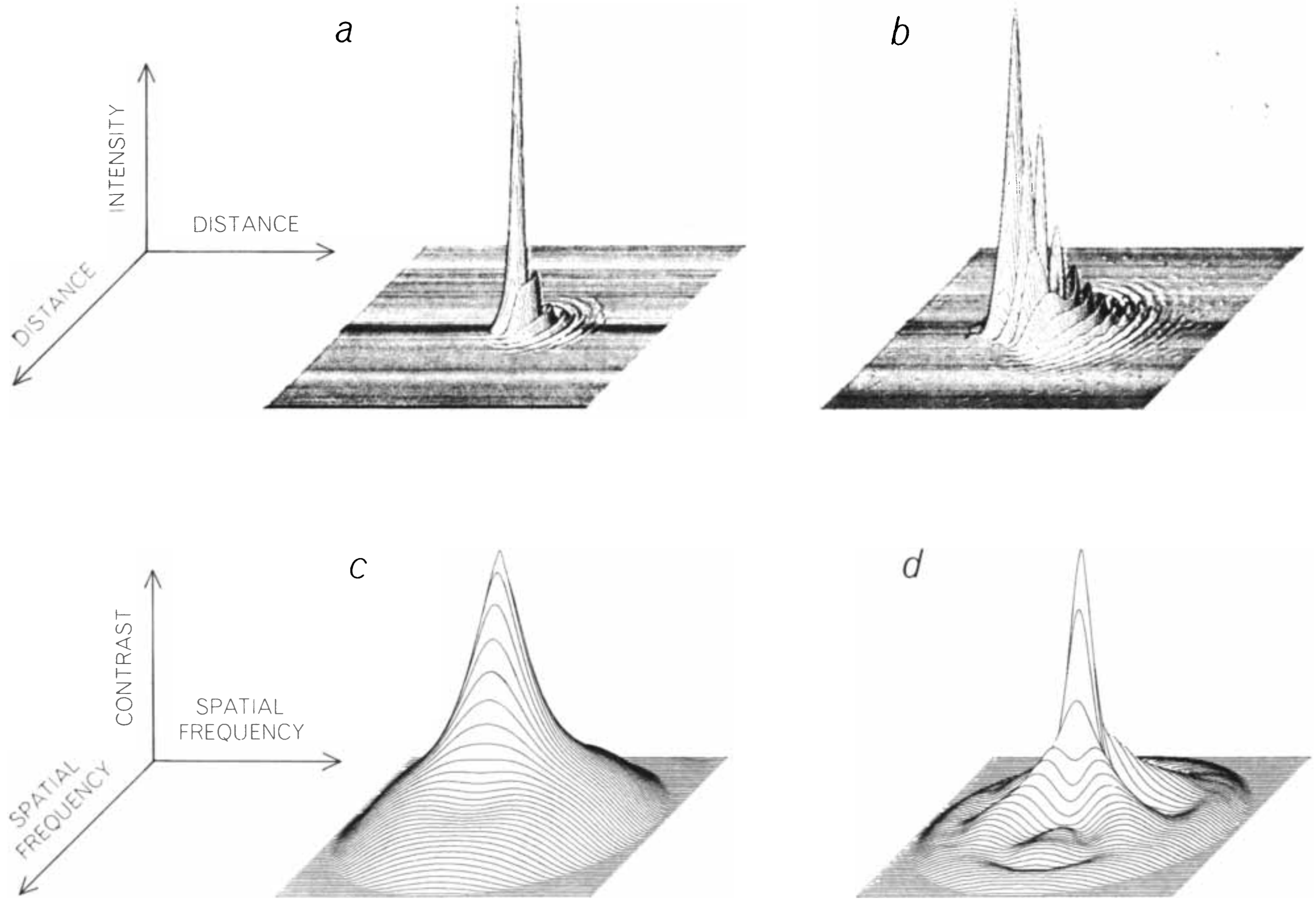


TRANSFER FUNCTION, a description of an optical system's ability to preserve contrast, is based on the change of contrast with decreasing spacing of an array of bars having a sinusoidal variation in contrast. Three such arrays and their intensity-v.-distance curves are shown (*top*) along with their images (*middle*). For a perfect system the falloff in contrast is given by the transfer-function curves (*bottom*). The value of the function at each spatial frequency (the ratio of the amplitudes of the sine waves above) is given by the colored vertical lines. The ratio is also given by the areas common to each pair of circles representing the aperture.

eter method has to do with extracting data from the fringe pattern; specifically, it is not easy to determine the reference surface from which the aberration distance to the wave front should be measured. Large computers can solve this problem. At the Itek Corporation, for example, we now scan the fringe pattern automatically; from the resulting data, the computer determines the "best fit" reference surface with the smallest average separation from the measured wave front and then maps the error contours at height intervals much smaller than the one-wavelength intervals of the original fringe data [*see illustration on page 101*]. The wave front map can be used to guide a technician in further stages of manufacture, to compare his result with the original design or to compute the transfer function and other criteria of image quality, such as the image of a point source or of more complex objects. The contour map, in other words, bridges gaps between divisions of optical technology more satisfactorily than earlier methods.

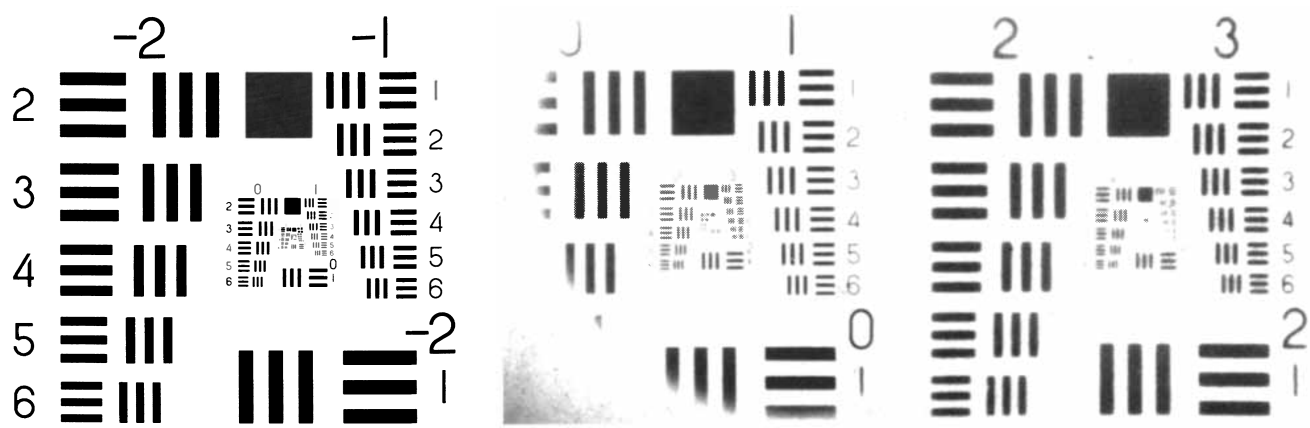
The importance of this bridge cannot be overestimated. The creation of an optical instrument such as an aerial camera or a telescope involves a number of steps. An overall design concept sets specifications for mechanical components as well as the lens itself, taking into account the relation with the image detector: photographic emulsion, television camera or photometer, for example. For the lens, there follow separate stages of design, fabrication and testing, each of which demands evaluation. Are the design aberrations small enough? Is a lens that is being polished smooth enough? Does the assembled lens produce a good enough image? Does the completed system produce test pictures on film that meet the original specifications? Over the years different criteria were developed for answering such questions at different stages, and the criteria could not be related accurately one to another. Now finally the optician can be sure when his optical surface is good enough and the assembler can be sure that the image he observes in the finished lens is what the designer predicted.

The developments I have described constitute important changes in optical technology. For decades much of optics has been an art, with craftsmanship and intuition playing dominant roles. Now there begins to be a connected scientific base for new technological developments. The advanced optical systems needed for space astronomy will

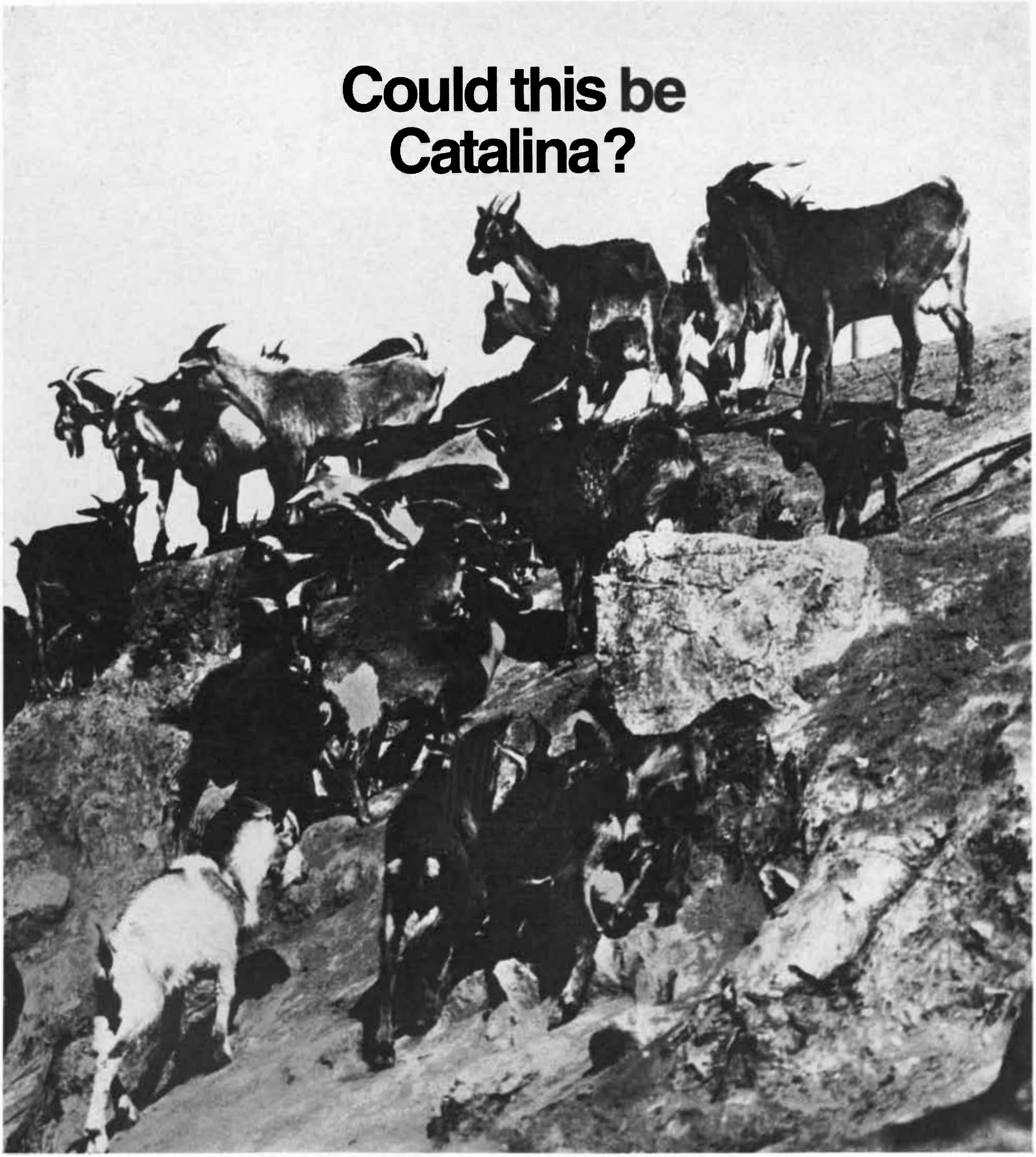


WAVE-FRONT DATA can be used to give the energy distribution, from which in turn the transfer function can be calculated. The transfer function can be plotted in three dimensions. Here energy-distribution (*top*) and associated transfer-function (*bottom*) graphs are shown for two instances of coma, an aberration in which light at an angle to the lens axis is focused asymmetrically.

be the first beneficiaries of this new technology, but the impact is already being felt in the development of commercial optics. Until recently commercial optical elements have had wave aberrations of from one to a few wavelengths. In that aberration range, ray optics provides an adequate description of performance, with light from each region of the aperture contributing incoherently to the image. When the wave aberration becomes a fraction of a wavelength, contributions from each part of the aperture combine coherently. As this begins to happen the energy within the image begins to concentrate rapidly and there is an improvement in quality quite out of proportion to the reduction in aberration. Even commercial lens systems are moving into this fractional-wavelength region. The new computer and measurement technologies will make practical increasingly complex optical systems of unprecedented performance.



BAR TARGET can be used to test the resolving power of a lens-film combination. The Air Force target reproduced here actual size (*left*) has groups of six target pairs, each group half as large as the preceding one. The large numbers give the lines per millimeter in powers of 2; for example, 2^0 means one line per millimeter, 2^3 eight lines. The smaller numbers specify intermediate sizes. Images (*center and right*) of successively smaller parts of the target were formed, after five-diameter reduction, by a large *f*/3.5 lens on aerial film. Read with a microscope, the image at the right indicates that the system can resolve to about 300 lines per millimeter.



Maybe you picture Catalina Island as a lush green paradise. It is not. Over 90% of the island is barren and dry—a great place for wild goats.

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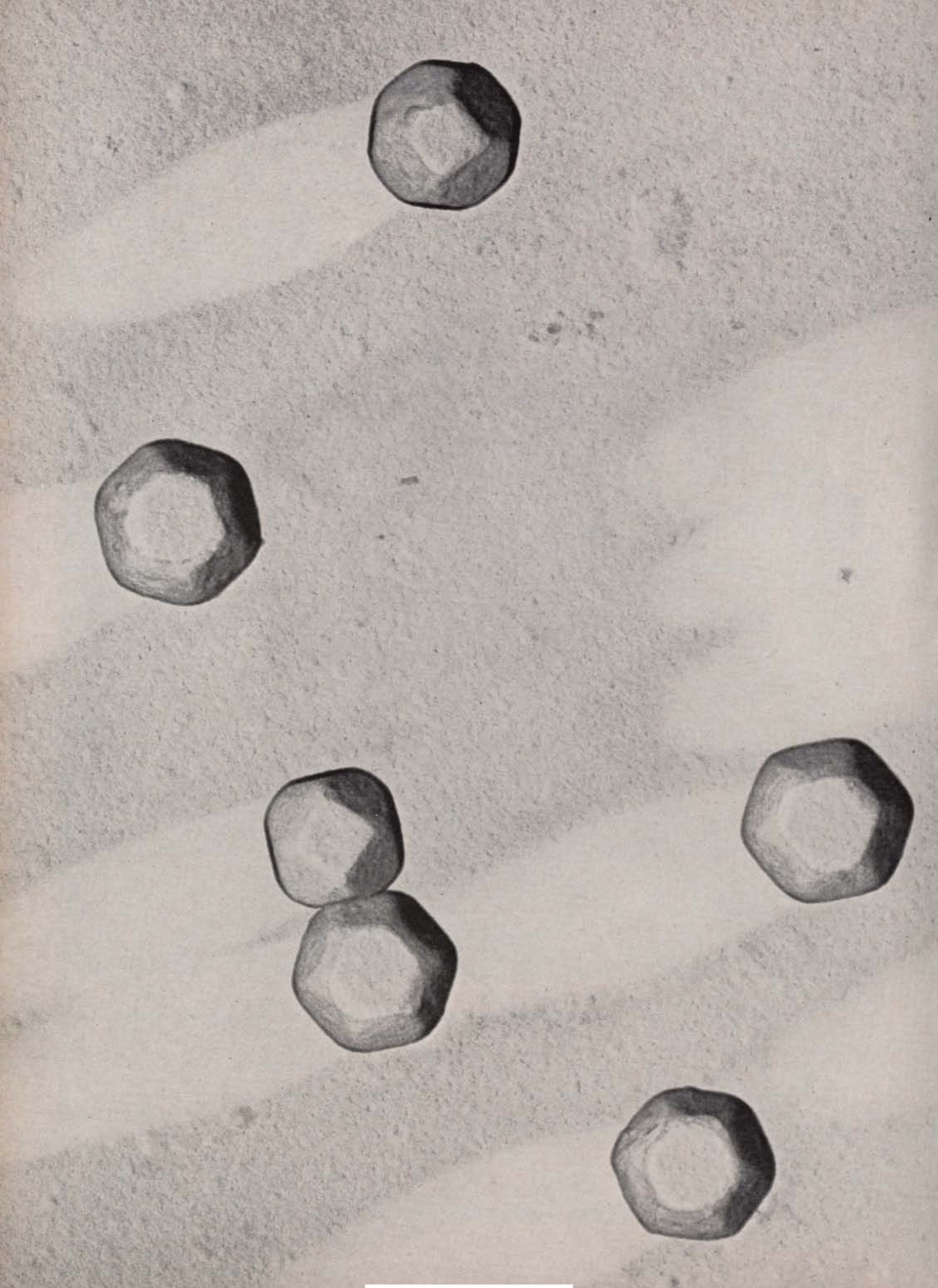


How Images Are Detected

The most versatile detector of light images is the visual system of vertebrates. Nonetheless, photographic emulsions and electronic image detectors improve on biological systems in significant ways

by R. Clark Jones

Today images are widely detected by such means as photographic emulsions and specialized electron tubes, but the most versatile detector of images remains the visual system of vertebrates. Even so, artificial image detectors can now outperform biological systems in certain highly important ways. In this regard it is instructive to compare the performance of the human visual system with artificial image detectors. The comparison can be made quantitatively by means of a measure called the detective quantum efficiency, or DQE. The DQE indicates the degree to which the signal-to-noise ratio in the output of the detector approaches the signal-to-noise ratio in the light image. In less exact language, the DQE is the ratio of the information in the detector's output to the information in the light image.

The train of thought that gave rise to the DQE, and the means of computing the DQE, are best dealt with later. The results of several computations, however, are shown in the illustration on page 114. It is evident from the illustration that over certain limited ranges of light intensity such electronic devices as the image orthicon tube (used in television) and the Carnegie image tube (used in astronomy) have a higher DQE than the eye does. Many photographic emulsions have a DQE nearly equal to the DQE of human vision but only over a very narrow range of light intensity.

The remarkable fact about the human visual system is that its DQE is substantially constant over an enormous range of light intensity. If the luminance of the scene is expressed in millilamberts, the visual system has a nearly constant DQE from 10^{-5} millilambert to 1,000 millilamberts—a range of 100 million to one. Considered on the same scale the typical image orthicon tube has a range of about 500 to one, and the range of the photographic emulsions listed in the illustration is about 50 to one.

The vast working range of the human visual system is the despair of the designers of image detectors but it is also their goal. How does this system achieve its remarkable performance? Let us briefly consider the structure and function of the eye.

The retina consists of millions of individual detectors: the rod cells and cone cells. There are about 100 million rods and five million cones, each of which has a firing rate proportional to the amount of light it receives at low firing rates and roughly proportional to the logarithm of the light intensity at higher firing rates. The rods and cones of course function as an assemblage, and their output is correlated in various ways along the visual pathway from the retina to the cortex of the brain.

The rods are involved in the detection of light at low levels of intensity. The cones function at higher levels. At very low levels, close to the threshold at which the dark-adapted eye can detect light, many of the rods—those in a region about one degree in diameter on the spherical surface of the retina—are connected so that they all feed one giant ganglion cell. If just a few rods in this region are triggered by absorbing as small a number of photons as one per rod, a flash of light is perceived. Indeed, a group of investigators in the Netherlands (led by Maarten A. Bouman of the State University of Utrecht) believes that only two rods need to be fired by one photon each to yield the perception of a flash. It is important that at least two rods be fired; otherwise the inevitable random thermal firing of the rods would give rise to constant spurious sensations of light.

As the luminance increases, the interconnection of the receptors is changed. When the luminance has reached the normal reading level of between 10 and 100 millilamberts, the best DQE is obtained for objects only a tenth of a degree in diameter. (The full moon is half a degree in diameter.) A comparison of the eye's DQE at various levels of illumination is shown in the illustration on page 115.

Over the eye's working range of 100 million to one in light intensity the speed of response changes by a factor of five. The area of best DQE changes by a factor of 100. The contrast that can be perceived runs from 100 percent to 2 percent. The area of the pupil changes by a factor of 10.

Not the least of the eye's remarkable capacities is that its gain control, which is roughly analogous to the automatic volume-control circuit of a radio receiver, is kept adjusted over the entire range so that the noise in the perceived image is held at just about the threshold of perception. The gain adjustment takes time, particularly when one is moving into a dark environment from a light one. Complete adaptation to darkness from sunlit conditions takes about 30 minutes. That period of time is entirely appropriate for the gradual darkening of the evening, but it can put serious limits on vision in other circumstances. An example is the demand placed on the vision

SILVER HALIDE GRAINS that are the light detectors in photographic emulsions appear greatly enlarged in the electron micrograph on the opposite page. The actual size of the grains is between 600 and 800 nanometers. Detection of an image begins when a photon of light from the image strikes a grain and changes the arrangement of electrons in the grain.

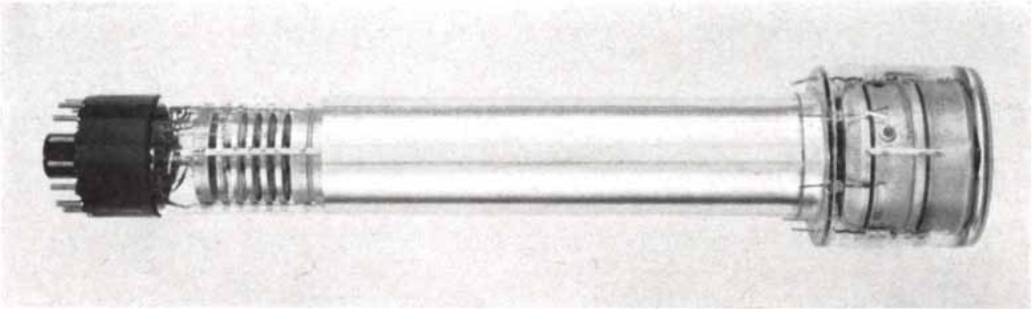
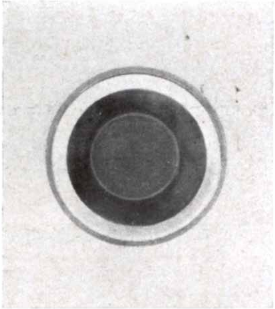
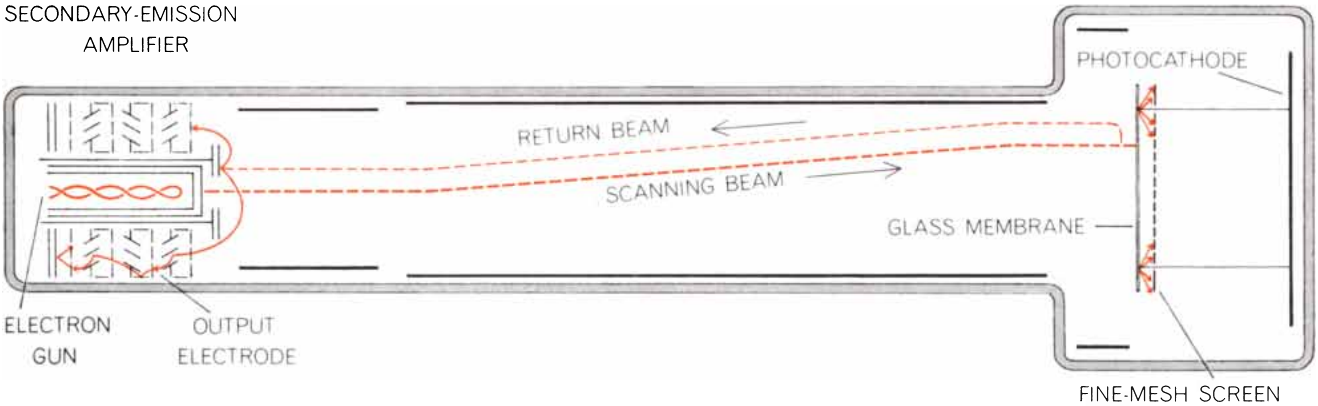



IMAGE ORTHICON TUBE used in television cameras is 15 inches long. Its three-inch light-detecting surface, which is at right in the side view, is shown end on in the adjacent view. Operating principle of an image orthicon tube is shown in the illustration below.



FUNCTIONING of an image orthicon tube is based on a photocathode on which light is focused by the lens of the television camera. The lens is not shown but in this instance would be to the right of the photocathode. The light causes the emission of electrons from the left side of the photocathode. They are accelerated by an electric charge and strike the glass membrane, where they are held briefly by a positive charge augmented by the fine-mesh screen that is 50 microns from the membrane. A beam of electrons from the gun at left scans the membrane and carries off the image. The return beam is amplified at left to yield output of tube.

of an airplane pilot facing the setting sun just before he descends through a heavy overcast for a landing.

The capability of the human visual system can be described in various other ways. Let us consider the system's ability to perceive stars. In a completely dark room an observer adapted to the darkness could detect with the unaided eye a star with a magnitude of +7. (The higher the positive magnitude number, the fainter the star. The brightest star in the Little Dipper, the star at the end of the handle, has a magnitude of +2.) The background light of the night sky limits this performance; outdoors on a dark night the best an observer can do is to perceive a star of about magnitude +5 at sea level and about +6 at mountain altitudes, where the background light of the sky is fainter.

The assistance provided by a telescope is in magnification rather than brightness. The largest telescope that could usefully be employed for direct viewing of stars should magnify the faintest visible star so that the image on the retina is about one degree in diameter. (This is not related to the diameter of the star; no star can be resolved into a disk, even by the largest telescope.) When stars are viewed with the unaided eye, the diameter of the image on the retina is about one second; hence an increase to one degree requires a magnification of 3,600 diameters. The magnification will be excessive and pointless, however, unless the light falls on the eye across the entire pupil. Since the pupil is about .8 centimeter in diameter under starlit conditions, the collecting lens must be 3,600 × .8, or nearly 30 meters in diameter. Inasmuch as the largest telescope—the one on Palomar Mountain—has a collecting mirror only five meters (200 inches) in diameter, it follows that no telescope in existence can do an optimal job of enabling the human eye to detect stars. On this basis the maximum useful magnification of a five-meter telescope for single stars is about 600. For larger and much brighter objects or systems such as the moon and close double stars, however, higher magnifications are useful.

Quite another kind of instrument used to aid vision is the image-intensifier tube, which has evolved in several forms. The key feature in each case is that the instrument has a collecting lens or mirror that, like the lens or mirror of a telescope, is much larger in diameter than the pupil of the eye. Within its range of light intensity the tube also has a better DQE than human vision does. For these reasons the tube greatly increases the signal-to-noise ratio in the output image that is viewed by a human observer. He is thus able to see things he could not see with unaided vision.

An intensifier tube, unlike a telescope, increases the luminance of the image. Moreover, there is no optical limit to the size of the collecting lens that can be used. Suppose one is looking at a starlit landscape or a very dim fluorescent X-ray screen at a luminance of 10^{-5} millilambert. The unaided visual system can perceive the scene, but the perception is slow. One reason is that the visual system is intrinsically slower at low levels of light. Moreover, one must slightly avert one's eyes, because the fovea—the small rodless area of the retina that provides the most acute vision—does not function at low levels of light, and one's perception of relations in the field of vision is slow with averted vision.

Suppose the luminance of the scene is

increased to 10 millilamberts—that is, by a factor of a million—by an image tube. If one has been using magnification to bring the diameter of the object of interest to one degree, the magnification can be reduced by a factor of 10, since at 10 millilamberts the critical object can be best perceived at a diameter of .1 degree. In addition the increase in luminance means that the visual system can use foveal vision, can scan the scene quickly and can use its normal ability to rapidly perceive the relations between the parts of the scene.

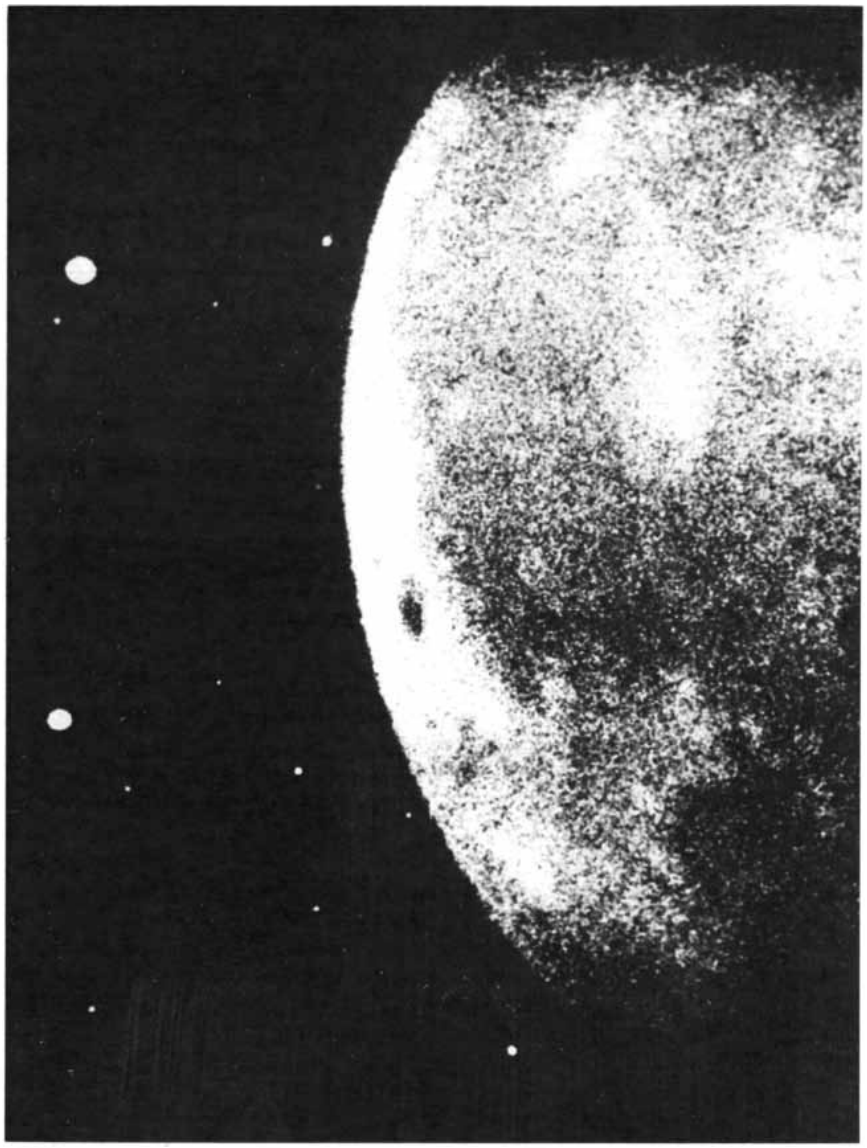
The principal use for image tubes to assist vision has so far been military. A recently developed device used by the U.S. Army employs six fiber-optic faceplates, together with electrostatic focusing to avoid the weight of the magnets used in the astronomical image tubes. It amplifies by a factor of 40,000 the light the unaided eye could receive from a scene. The tube has three stages of amplification, each consisting of a photocathode at the forward end and a phosphor at the rear. When light strikes the photocathode, electrons are ejected toward the phosphor. The beam of electrons is accelerated by an electrostatic field and focused on the phosphor, which converts the energy of the beam into visible light. The third stage of the device is coupled to a magnifying eyepiece. Power is supplied by a battery.

An important class of image detectors is made up of instruments that involve scanning with an electron beam, so that the light image is converted into a video signal. A convenient but not too specific term for the class is electronic image detectors. Their major role is in technology: they are the image detectors in television cameras. Such detectors are also becoming increasingly useful in astronomy.

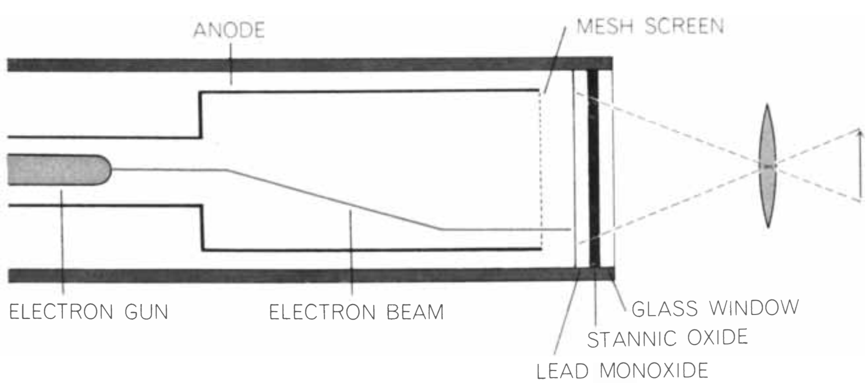
Most of the electronic image detectors are photoemissive. When a photoemissive surface absorbs light, it emits electrons. One kind of device, the modern vidicon used in television cameras, is photoconductive: when the light-sensitive surface absorbs light, its electrical conductivity changes.

All the photoemissive devices receive the light image on a semitransparent photocathode that is on the inside of an evacuated chamber. Light striking one side of the photocathode causes photoelectrons to be ejected from the other side into the vacuum. The spatial distribution of the electrons as they leave the photocathode is an excellent replica of the light that falls on the photocathode.

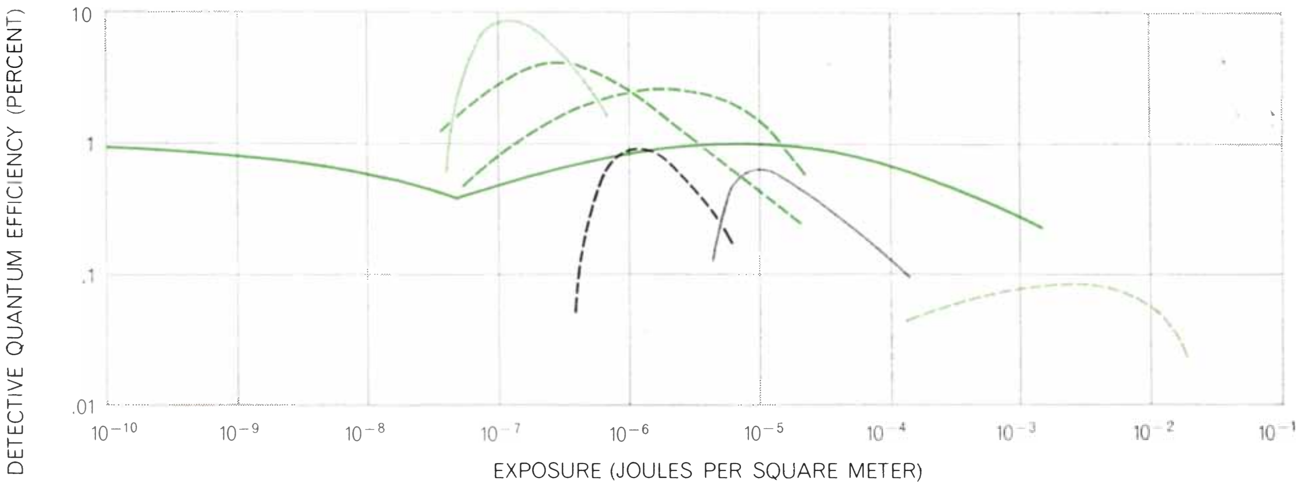
The emissive devices differ only in the



MOON IN ECLIPSE by the earth was photographed during totality through a telescope equipped with an image orthicon. Because the image orthicon has a higher level of efficiency in detecting light than photographic emulsion does, the half-second exposure was only about a fiftieth as long as would have been needed otherwise. The photograph was made by J. R. Dunlap of Northwestern University's Corralitos Observatory in New Mexico.



VIDICON TYPE of image detector for television cameras operates by photoconductivity. In the Philips Plumbicon, for example, a glass window (*right*) has on its inside a transparent layer of stannic oxide and a photoconducting layer of lead monoxide. Light striking the stannic oxide is conducted as a current by the lead monoxide. The photoconducting layer is scanned by an electron beam that is accelerated by the anode. The fine-mesh screen makes the electric field between the anode and the photoconducting layer more uniform.



CAPABILITY OF DETECTORS over a range of light intensity is compared by means of the detective quantum efficiency, a measure of performance. The three top curves represent respectively the Carnegie image tube used in astronomy and two of the orthicons used in television cameras. The long colored curve represents human vision; the notch in the curve indicates where the system switches from rod to cone vision. Black curves represent two kinds of photographic film. Colored curve at right reflects the performance of an early-model vidicon used in television cameras; vidicons have been considerably improved since evaluation was made.

way they convert the image formed by the photoelectrons into an image that is visible to a human observer. One such device, the image orthicon, is used both in television cameras and in astronomy. Two others, the Lallemand electronic camera and the Carnegie image intensifier, are used only in astronomy.

The development of the image orthicon tube by the Radio Corporation of America in the late 1930's made commercial television practical. In an image orthicon tube the photoelectrons from the photocathode are accelerated by a charge of about 300 volts and are magnetically focused on a glass membrane that is only two microns thick [*see lower illustration on page 112*]. Each electron that hits the glass membrane ejects several secondary electrons. Since the electrons have a negative charge, the result is that the membrane acquires a positive charge whose magnitude is several times the charge of an electron. A metal screen with a very fine mesh is located about 50 microns from the membrane and held at a potential one or two volts positive with respect to the resting potential of the membrane. The effect of the screen is to increase the length of time the glass membrane can hold its charge and to make the potential of the membrane more nearly proportional to the charge; the result is that the membrane holds a replica of the original image.

Each point on the membrane is scanned every thirtieth of a second by a beam of electrons from an electron gun; the beam is focused and deflected by magnetic fields. The negative electrons discharge the positive membrane and carry away its image. The beam is carefully adjusted in two ways. First, its electrons are given just enough energy to return the glass membrane to zero potential. Second, the current of the beam—the number of electrons per second—is adjusted so that the beam can supply just enough charge to return the membrane to zero potential at the places where the membrane charge is greatest. At other places, where the membrane has less charge, some of the electrons will be reflected. They return toward the electron gun and there are deflected into a secondary-emission amplifier. The output of the amplifier is the television signal, which can be used to produce a visible image on the cathode ray tube of a television set.

When the image orthicon is used in astronomy, the glass membrane is usually replaced by a thin sheet of magnesium oxide. The magnesium oxide has a higher secondary-emission gain than the glass membrane and allows the charge to be stored for a much longer time. A telescope equipped with an image orthicon is particularly useful for astronomical problems where short exposures are essential. It is conceivable that a telescope thus equipped could be programmed to survey galaxies automatically so that they could be checked for supernovas by the comparison of two photographs made at different times.

In the Lallemand electronic camera, invented by André Lallemand of the Paris Observatory, the electrons from the photocathode are accelerated by a potential of between 20 and 40 kilovolts. They fall directly on an electron-sensitive photographic plate [*see illustration on page 116*]. This camera has been used successfully in France at a number of observatories and in the U.S. at the Lick Observatory and the Flagstaff Branch of the U.S. Naval Observatory. It is not likely to come into wide use, however, because great skill and application are required to operate it.

The basic difficulty is that the photocathode requires a very high vacuum for good performance. In such a vacuum it is extraordinarily difficult to handle the gases that leave the photographic plate. They can easily contaminate the photocathode, which is specially designed to release electrons easily but for that reason is highly reactive and readily oxidized. As a result the apparatus requires rigorous cleaning of internal parts, refrigeration of the photographic plate to hold down the escape of gas and various other steps to protect the cathode. For these reasons it requires about eight hours of painstaking work to prepare the Lallemand camera for a night's use.

A variant of the Lallemand tube has been developed by J. D. McGee of the Imperial College of Science and Technology. In it the electrons go through a mica window about 4.5 microns thick. The mica protects the cathode because it is impermeable to oxygen, but with 40-kilovolt acceleration most of the electrons go through. When the window is made in the form of a long, narrow strip (seven by 30 millimeters), it will withstand atmospheric pressure, but it requires very careful handling.

Under the best conditions the Lallemand camera has a DQE of 10 percent. This enables it to reduce exposure times by a factor of 10. These cameras also yield an image density that is directly proportional to the light exposure, which is not the case with photographic emulsions exposed to light. This feature simplifies the photometric analysis of spectrograms.

The Carnegie image tube arose from the desire of a number of astronomers for an image detector that would provide the gain of 10 to 20 in DQE that photocathodes have over photographic film. The Carnegie Institution of Washington initiated a project to develop such a detector. Under the leadership of Merle A. Tuve the group considered a wide variety of approaches and finally settled on a type of image intensifier.

In the Carnegie image intensifier, which is manufactured by RCA, the electrons from the photocathode are accelerated by about 10 kilovolts and are magnetically focused on a membrane formed like a sandwich [*see top illustration on page 117*]. The sandwich is a sheet of mica four microns thick with a phosphor on one side and a photocathode on the other. As the electrons from the first photocathode reach the sandwich they pass through an opaque film of aluminum, which prevents the feedback of light to the first photocathode, and then are absorbed by the phosphor. The light produced by the phosphor goes through the sheet of mica and produces photoelectrons at the second photocathode. The electrons from this photocathode are accelerated by 10 kilovolts and focused on a second phosphor screen, the image on which is focused on a photographic film by a lens system.

The sandwich has a gain of about 50, that is, about 50 electrons leave the second photocathode for every electron that strikes the adjacent phosphor. The total light gain of the tube is about 3,000. The lens system, however, can deliver only a small fraction of the phosphor's light output to the photographic film, so that the overall gain is only about 15. Some 35 of these tubes have been delivered to observatories, mostly in the U.S. They are used chiefly for spectroscopy of dim objects.

The vidicons, which operate on the principle of photoconductivity, surpass orthicons in simplicity and ease of operation. The early vidicons, however, were of limited usefulness because the picture they supplied was uneven at low levels of light and also because the vidicons had too slow a response at low levels. The vidicons were therefore restricted to applications where very high illumination could be provided; a typical use was in scanning motion-picture film for television broadcasting.

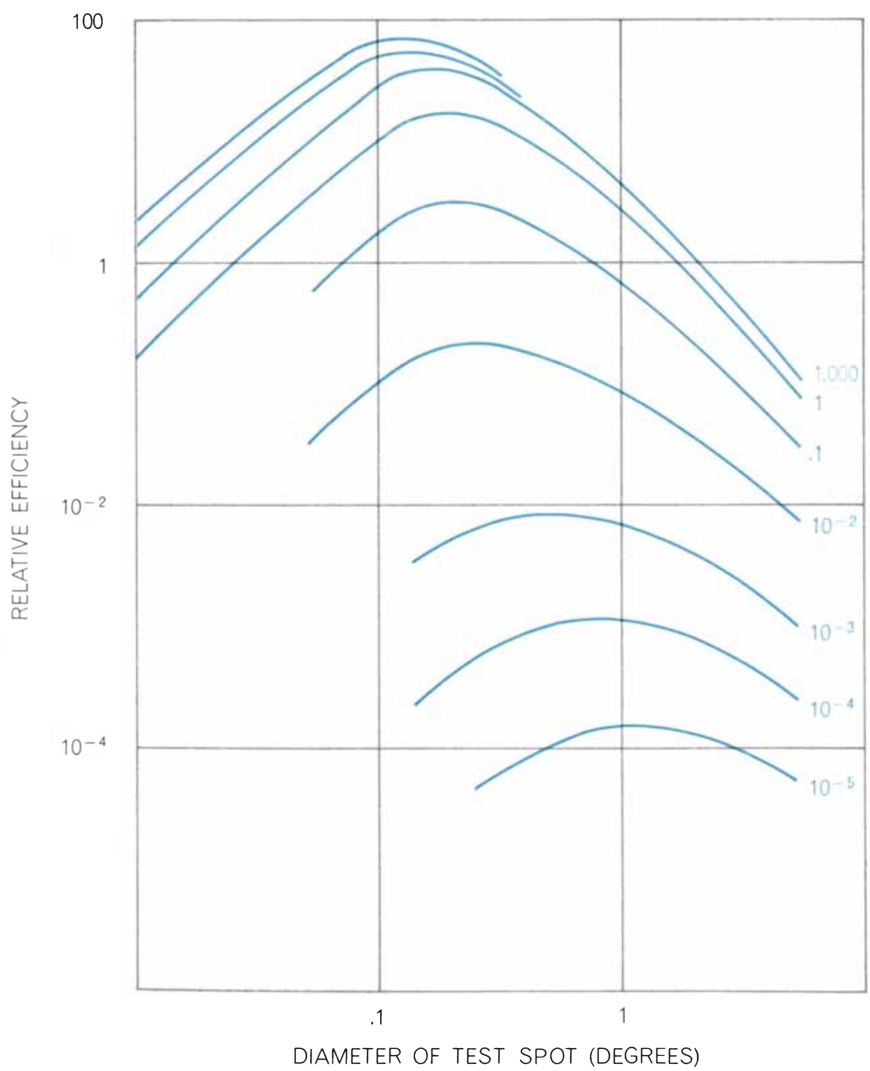
Vidicons have been considerably improved in recent years. As a result they have partly supplanted orthicons as the image detectors in television cameras. They are particularly valuable in the cameras used for color television.

A widely used modern device of the vidicon type is the Plumbicon, which was developed at the Philips Research Laboratories in the Netherlands. The heart of the device is a glass plate coated with a thin, transparent conducting layer of stannic (tin) oxide. A thin layer of lead monoxide, which is a photoconducting material, is deposited on the stannic oxide.

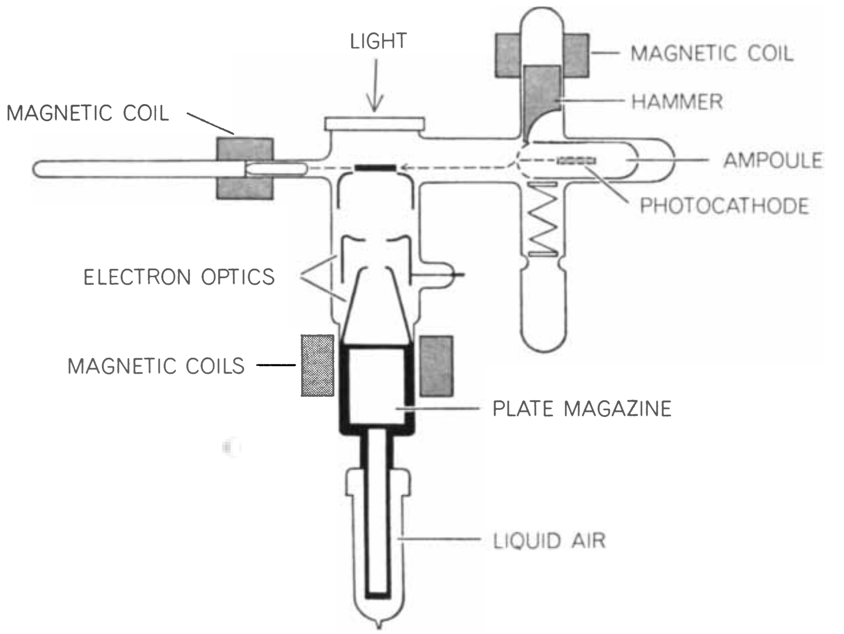
The scene to be transmitted is projected through the glass plate and the layer of stannic oxide onto the lead monoxide. A beam of slow electrons scans the other side of the lead monoxide layer; the current that flows to the stannic oxide varies with the conductivity of the lead monoxide and hence with the light level at different points in the scene. Thereafter the image is amplified by conventional means and delivered to the transmitter.

The Philips Plumbicon differs from earlier arsenic trisulfide vidicons in that the photoconductive layer is a sandwich of three layers. The vacuum side of the lead monoxide layer is made positive (*p*-type) by chemical processing. The side of the lead monoxide layer adjacent to the stannic oxide is strongly negative (*n*-type). The major part of the layer is "intrinsic," or not active, so that the layer is a *p-i-n* junction. This structure is responsible for the low dark current of the vidicon—the fact that it conducts only a small amount of current in darkness—and for several other advantages.

Photographic emulsions clearly con-



HUMAN VISION'S capabilities are indicated in curves that show by their height on the vertical scale how the detective quantum efficiency of the visual system varies with changing diameter of test spot. Colored numbers give background luminance in foot-lamberts. The curves cannot be compared with one another. The vertical scale is actually the reciprocal of the square of the product of the test-spot diameter and the threshold contrast.



LALLEMAND ELECTRONIC CAMERA employs a photocathode that is stored in an ampoule to prevent its contamination by gases. After the camera has been prepared and a high vacuum has been established the ampoule is broken by the hammer, and the photocathode is magnetically pulled into position over the photographic plate. Light striking the photocathode causes the emission of electrons that strike the electron-sensitive photographic plate.

stitute another major class of image detectors. Every photographic film or plate has a layer about 100 microns thick that is a suspension in solidified gelatin of a myriad of grains of silver halide. Each grain is about one micron in size.

The grains are laid down rather rapidly so that they will be irregular, with numerous points of imperfection on the surface. After deposition the grains are subjected to processing designed to increase their sensitivity to photons. Finally the surface is partly covered with a single layer of dye molecules.

When light strikes one of the grains, the blue part of the light is absorbed by the grain; the green and red parts are absorbed by the molecules of dye. In either case what happens is that an electron is put into the conduction band of the silver halide crystal. As a result the electron is free to move around. Many things can happen to the electron, but the important thing for photography is that the electron may be trapped at an imperfection. If it is, it may convert a silver ion into a silver atom.

This atom cannot exist long by itself, but if another silver ion in the same imperfection is neutralized within about a second, the two-atom combination is more stable and will last for several weeks. The liberation of two electrons will give rise to a four-atom combination that is quite stable and is large enough to catalyze the development of the grain. (For astronomical purposes the single-atom decay time of roughly a second can be increased to as much as an hour by making the environment of the grains more reducing. This increase in decay time is achieved at the cost of rapid fogging at room temperature, so that the plates must be shipped and stored under refrigeration.)

After the film has been exposed to light, it must of course be developed to make the image visible. Developing involves immersing the film in a water solution that contains a reducing agent. The agent is carefully chosen so that it does not have the ability to develop an unexposed grain during the normal duration of developing, but when the agent is aided by the group of silver atoms at the imperfection, it is able to start the reduction. Once the reduction begins, more silver is formed and the entire grain is converted to silver.

The amplification involved in the developing process is enormous. As few as four photons effectively absorbed in a grain of silver halide with a volume of one cubic micron will produce more than 10^{10} silver atoms. This is an amplification of more than a billion.

It is important for the success of the photographic emulsion that more than one photon must be received within a short time. If only one photon were needed, thermal excitation would soon make all the grains developable. As we have noted, the human visual system uses a similar method of avoiding thermal excitation. Both systems employ what electrical engineers call a coincidence gate.

Judging the efficiency of an image detector is more difficult than one might expect. The judgment is straightforward enough if one merely wants to establish the ratio of photoelectrons to incident photons—the output to the input—in the operation of a photocathode. That is a ratio of countable events. The ratio establishes what can be called the responsive quantum efficiency of the photocathode.

The trouble with the concept is that one cannot extend it to other detectors without ambiguity. In a photoconductor, for example, is the output event an electron in the conduction band, or is it the flow of an electron in the external circuit? These two phenomena can have greatly different counts, so that the distinction is an important one.

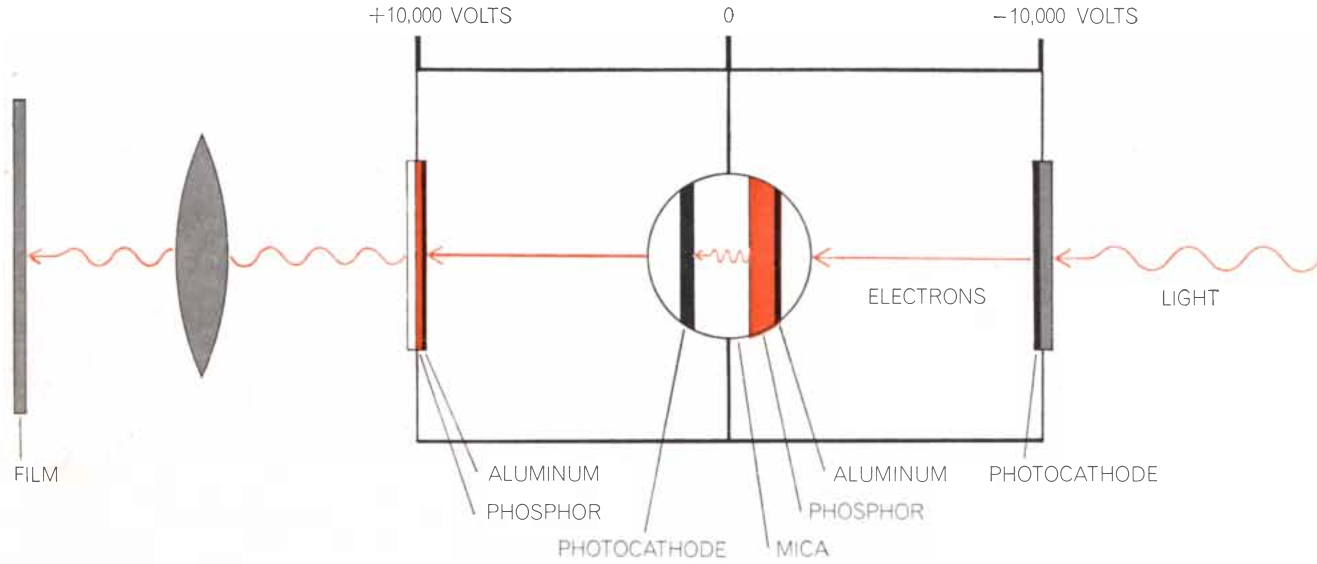
What is the output event in photographic film? Is it an electron in the conduction band of the silver halide grain, a silver atom added to the latent image or a grain made developable? Again, the different events have greatly different counts.

What is the output event in human vision? Is it the firing of the nerve cell connected to a rod? Or is it the perception of a flash or the perception of the color of a flash?

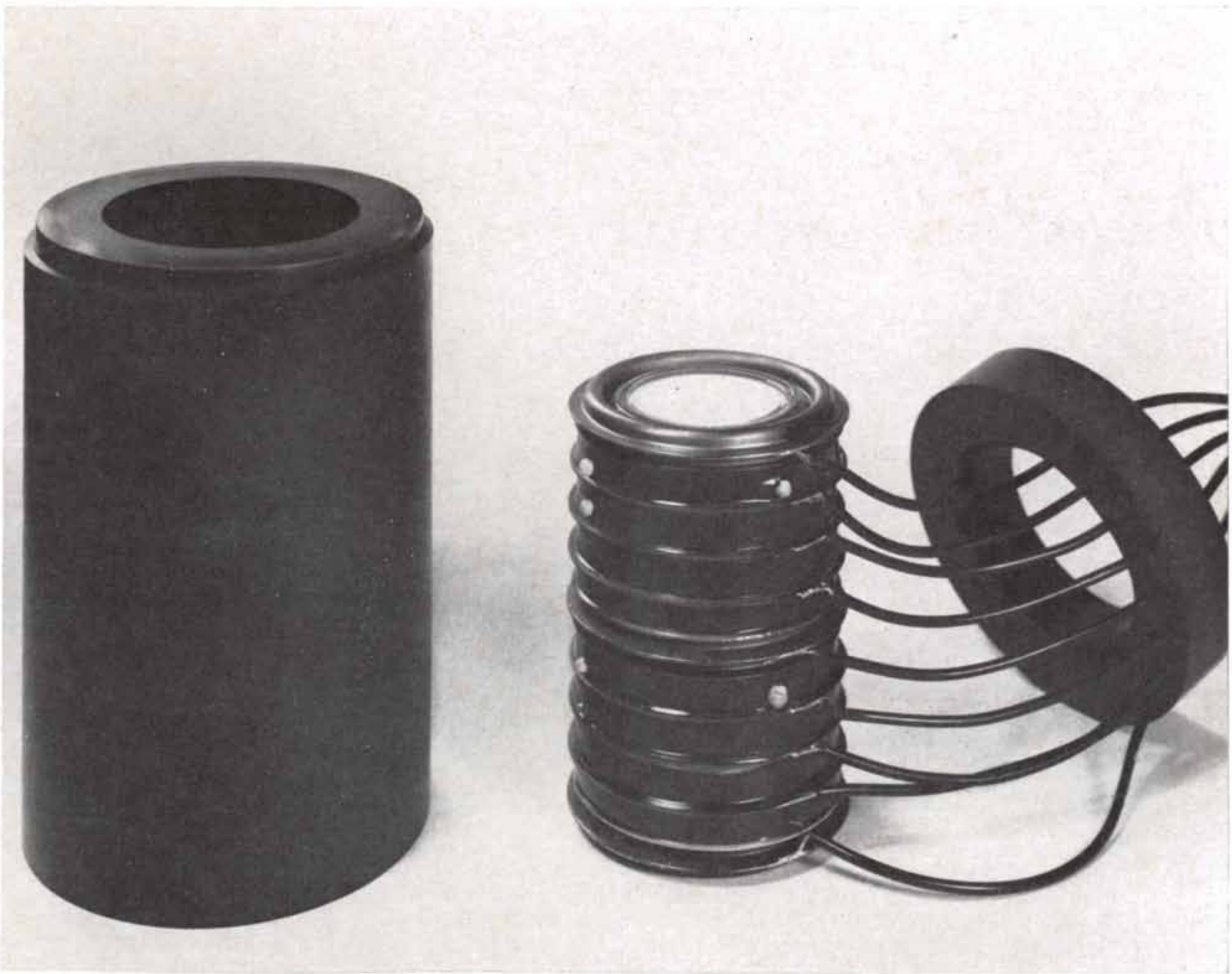
Uncertainties of this nature led Albert Rose of RCA to develop an important new concept that he called performance. This is the concept I have termed detective quantum efficiency. The DQE is defined not by comparing input and output counts but by comparing input and output signal-to-noise ratios. The formula for calculating a DQE is to divide the output signal-to-noise ratio by the input signal-to-noise ratio and then to square the result.

With human vision the output noise cannot be measured directly. Instead one tests the performance of the visual system on certain well-defined tasks and compares the result with the performance of an ideal device that uses all the incident photons. The task is then varied until the level at which the eye performs best is found. The result is the DQE of vision.

The significant point about the DQE of any detector is that it allows unambiguous evaluation of the detector's efficiency. The DQE is thus a key to the understanding of all detectors.



CARNEGIE IMAGE TUBE was devised as an image intensifier for use with astronomical telescopes. Light from the telescope enters the glass window at right and strikes the photocathode, causing the emission of electrons. They are accelerated to a mica sandwich in the middle of the tube. There, with an aluminum film preventing feedback, they are absorbed by a phosphor. Resulting light strikes the second photocathode, producing an increased number of electrons that strike phosphor at left. Its light is recorded on film.



ELECTRODE ARRANGEMENT of a Carnegie image tube is evident when the tube (*center*) is separated from the telescope with which it is usually associated. The electrodes carry the charges that accelerate the electrons in the tube. Cylindrical objects to the left and right of the tube are plastic insulators that hold it in its operating position and prevent the 20,000-volt tube from sparking.

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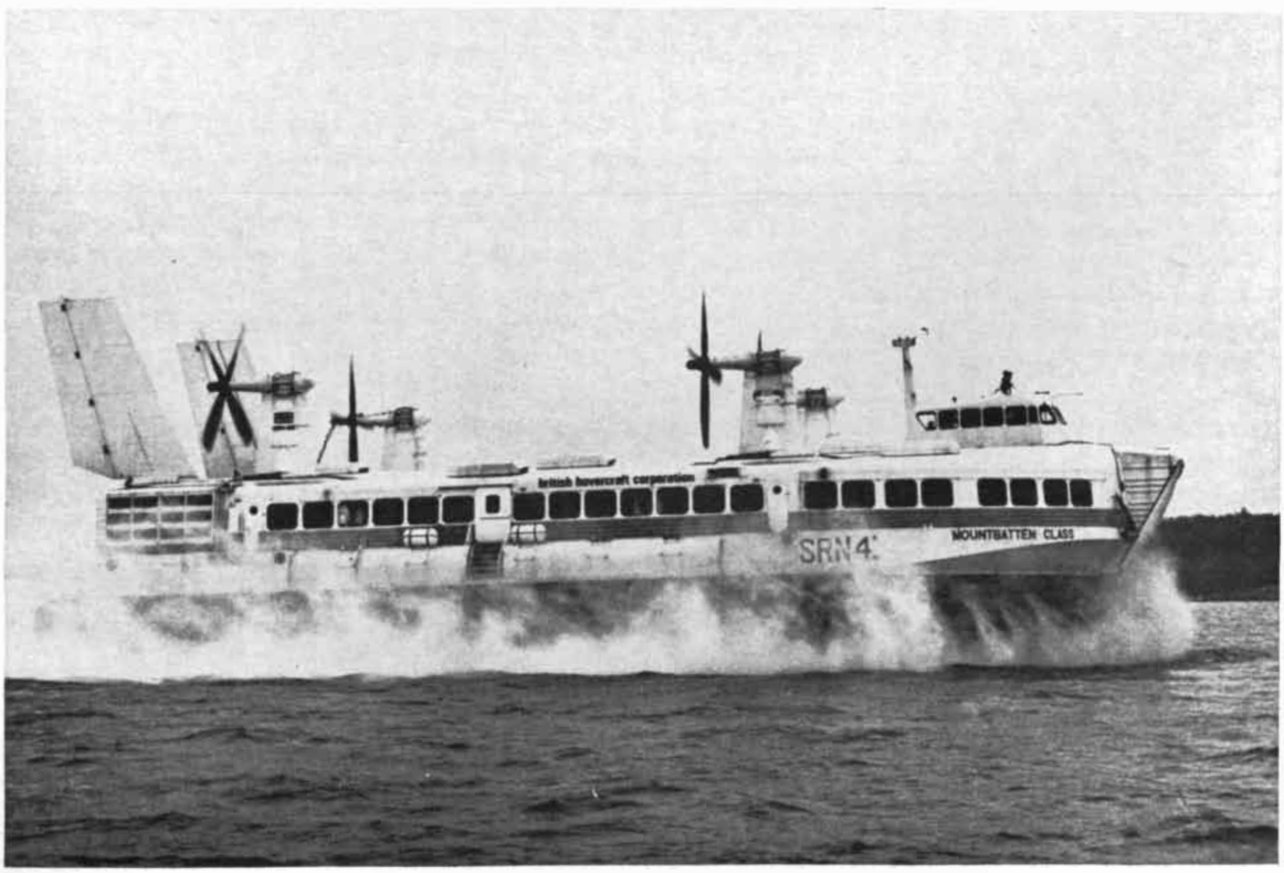
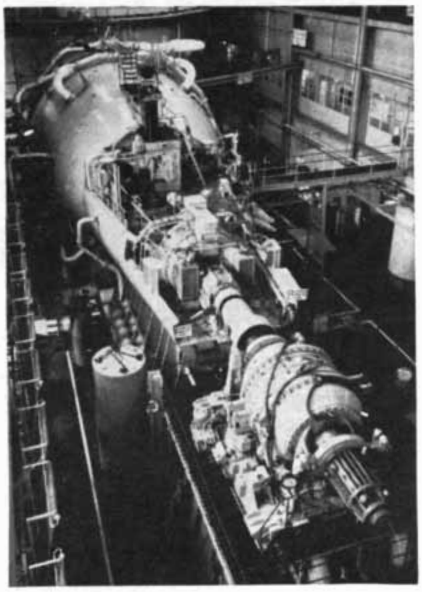


World's fastest ferryboat flies the Channel at an altitude of seven feet.

It looks like a ferryboat, 165 tons squatting in the water, absorbing 254 passengers and 30 cars. But when its four 3,400-horsepower Rolls-Royce Marine Proteus engines come to life, it's no longer just a ferry but the world's largest Hovercraft. It rises on its own cushion of air, surges out into the Channel, ironing out waves as it goes. At 50 miles an hour, it cuts the Channel crossing from a queasy hour and a half to an agreeable 35 minutes.

Hovercraft have a short but spectacular history to date. They can travel over virtually any surface. Case in point: the SRN.6 that recently explored the Amazon River, crossing rocks, rapids and sandbars at an unruffled 50 miles per hour. Canada is testing an SRN.5 for Coast Guard duty. Its 900-horsepower Rolls-Royce engine (actually, all gas turbine Hovercraft have Rolls-Royce engines) gives it a range of 260 miles, and a top speed of 72 miles per hour. Canada is also testing this same craft for Arctic exploration.



△ **Corporate offices go intercontinental.** Now corporate aircraft are doing things that only scheduled airliners could do just a few years ago. Recently, on a routine business trip a Grumman Gulfstream II corporate aircraft made a nonstop transatlantic crossing from Teterboro, New Jersey, to London's Gatwick Airport. After short hops into Belgium and Scandinavia it crossed the Atlantic again, nonstop from London to Burlington, Vermont.

Best time was eastbound, 3,500 miles in 6 hours 55 minutes at 518 miles per hour. Power is from twin Rolls-Royce Spey fanjets, the same engines that power BAC-111 airliners operated by Aloha, American, Braniff and Mohawk airlines.

◁ **Landlocked half-submarine** is doing yeoman service at Dounreay, Scotland, as a test bed for a new type of nuclear reactor core built by Rolls-Royce. This new core may allow Britain's nuclear submarines to stay at sea twice as long as they do now. Rolls-Royce has already built the reactor cores for all of Britain's nuclear submarines.

Commuting by Rolls-Royce is routine in Toronto, where Canadian National Railways operates self-propelled, Rolls-Royce diesel-powered rail cars like this one. The idea is to make rail travel attractive enough to woo drivers off overcrowded roads. The rail cars do it with soft music, tinted windows, contour seats and air-conditioning. ▷

△ **Forty gallons of anything, please.** If you're driving a vehicle with a Rolls-Royce K-60 engine, that's a reasonable request. This extraordinary multifuel engine runs on gasoline, kerosene, diesel fuel or jet engine fuel without losing power or performing differently.

It's working fine right now in Britain's Abbott self-propelled gun, shown here, and Sweden's S Tank. The standard K engine offers 210 horsepower, but Rolls-Royce engineers have squeezed out an amazing 500 horsepower from an experimental version.

ROLLS ROYCE

Rolls-Royce Limited, Derby, England
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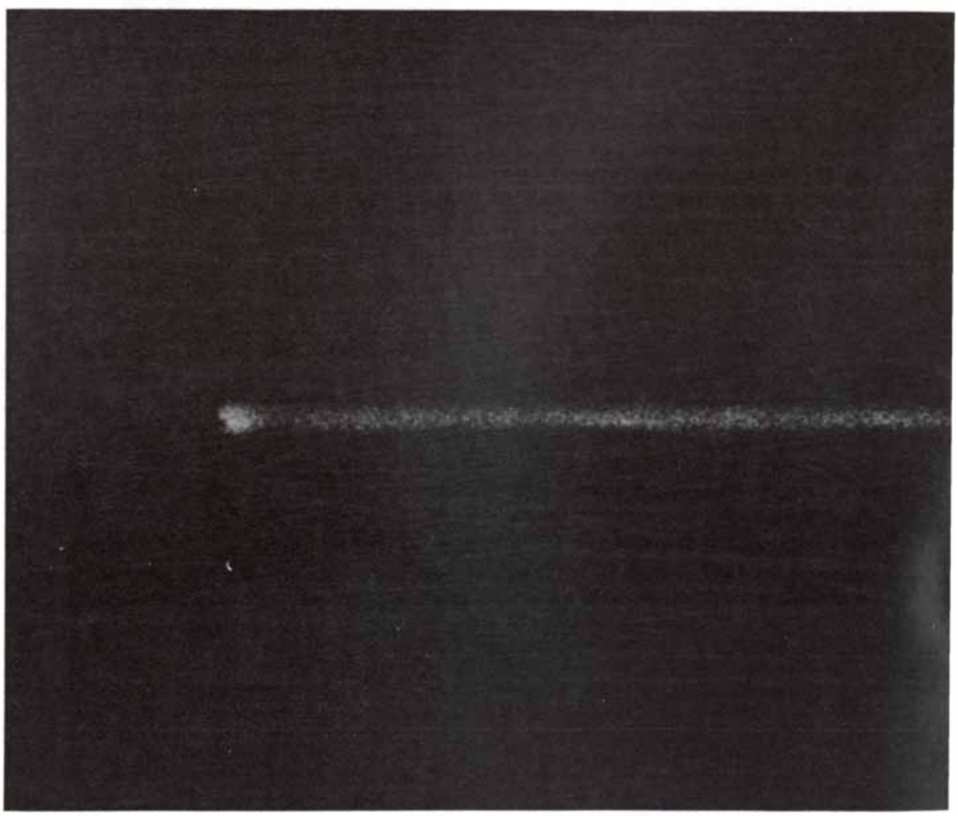
Laser Light

Its outstanding characteristic is that its waves, unlike the waves from ordinary light sources, are coordinated in space and in time. It is also remarkably intense, directional and chromatically pure

by Arthur L. Schawlow

How does laser light differ from ordinary light? In brief, it is much more intense, directional, monochromatic and coherent. The light emitted by an ordinary source such as a candle or an incandescent lamp consists of uncoordinated waves of many different lengths, that is, it is incoherent and more or less white. The waves of laser light are coordinated in space and time and have nearly the same length. This coherence and chromatic purity, and also the intensity of laser light, results from the fact that in a laser excited atoms are stimulated to radiate light cooperatively before they have had time to do so spontaneously and independently. The directionality of laser light arises from the geometry of the laser. These properties of laser light suggest many uses for it not only in technology [see "Applications of Laser Light," by Donald R. Herriott, page 140] but also in physics.

Most lasers consist of a column of active material that has a partly reflecting mirror at one end and a fully reflecting mirror at the other. In a typical solid laser material, a ruby crystal, the active ingredients are chromium atoms interspersed in the crystal lattice of aluminum oxide. The laser is primed by pumping these atoms, by means of a flash of intense light, to an excited state. With a preponderance of atoms in that state the system can be stimulated to produce a cascade of photons, all the same wavelength and all in step, by triggering the emission of energy that drops the atoms from the excited state to a lower energy state. A photon carrying this quantum of energy, on striking an excited atom, causes it to emit a photon at the same frequency, and the light wave thus released falls in step with the triggering one. Waves that travel to the sides of the column leave the system, but those that go to the ends of the column along its axis are reflected back and forth by the mirrors. The column, whose length is a whole number of wavelengths at the selected frequency, acts as a cavity resonator, and a beam of monochromatic, coherent light rapidly builds in intensity as one atom after another is stimulated to emit photons with the same energy and direction [*see illustration on page 130*]. It is as if tiny mechanical men, all wound up to a certain energy and facing along the axis of the laser enclosure, were successively set in motion by other marchers and fell into step until they became an immense army marching in unison row on row (the plane wave fronts) back and forth in the enclosure. After the laser light has built up in this way it emerges through the partly reflecting mirror at one end as an intense, highly directional beam. Light intensities as high as a billion watts per square centimeter have been produced.



SHORTEST LASER PULSES EVER PHOTOGRAPHED were discovered by workers at the Bell Telephone Laboratories to be components of what was previously believed to be one long pulse from a high-power neodymium-glass laser. The pulses appear as a series of bright

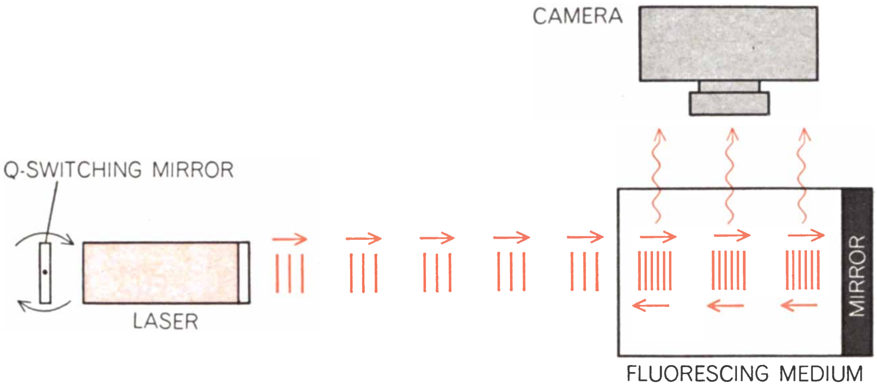
The output from the first solid laser was in the form of brief pulses. A continuous beam can now be produced by several kinds of solid laser, but such a beam is more easily generated by a gas laser. A common laser of this type contains helium and neon, with neon as the active material. A continuous glow discharge is used to pump the neon atoms to a certain energy level, and they are stimulated to emit photons that drop them to the next lower level (not the ground state, or lowest level). As in a solid laser, the beam builds up and is made coherent by being bounced back and forth between end mirrors. Among the many other kinds of laser system are those based on laser action in semiconductors, liquids and molecular gases such as carbon dioxide.

Laser light shows itself to be different from ordinary light even when it merely illuminates a surface. The surface looks grainy and seems to sparkle. The graininess is so distracting that when a printed page is illuminated by laser light, it is hard for the eye to focus on the writing. The reason lies in the coherence of the laser light waves. As the waves are scattered from neighboring points on the paper they interfere with one another everywhere, producing bright spots where the waves overlap and reinforce one another in phase, and leaving dark spots where they cancel one another out of phase. The interference pattern depends on the angle at which the paper is viewed; the pattern changes with a slight movement of the eyes or head and the shifting bright spots seem to sparkle. Ordinary light does not produce such interference because the light waves are unrelated to one another in phase. The waves' mutual interference is chaotic and consequently produces no diffraction pattern.

Interference is of course one of the most basic properties of waves. When two waves arrive in the same phase, they will add to a higher intensity than either wave alone can. If, on the other hand, the waves arrive in opposite phase, the resulting intensity is less and can even be zero. Yet it is contrary to all ordinary experience to shine two beams of light on a surface and find darkness where they overlap. This does not happen because the phases of the light waves in the two beams are not fixed but fluctuate randomly. The reason is that in ordinary light sources the waves come in short bursts emitted independently by enormous numbers of individual atoms. Even if the beams come from nearby places in the same source, there is little or no phase correlation between them.

It is nonetheless possible to demonstrate interference with ordinary light, if we filter out those waves that happen to have related phases. If we have a wave that travels in a definite direction, the wave fronts form planes at right angles to the rays. At any two points on such a wave front the phase of the wave is the same. If we now take waves from two parts of the front and direct them so that they overlap, they will interfere. This is the way Thomas Young first did the celebrated experiment in which he demonstrated the wave aspect of light [see "Light," by Gerald Feinberg, page 50]. In that experiment a plane wave falls on two narrow slits, side by side and fairly close together. Part of the wave passes through each slit, and since the slits are narrow the beams spread out and overlap on a distant screen. On the screen a pattern of light and dark bands can be seen, corresponding to the places where the waves from the two slits arrive in phase or out of phase.

spots on a background track. Each pulse is about three-tenths of a millimeter in length and less than a picosecond, or trillionth of a second, in duration. The technique used to photograph the pulses is illustrated on the next page. The extremely high peak powers that can be got in picosecond pulses from such "mode-locked" lasers promise fresh insights into interactions of light and matter.



TECHNIQUE used to record the picosecond laser pulses shown in the photograph on the preceding two pages is illustrated in this schematic drawing. The neodymium-glass laser is mode-locked by a rotating mirror (*left*), producing intense bursts of light, each of which in fact consists of a train of closely spaced picosecond pulses. The pulses enter a glass cell containing a highly transparent fluorescent liquid solution and are reflected back on themselves by a mirror at one end (*right*). The molecules in the solution are such that they emit a photon of light only after absorbing two photons from the laser. As a result intense fluorescence from the release of a large number of photons occurs only in the regions where a pulse traveling toward the mirror overlaps a pulse reflected from the mirror. Fluorescent spots are photographed and their length is measured in order to determine their duration.

If Young's experiment is tried by placing an ordinary light source near the pair of slits, it will not work. The screen will be uniformly illuminated because the phases of the light waves coming through the slits fluctuate randomly. If a laser is placed near the slits, however, it will produce an interference pattern because its light is coherent. To perform Young's experiment we can produce nearly coherent light from ordinary sources, but only by discarding most of the light and selecting a small portion of it. Thus there was coherent light before lasers. Even the sparkling appearance of a surface under coherent illumination was observed and explained before lasers.

Ordinary lamps cannot produce light that approaches true monochromaticity. The light from even a single spectral line of the best low-pressure gas lamp is spread over a band of frequencies that typically is at least 1,000 megacycles wide. Light from a gas laser, on the other hand, can be confined within a single megacycle in breadth, which amounts to a frequency spread of considerably less than one part in a million. In a gas laser with a mirror spacing of 30 centimeters a round trip between the mirrors covers about a million wavelengths. Accordingly a shift in frequency of only one part per million will convert the laser from one mode of resonance to another. Typically there are a dozen or more such modes within the frequency range of the laser medium. If certain precautions are not taken, the laser may oscillate on many or all of these frequencies simultaneously. For most applications this is undesirable; for example, a frequency spread of less than one part in two million is essential if two beams of light are to interfere sharply after traveling paths that differ in length by one meter (two million wavelengths).

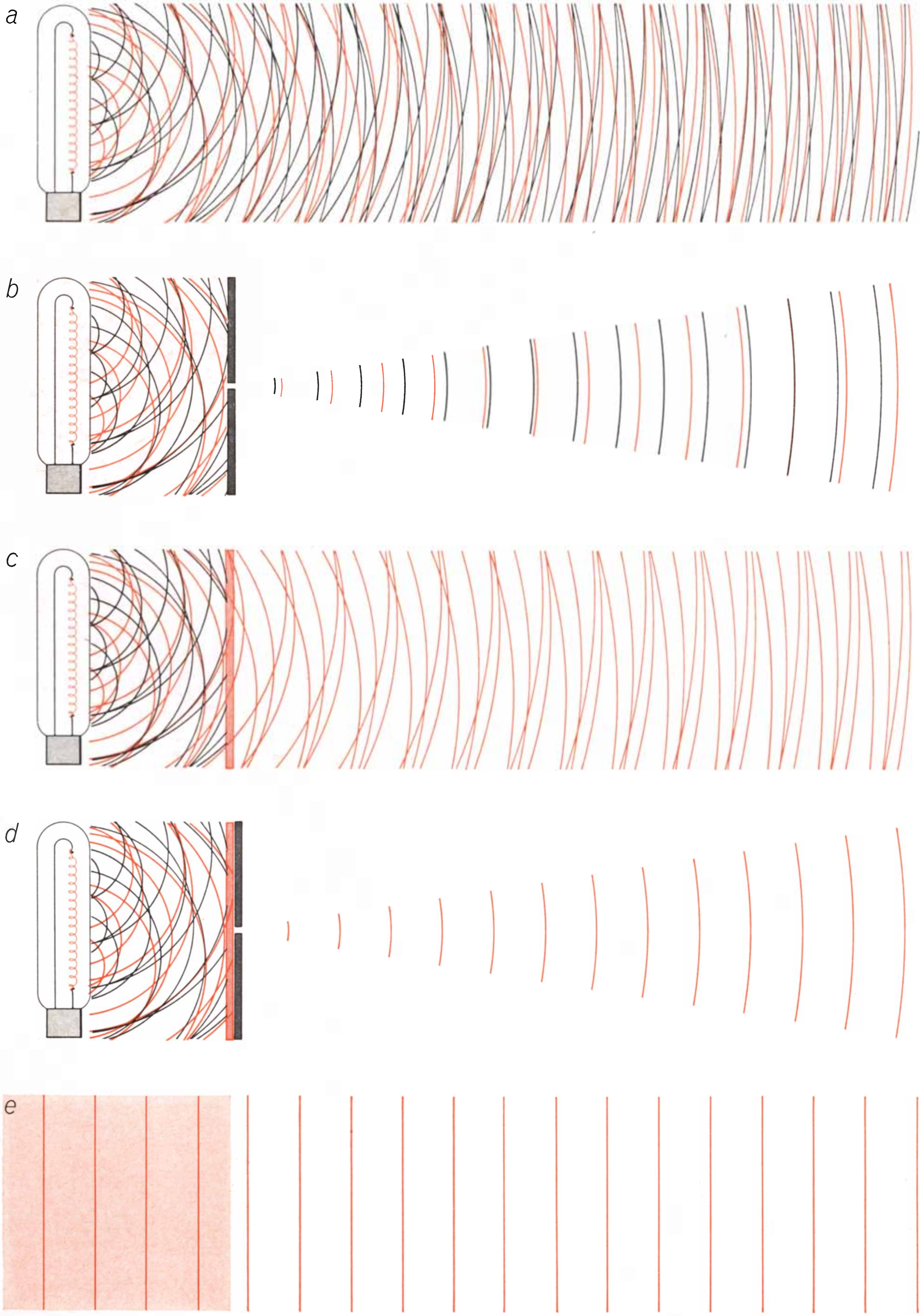
There are several ways to refine the output of a gas laser to the desired purity. One is to use an etalon as an end mirror in the laser. The etalon is a piece of glass, quartz or sapphire with parallel surfaces that form a resonant cavity much shorter than the laser as a whole. The resonant frequencies of this short cavity are much more widely spaced than the frequencies of a long cavity, and the cavity can be designed so that it will allow only one mode of oscillation in the band of possible laser frequencies. The best gas lasers now generate light that is restricted almost entirely to a single wavelength.

With this exquisitely refined instrument it has become possible to examine materials and physical phenomena in new ways. Among the interesting applications of the laser is the probing of materials by the study of their Brillouin scattering of light.

In 1915 the French physicist Louis Brillouin suggested that light traveling through a material must undergo slight changes in wavelength as the result of encounters with the high-frequency sound waves that arise from the ordinary thermal vibrations of atoms in the material. He published a brief account of his calculations leading to this conclusion and then entered the French army. After the war he decided to publish a more complete report on this work but found himself unable to understand his old notes. He then found a pictorial way to describe the phenomenon he had originally deduced by mathematical means, and this led to an illuminating view of the subject.

The sound waves from the vibrating atoms fan out in all directions, and since the vibrations may vary considerably in frequency the waves have a wide range of frequencies up into the infrared. Like other sound waves, they consist of alternate compressions and expansions in the direction of the wave propagation. Since the velocity of such a wave is much slower than that of a light wave, it follows that the sound wave is much shorter than an electromagnetic wave of the same frequency. Hence a wave of visible light passing through a liquid in the same direction as a sound wave of the same frequency will encounter regularly spaced maximal compressions and expansions of the sound wave. A small part of the light will be reflected from each sound-wave crest, and if the spacing between the crests is just half the wavelength of the light, the reflections will add in phase to produce an appreciable amount of light. Because of the Doppler effect the reflected light will be shifted to a slightly lower frequency, since it is reflected from a moving "mirror" traveling in the same direction as the incident light beam. Conversely, light reflected from sound waves moving in the opposite direction will be shifted to a higher frequency. The magnitude in each case is readily calculable: it is twice the velocity of sound divided by

ORDINARY LIGHT AND LASER LIGHT are compared in the illustration on the opposite page. In an ordinary thermal light source, such as an incandescent lamp (*a*), the atoms radiate independently, producing light waves that are both spatially incoherent (out of step) and temporally incoherent (with various wavelengths). A pinhole can be used to obtain spatially coherent light from the ordinary light, but only by sacrificing most of the power output of the lamp (*b*). Similarly, a color filter can be used to obtain temporally coherent light from the ordinary light, but again a large part of the lamp's power is lost (*c*). By combining a pinhole and a filter one can obtain a light beam that is both spatially and temporally coherent, but its power output will be a tiny percentage of the total output of the lamp (*d*). In contrast, all the light produced by a laser is both spatially and temporally coherent (*e*).


a
b
c
d
e

the velocity of light, and it amounts to a frequency shift of about 10 parts in a million.

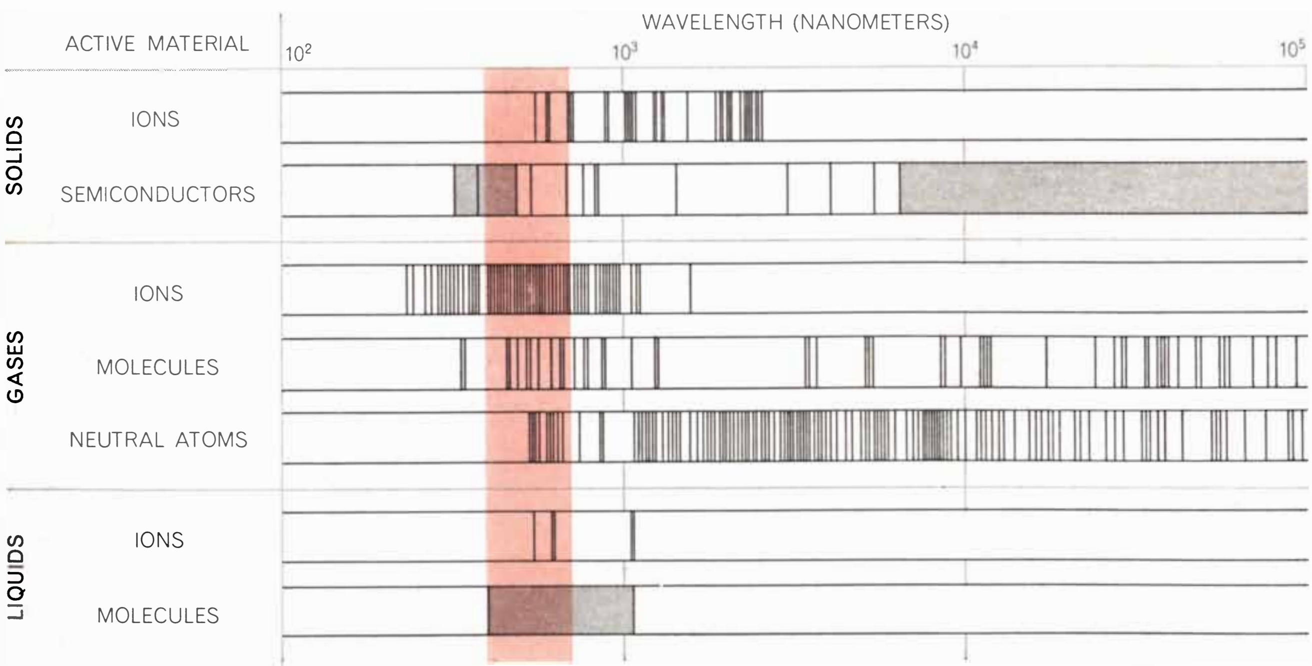
The formula for Brillouin scattering makes it possible to measure the velocity of sound at various wavelengths in any liquid and thus to study important properties of materials. Observation of the scattering is so difficult with ordinary light sources, however, that little work was done along this line before the laser became available. With a laser beam, thanks to its monochromaticity and directionality, it is now relatively easy to observe Brillouin scattering. In 1964 George B. Benedek, Joseph B. Lastovka, Klaus Fritsch and Thomas Greytak of the Massachusetts Institute of Technology and Raymond Y. Chiao and Boris P. Stoicheff of the University of Toronto used gas lasers to study Brillouin scattering in a number of liquids and solids. They found that in some substances the velocity of sound depends on the sound-wave frequency. For example, in liquid benzene high-frequency compression waves, at five billion cycles per second, travel 15 percent faster than those at low frequencies.

By bringing together the incident laser beam and the scattered light on the cathode of a phototube, extremely small shifts in the frequency of the scattered light can be measured. The phototube current shows a beat signal at the difference frequency, even when the shift amounts to only a few cycles per second. Benedek and N. C. Ford of M.I.T. and S. S. Alpert, David Balzarini, Robert Novick, Lester Siegel and Yen Yeh of Columbia University have measured shifts of a few hundred cycles per second in light of 10^{14}-cycles-per-second frequency; these shifts arise from thermal fluctuations in a liquid near its boiling point. Herman Z. Cummins, Norman Knable and Yeh at Columbia have observed similarly small shifts in a dilute solution of polystyrene.

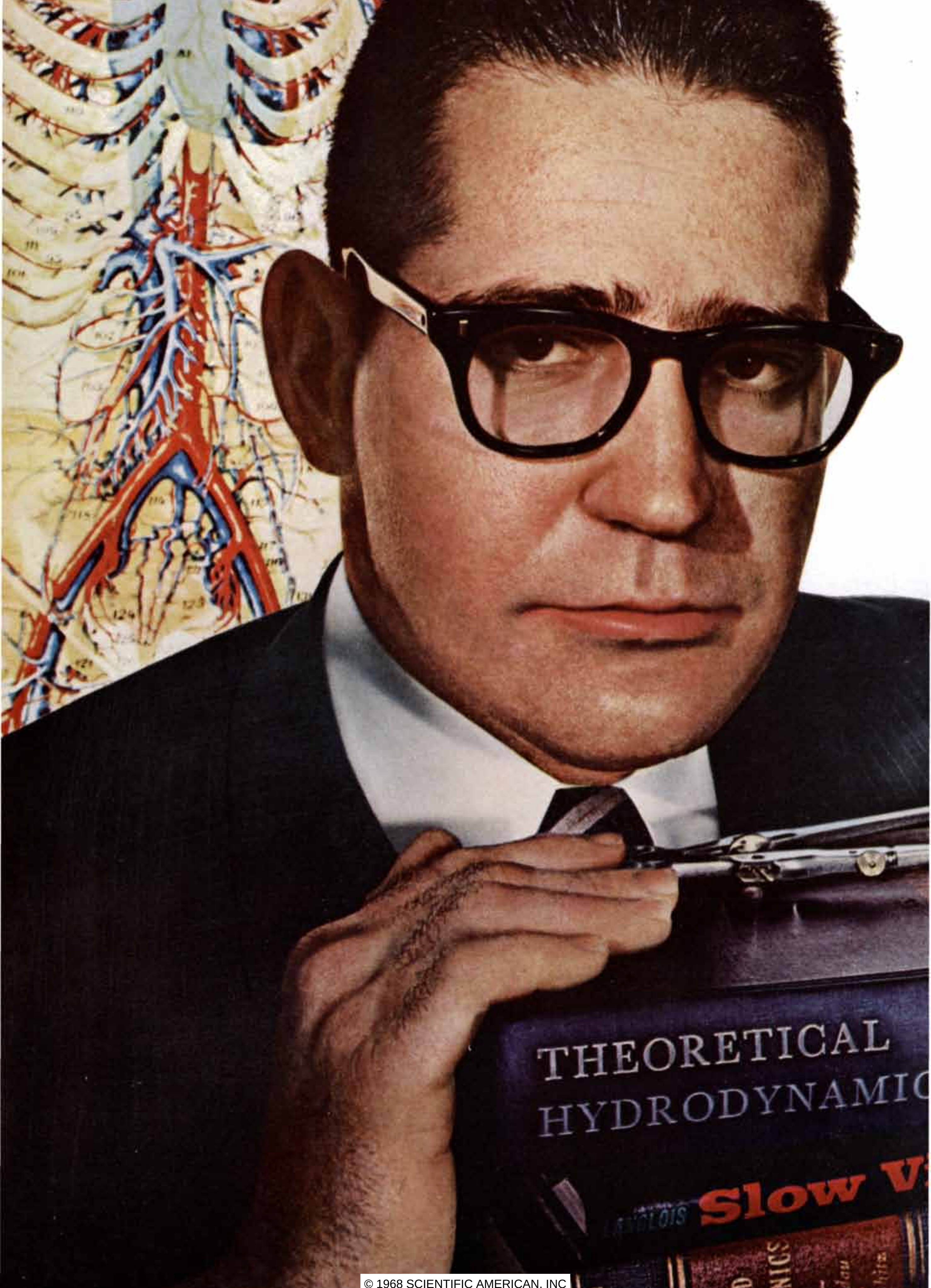
The laser is being applied to probe the internal structure and behavior of molecules, by examining the light-scattering phenomenon known as the Raman effect. In this effect, discovered by C. V. Raman of India in 1928, the light frequency shifts as photons take up or give energy to molecular vibrations, rotations and other motions. It is evidenced in frequency shifts that are much larger than those from Brillouin scattering, but the shifted light is much weaker, so that the intense, monochromatic light of the laser is of great value in studying it. Gas lasers employing neon, argon or krypton as the active material, which can provide continuous beams at powers up to several watts, are used in these studies.

Before the advent of the laser the Raman effect could be seen only in liquids, a few solids and (with difficulty) in large volumes of certain gases. With a laser Sergio P. S. Porto (then at the Bell Telephone Laboratories) and Alfons Weber, Leonard E. Cheesman and Joseph J. Barrett of Fordham University have been able to observe Raman scattering even in small samples of gas at ordinary pressure—one atmosphere or less. The spectra they have obtained clearly resolve the fine structure of light-scattering produced by the rotation of molecules. The sensitivity made possible by the laser has also disclosed motions at a finer level than the rotation or vibration of the molecule itself. For example, in crystals of manganese fluoride at cryogenic temperatures Porto, P. A. Fleury and Rodney Loudon at Bell Laboratories have detected Raman scattering produced by waves from the spin of atoms. In praseodymium chloride J. T. Hougen and S. Singh at the National Research Council of Canada have even observed a Raman effect arising from the motions of electrons.

When one thinks of lasers, one usually thinks of a very bright light source. Actually all but the most powerful continuous-beam lasers put out scarcely more total visible light than a flashlight. The laser, however, puts all its output into light with one narrowly defined wavelength. Thus its power per interval of wavelength is much greater



LASER LIGHT IS NOW AVAILABLE at a large number of wavelengths, ranging from the ultraviolet region (*left*) to the far-infrared region (*right*) of the electromagnetic spectrum. (The visible region is indicated by the vertical band in color.) Most of the wavelengths obtained to date from a variety of solid, gaseous and liquid materials are represented in the chart. The chart does not include those additional wavelengths that can be obtained from nonlinear optical processes by passing a laser beam through certain substances. Solid-state lasers of the semiconductor type and liquid lasers that use organic dye molecules as the active medium can be "tuned" over a range of wavelengths (*gray bands*) by changing the proportions of the active materials in the host material.


THEORETICAL
HYDRODYNAMIC
Slow

This mechanical engineer is trying to decipher the mysteries of blood circulation.

Who'd guess he's in the computer business?

"Medical research may seem an odd field for a man in the computer business," says IBM's Louis Lopez, "let alone for a mechanical engineer. But we're applying engineering techniques to a study of the bloodstream.

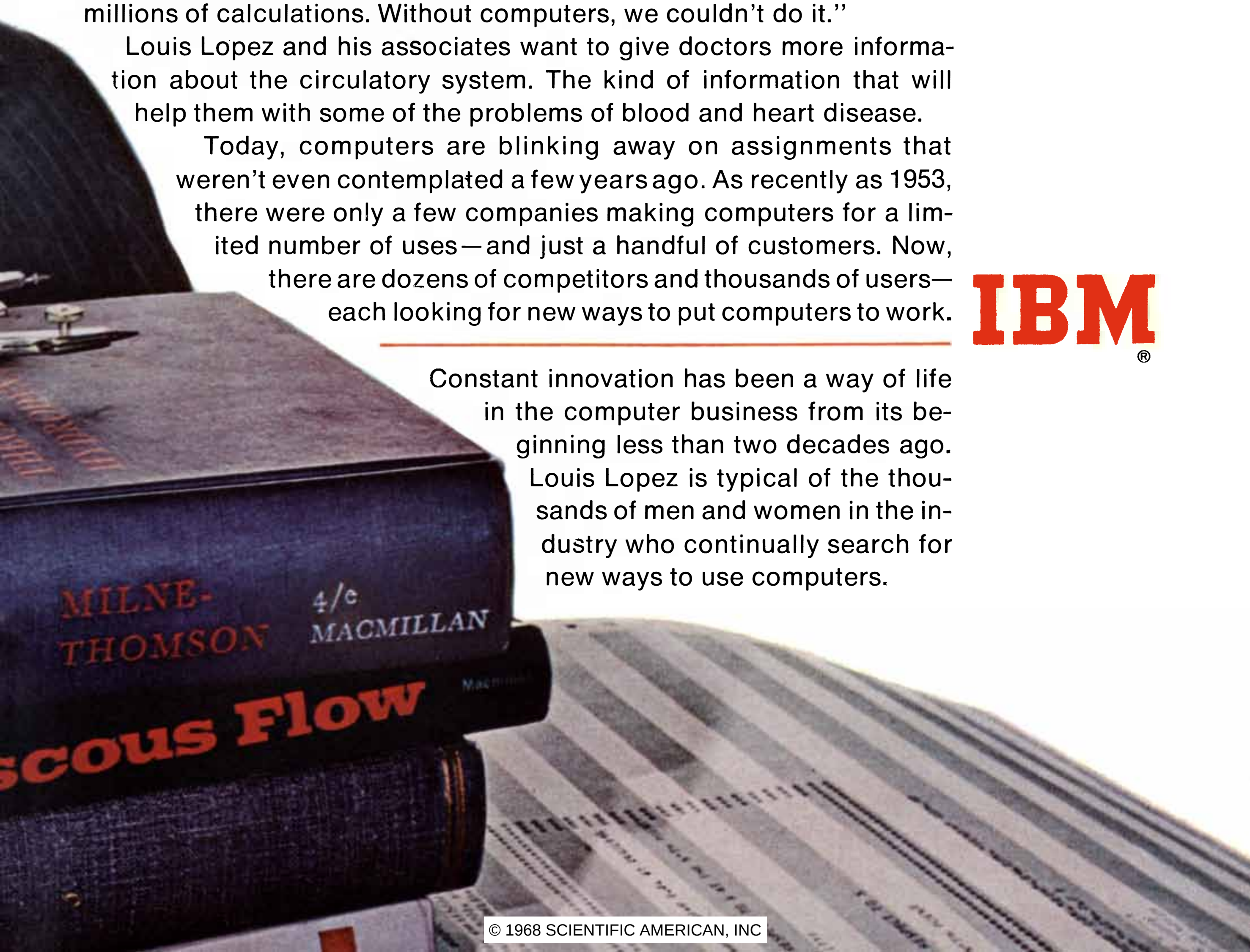
"In some aspects the human circulatory system resembles a hydraulic system. It has a pump, valves and fluid in motion. We're trying to express its mechanics in precise mathematical equations. This requires millions of calculations. Without computers, we couldn't do it."

Louis Lopez and his associates want to give doctors more information about the circulatory system. The kind of information that will help them with some of the problems of blood and heart disease.

Today, computers are blinking away on assignments that weren't even contemplated a few years ago. As recently as 1953, there were only a few companies making computers for a limited number of uses—and just a handful of customers. Now, there are dozens of competitors and thousands of users—each looking for new ways to put computers to work.

IBM®

Constant innovation has been a way of life in the computer business from its beginning less than two decades ago. Louis Lopez is typical of the thousands of men and women in the industry who continually search for new ways to use computers.



Next summer, the petroleum industry will be 2,000 feet closer to a sea of oil.

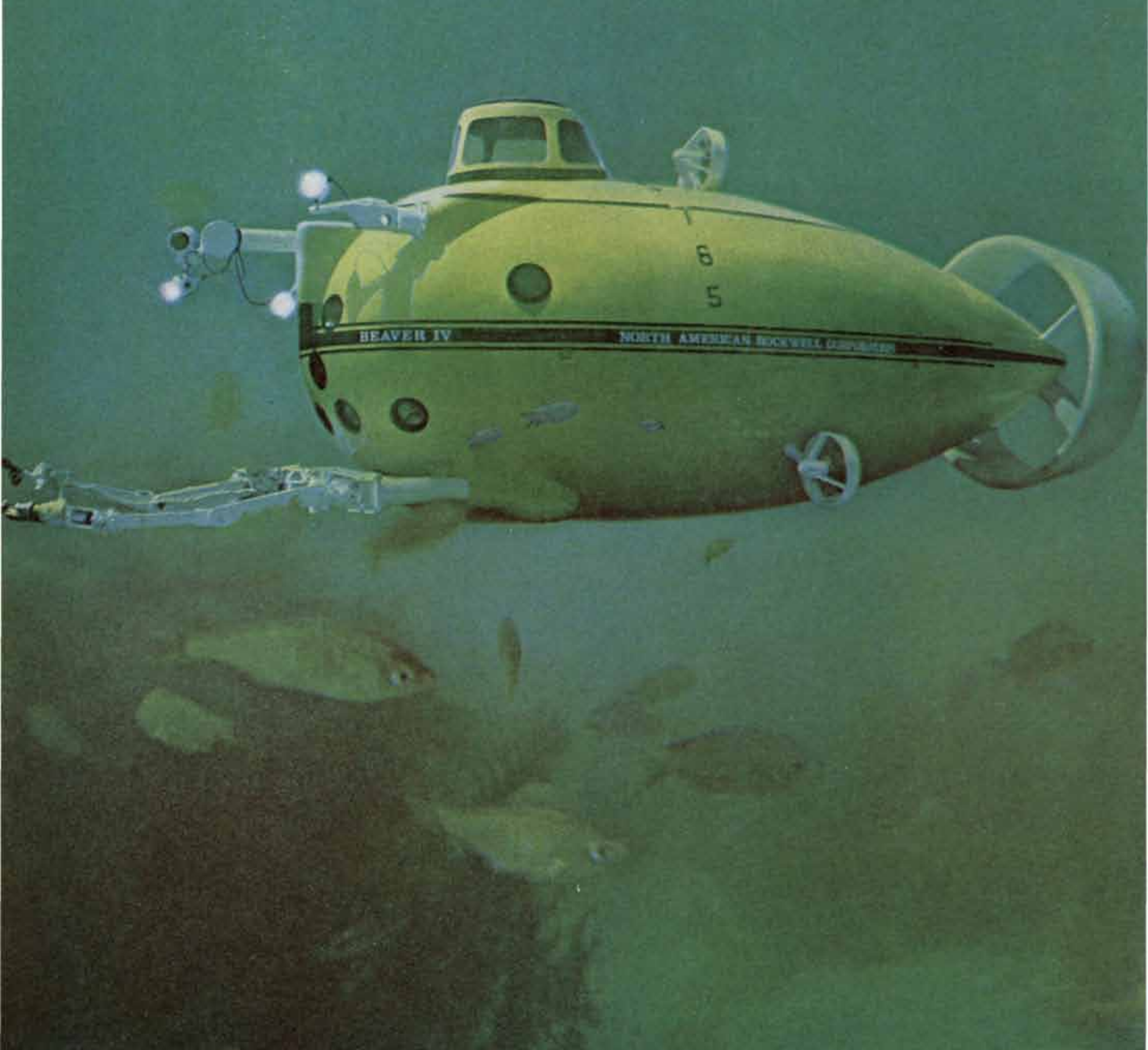
The United States' known oil reserves will hold out for about 15 years. By that time we'll have to make some pretty big advances in discovery and production techniques if we're going to keep burning oil.

One of the answers is the Beaver Mark IV workboat . . . designed and built by our Ocean Systems Operations. Beaver is a workboat that really works. And we'll put it to work next summer at the bottom of the ocean.

Its two arms can lift and shift heavy objects. A special compartment gives divers the freedom to come and go. Beaver can go down to 2,000 feet—about twice as deep as divers have ever worked before. And stay down for 12 hours at a time.

Because Beaver will help companies drill for oil, or lay pipelines, or bring up minerals from the ocean's floor, we expect to sell and lease a lot of these vehicles in the future.

Small wonder that the financial community refers to Oceanography as one of the great emerging industries.



North American Rockwell

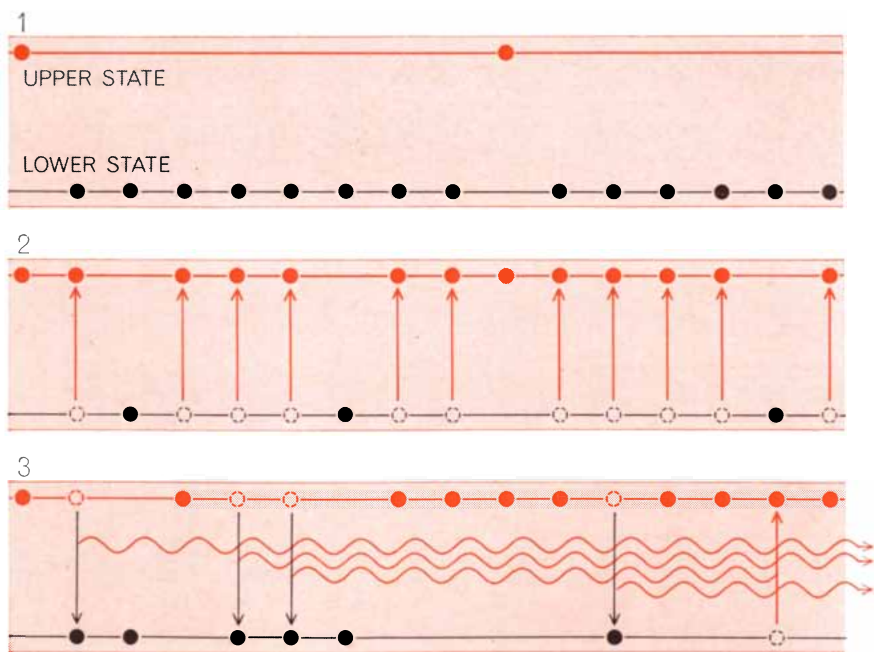
than the power available from other sources simply because of its greater monochromaticity.

An additional advantage of the laser in this regard arises somewhat independently from its high coherence. All the light from the entire diameter of the end of the laser is in phase. It can therefore be focused to a single point with a startling increase over any other optical source in power per square meter within the focused spot.

To date the only continuous laser that is capable of a large power output is the carbon dioxide type, whose "light" is in the infrared [see "High-Power Carbon Dioxide Lasers," by C. K. N. Patel; SCIENTIFIC AMERICAN, August]. Carbon dioxide lasers can generate up to 8,800 watts of continuous power. The unfocused beam from a carbon dioxide laser at a few hundred watts of power will cause a wooden board to emit a flaming jet almost instantly. It will cut through a hacksaw blade within seconds. (Incidentally, at the time the motion picture *Goldfinger* was produced its demonstration of a laser's power was ludicrous in terms of existing lasers; the performance it showed did not become possible until several months after the motion picture's release, when Patel invented the carbon dioxide laser.)

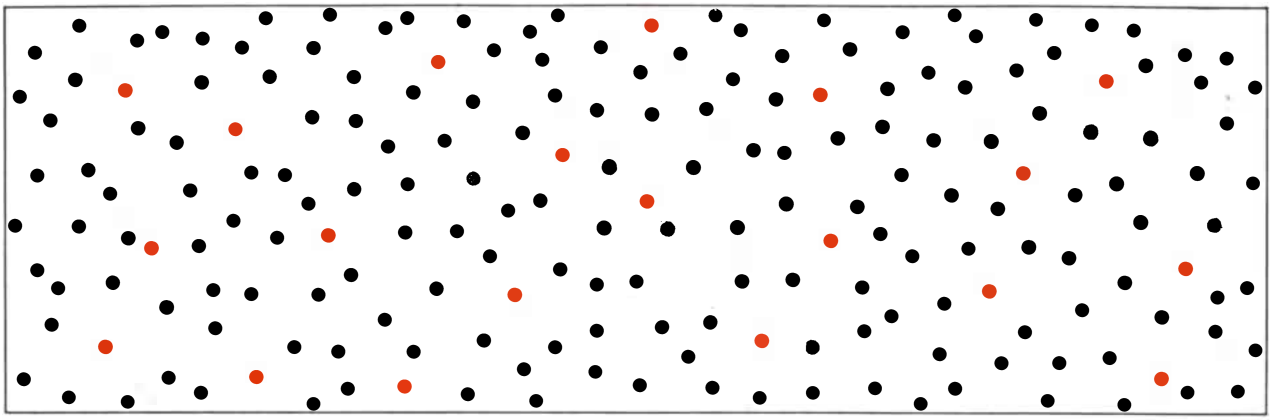
Even the early lasers could, to be sure, produce a great deal of power in a short pulse. The very first operating laser, the ruby laser constructed by Theodore H. Maiman of the Hughes Aircraft Company, had a power output of several thousand watts for about half a millisecond. The beam from such a laser can vaporize a speck of substance within microseconds. The heating is so rapid, however, that it is only superficial; vaporization carries away the heat before it has had time to penetrate below the surface by conduction. With a laser pulse it is possible to vaporize ink from paper or even from an inflated rubber balloon without appreciably heating the underlying material.

The power of the pulse from some solid lasers (including ruby) can be built up to several hundred million watts by using a kind of shutter that delays the release of the energy stored in the active pulse until it has reached its peak power. Then, when the shutter is opened, the laser emission can proceed. In one version of this method (known as the *Q*-switching technique) a light-absorbing but bleachable dye is interposed before



ENERGY-LEVEL PICTURE of laser action begins with the normal, or unexcited, state of affairs in the laser medium (*1*), in which the vast majority of atoms are in a lower energy state. The medium is then subjected to some external excitation (*2*), which "pumps" a sizable percentage of atoms into an upper energy state. This situation is known as population inversion. An atom falling spontaneously from the upper level to the lower level can then emit a photon of light that is capable of stimulating other atoms to emit photons with the same frequency and phase (*3*). Since a stimulating photon can just as easily be absorbed by an atom in going from the lower level to the upper level (*at right in 3*), it is important that population inversion be maintained, so as to make absorption less likely to occur than stimulation. As long as this condition is satisfied, the output will continue to be amplified.

1



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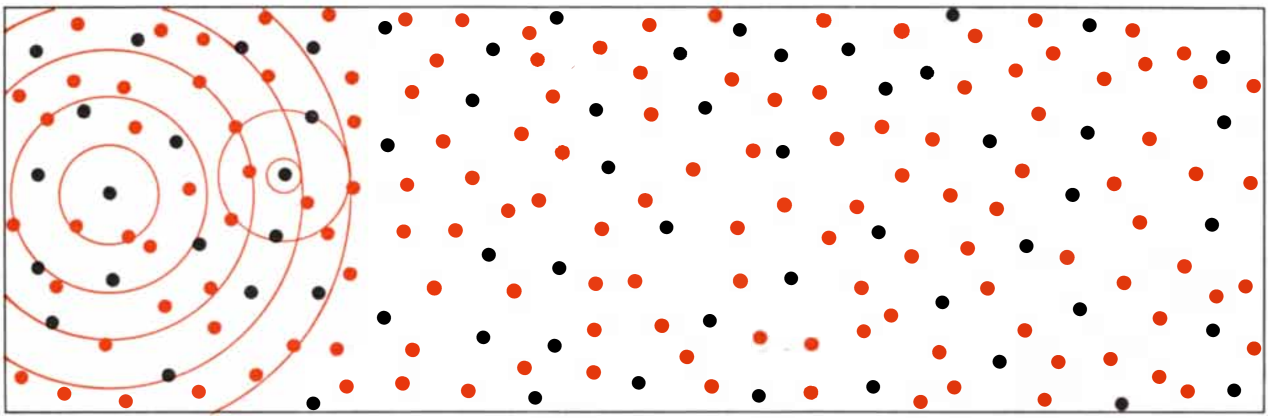

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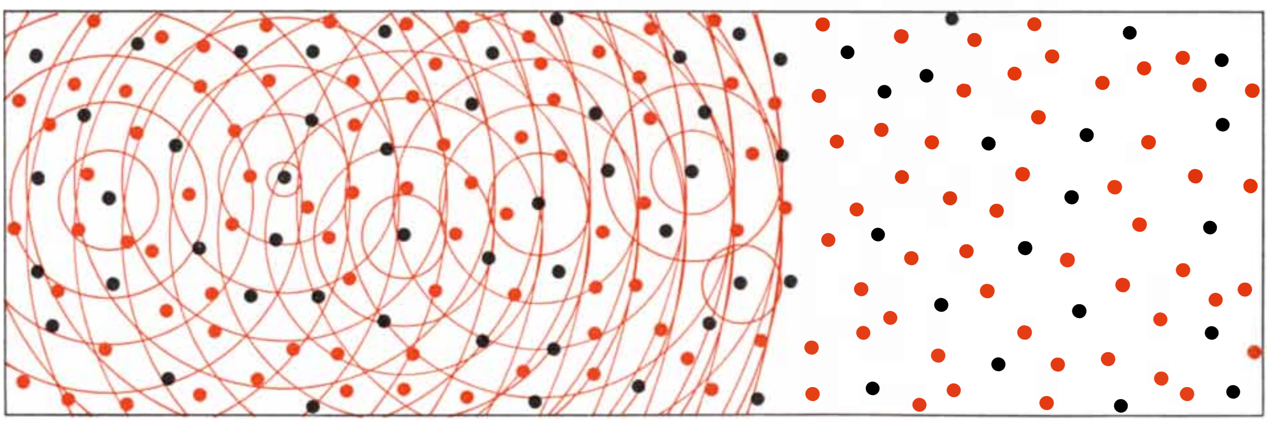

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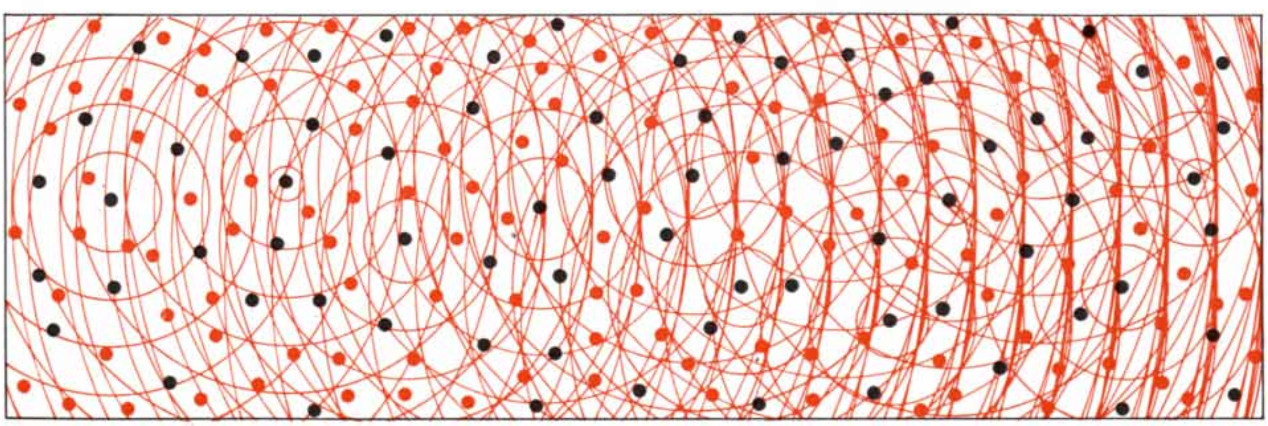


the end mirror where the laser beam is to emerge. Blocked by the shutter, the optical energy emitted spontaneously and incoherently by the excited atoms grows until the shutter is bleached; then all the stored energy is released from the laser in a giant coherent pulse, lasting about 10 billionths of a second.

At power levels in the millions of watts per square centimeter the electromagnetic wave's electrical effects on a material become important. A visible laser beam with 100 million watts of power per square centimeter, for example, produces an electric field amounting to 100,000 volts per centimeter. Such a field modifies the properties of any material through which the beam passes. As a result the monochromatic wave may become distorted so that harmonic waves are generated at two or more times its frequency. Infrared wavelengths may be converted in this way into visible light, and visible light into ultraviolet rays. Moreover, intense laser light can increase the refractive index of material through which it passes, by compressing the material, by aligning its molecules or by other mechanisms. The changes in refractive index have important consequences, some of which can be put to good use.

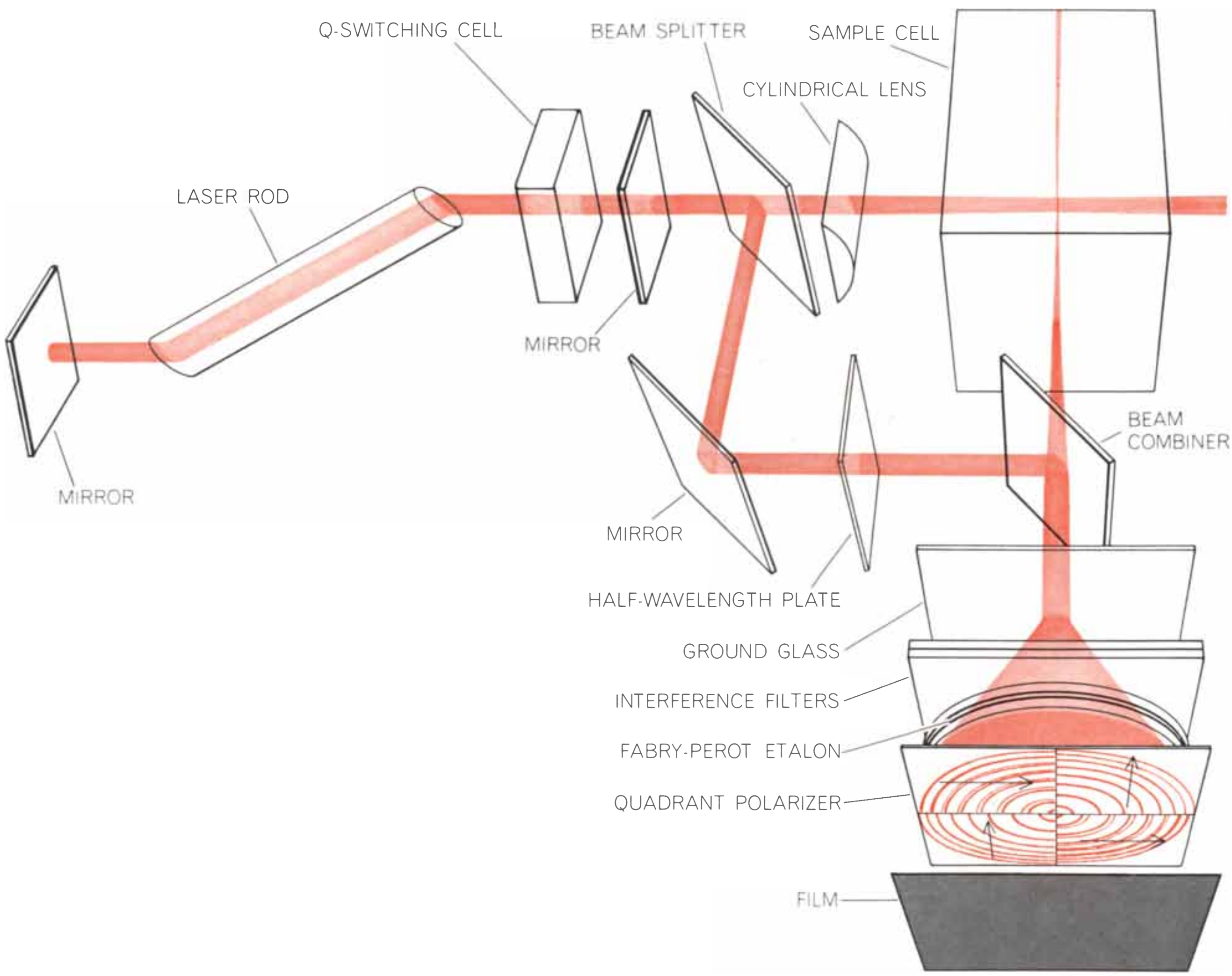
By producing changes in the refractive index within the laser medium, very intense laser light can greatly magnify the effects of Brillouin or Raman scattering. For example, when thermal fluctuations cause Brillouin reflection, the reflected beam adds to the laser light at some places and partly cancels it at others. At those places where the intensity is highest, the refractive index is increased most, and these are just the places where the index was already high. Thus above a threshold intensity very strong light reflection occurs, at the downward-shifted Brillouin frequency. Indeed, most of the laser light can be reflected in this stimulated Brillouin scattering, as was first demonstrated for solids by Elsa Garmire and Charles H. Townes at M.I.T., and for liquids by

WAVE PICTURE of laser action also begins with most atoms in the laser medium in the unexcited state (*1*). Unexcited atoms are in black, excited atoms in color. After an external excitation has created a condition of population inversion (*2*) the spontaneous emission of a photon by a single atom can again begin the process of light amplification by stimulating coherent emission from other excited atoms (*3, 4*). Usually the energy of the laser beam is built up further by reflecting it between two end mirrors.

Richard G. Brewer and Klaus E. Rieckhoff of the International Business Machines Corporation. Stimulated Raman scattering can also occur and had been observed earlier by Eric J. Woodbury and N. W. Ng of the Hughes Aircraft Company. In both cases the light drives strong vibrations in the material and the stimulated light beam has a wavelength different from that of the laser. In a solid the vibrations induced by laser light can be strong enough to cause fracturing. John L. Emmett of Stanford University found that by using a cylindrical lens to focus the laser light along a line transverse to the direction of the laser beam, the stimulated reflected beam could be made to emerge transversely along the line of the focus. The stimulated beam could then be studied without being obscured by the intense laser light.

Curiously, in the investigation of the nonlinear effects produced by high laser intensity—the generation of harmonic frequencies and the stimulation of Brillouin and Raman scattering—it was found that these effects generally occurred at laser intensities considerably lower than one should have expected them to be on the basis of the known physical processes at work. Chiao, Mrs. Garmire and Townes discovered a phenomenon that accounts for this apparent anomaly. In a powerful laser beam the refractive index of the medium is increased most at the center of the beam. Consequently the medium acts as a converging lens, focusing the beam to narrower dimensions and thereby increasing its intensity. This self-focusing process quickly gives the beam the intensity required for the nonlinear effects. Actually the light breaks up into a large number of small filaments, and within a filament it is bright enough to cause all the nonlinear scattering processes. Thus nearly as soon as the light is strong enough for self-focusing the stimulated Brillouin or Raman scattering begins.

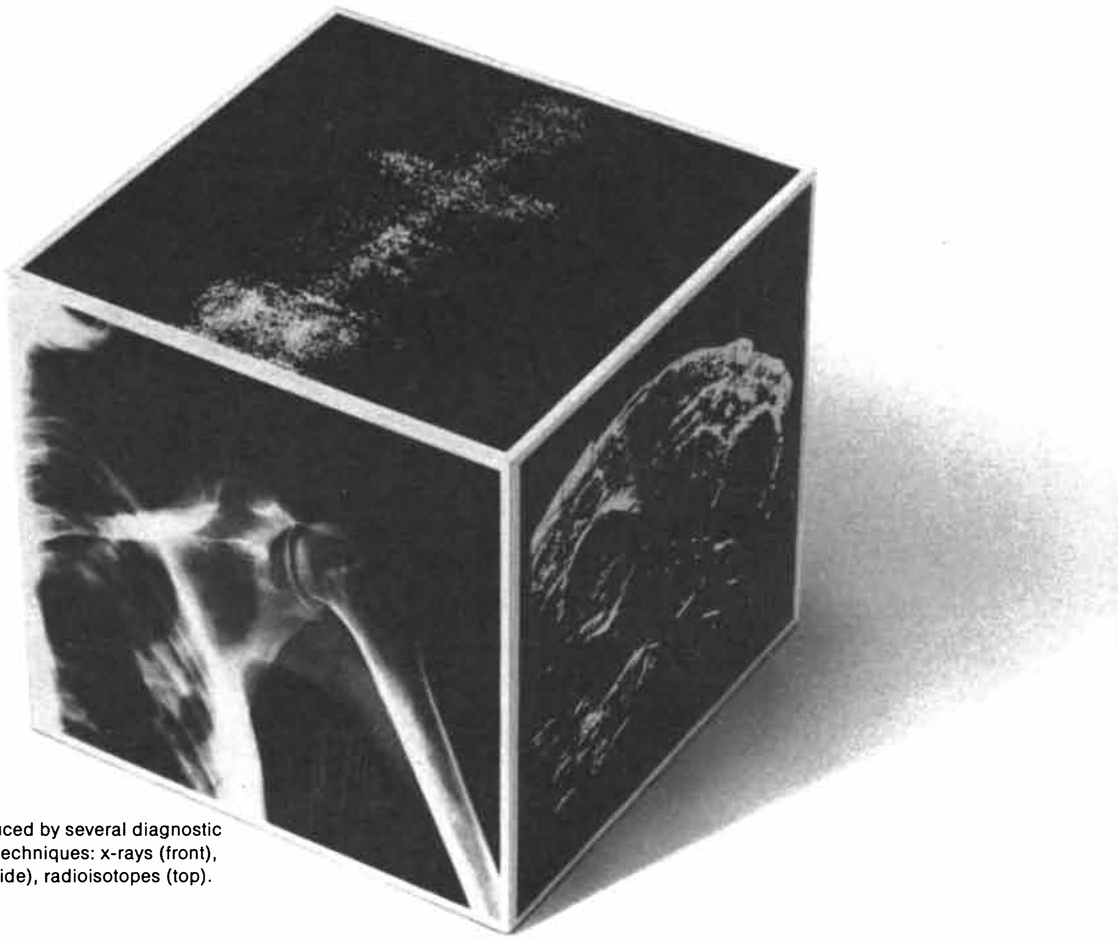
Several groups of investigators are now working on the development of coherent light sources that are tunable, that is, sources whose wavelength can be changed. The main approach is being made through the construction of optical-frequency parametric amplifiers and oscillators. Such devices allow the amplification of a variable low frequency at the expense of power put in at a fixed higher frequency. Their operation calls for a medium with an unusually large nonlinear response and at the same time high optical and mechanical quality. A tunable parametric oscillator that operates in the near infrared has been built at Bell Laboratories by R. G. Smith, J. E. Geusic, H. J. Levinstein, Singh and L. G. van Uitert. A parametric oscillator in



EXPERIMENTAL ARRANGEMENT used to study stimulated Brillouin scattering of laser light by sound vibrations in various materials was devised by John L. Emmett and the author at Stanford University. The distinguishing feature of their arrangement is the use of a cylindrical lens to converge the laser beam to a line focus, so that the scattered light is stimulated to emerge transverse to the beam; thus the scattered beam can be studied without being obscured by the intense laser light. The interferometric system and quadrant polarizer shown in the illustration are used to produce a photographic image in which the interference fringes that are due to the scattered light can be compared directly with the interference fringes due to the laser light (*see illustration on page 134*).

Next time you think you need an x-ray, you may not get one.

A progress report on x-ray diagnosis and some other visualization techniques.



Images produced by several diagnostic visualization techniques: x-rays (front), ultrasonics (side), radioisotopes (top).

No one argues the contribution of x-ray diagnosis to the practice of medicine, which some consider to be one of the three greatest boons to health in the last 50 years. But despite the impressive contributions of the past and the continuing flow of improvements in diagnostic x-ray procedures and equipment, much is still being done. New techniques are being perfected, and one vital area in which work never stops is lowering the dosage of x-rays without compromising the physician's needs for diagnostic data.

Leaders in the diagnostic x-ray field—not just Picker, of course—work to reach the irreducible minimum dosage that still yields the desired information. The problem is being tackled on a diversity of fronts by a variety of specialists: radiologists and other physicians, radiologic technologists, engineers, nuclear physicists, and chemists.

Progress to date has come in several ways. New methods have been developed to shape and direct the radiation beam, thus reducing the area of the body exposed. Other advances reduce the duration of exposure. Still others prevent the production of waste x-rays. New shielding devices help protect both patients and physicians. And the industry helps train physicians and their technologists on how to use new equipment safely as well as efficiently.

Newer tools: isotope-imaging and ultrasonics

The development of other approaches for visualization is bearing fruit, too. Picker has led with instruments used in nuclear medicine and currently offers the medical community the widest spectrum of isotope-imaging devices in the world. Contributions of this newer diagnostic use of radiation to health are of steadily increasing importance.

Now Picker is perfecting an entirely different kind of diagnostic tool: ultrasonics. Ultrasonic instruments offer the medical profession a technique that differs from both x-ray and isotope-imaging by providing visualization with sound waves, not radiation. Diagnostic ultrasonics is not being used by radiologists alone. A growing number of specialists including neurologists, cardiologists, obstetricians, and gynecologists are finding ultrasonics can complement, and sometimes supplant, other diagnostic procedures.

Such introduction of new techniques and equipment, coupled with continued developments in x-ray diagnosis, will supply physicians with the safer, more efficient diagnostic tools they need to protect your health. As always, however, it is the physician who must make the judgment on the best technique for each case.

Picker Corporation, White Plains, New York

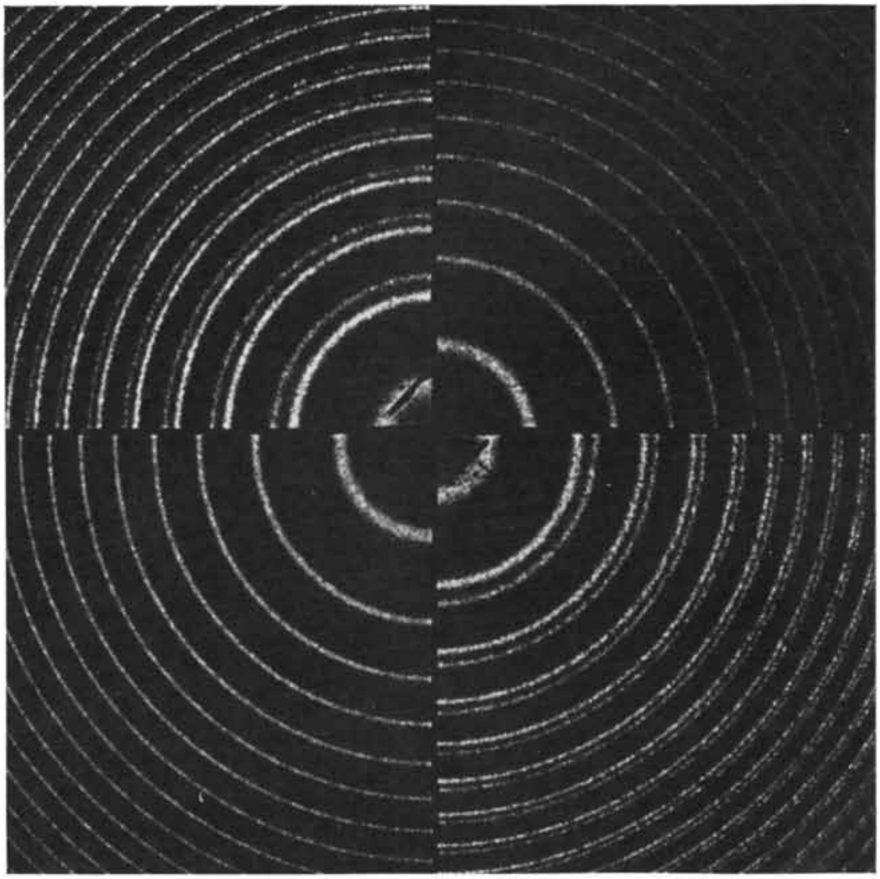
PICKER

the visible range that produces tunable beams at a power of half a milliwatt has been constructed at Stanford by R. L. Byer, M. K. Oshman, J. Young and S. E. Harris.

Another current development in the refinement of lasers is the production of extremely short pulses. The pulses from most solid lasers range in duration from thousandths to millionths of a second. It has now been found possible to generate pulses whose length is measured in picoseconds (10^{-12} second). The technique employed is known as mode-locking. A laser beam can comprise waves of several slightly different wavelengths, such that one wave undergoes precisely one more cycle than another in the round trip between the mirrors. These components are called the modes of the beam. The trick in generating very short pulses is to bring all the modes into synchronization at some point in the laser column so that they produce a single, sharp maximum of intensity at that point. They can be "locked" in this cyclic pattern by placing a bleachable dye at the synchronizing point; the dye is bleached sufficiently for the waves to pass through most easily only when they all arrive simultaneously, and the laser therefore generates a brief pulse just at that moment at the end of each round trip of the waves.

In a picosecond light travels three-tenths of a millimeter. Hence the train of light waves in a picosecond pulse is only three-tenths of a millimeter long and contains only a few hundred cycles of the wave. Since pulses of such extreme brevity place relatively little strain on the laser material, the laser can be raised to high peak powers. Nikolai G. Basov and his associates in the U.S.S.R., using a mode-locked laser of neodymium glass and three subsequent stages of amplification, have produced laser pulses of more than a trillion watts. The pulses were so powerful that they attacked the nuclei of atoms; focused on a target of lithium deuteride in a vacuum, the pulse somehow caused neutrons to be released from the nuclei.

It seems likely that picosecond laser



BRILLOUIN-SCATTERING PHOTOGRAPH obtained using the experimental arrangement shown on page 132 is essentially a Fabry-Perot interferogram with the interference fringes due to the scattered light occupying the quadrants at upper right and lower left and the interference fringes due to the laser light occupying the quadrants at upper left and lower right. The two sets of fringes can be measured directly to determine the amount of Brillouin scattering associated with a given liquid or solid material. This knowledge in turn can be analyzed to yield information about the structure and properties of the material.

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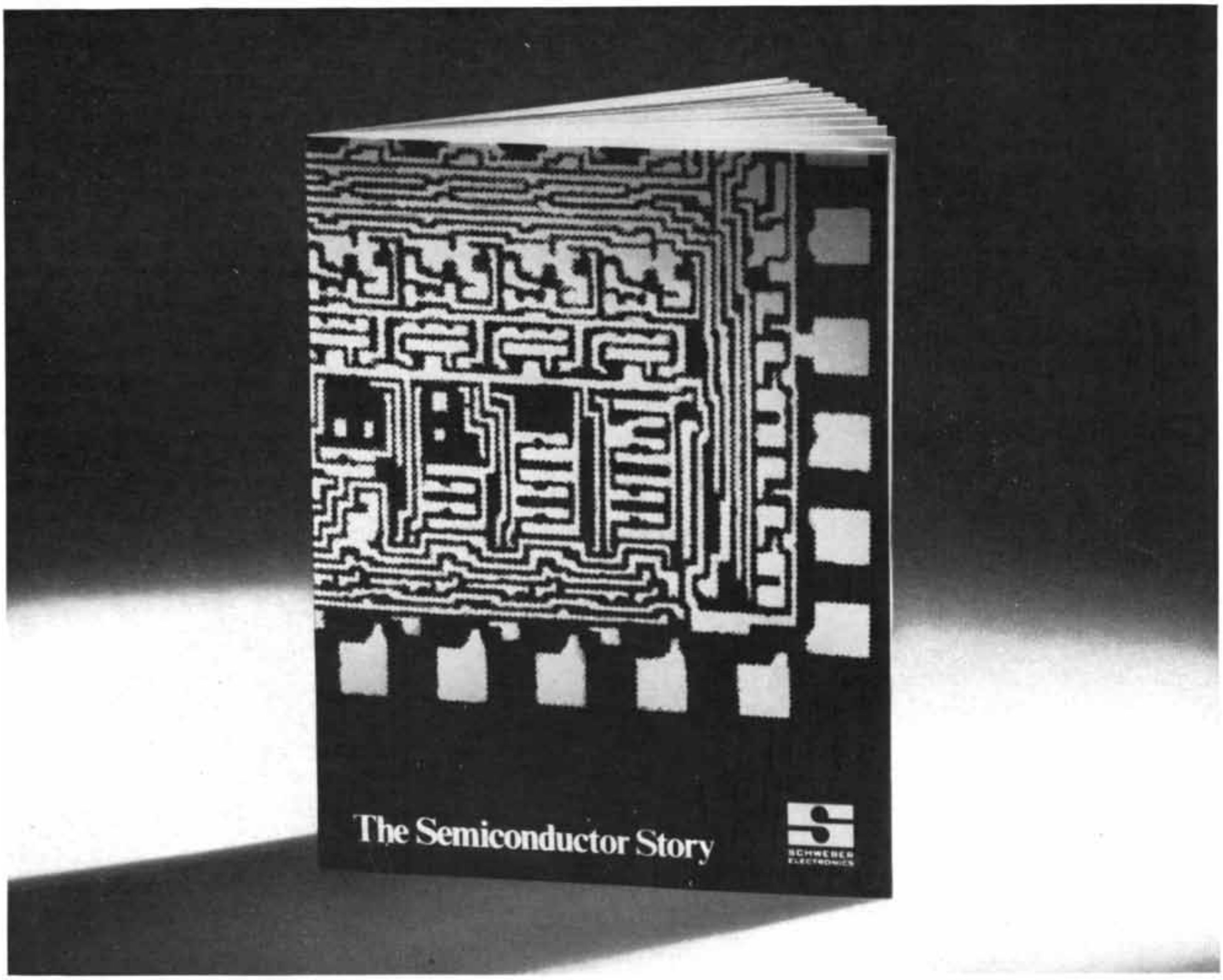

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pulses will be highly useful in exploring the interior of atoms. When such a short light pulse is absorbed, the entire encounter is usually over before there is time for the absorbing atoms to be perturbed by the surroundings. Many kinds of transient effect showing the inertia of the absorber should therefore be observable. Most atoms in solids "relax" in less than a nanosecond, so that the transient effects are observable only with shorter pulses. Thus the interaction of many media may be quite different for picosecond pulses from what it is for longer wave trains.

There are now hundreds of masers and lasers, generating frequencies over most of the electromagnetic spectrum, from the radio region far into the ultraviolet. Indeed, it seems that before long the art of stimulating emission will be extended into the X-ray region. Most likely the visible-frequency laser will be employed to pump atoms to the energy levels necessary for X-ray emission, as radio generators are used to pump the gas laser. Very intense excitation will be needed to raise atoms to the X-ray emission level, because excited atoms spontaneously shed their energy more and more promptly as they go up the quantum ladder of energies. It can be shown that the power required to simultaneously boost enough atoms for stimulated X-ray emission may be as high as a million billion watts per cubic centimeter. That is well within the range, however, of what can be attained by focusing a pulsed laser. An X-ray laser might consist of a column of active material only a millimeter long and about a micron in diameter. Even without mirrors such a column should produce a fairly directional X-ray beam. Presumably the wavelengths of the output would be in the range of just a few angstroms, but precisely what emissions would come out of such a system is not easy to predict; it is a matter of record that most gas lasers were discovered experimentally.

Meanwhile the development of visible-light lasers is providing excitement enough. As we go to higher and higher powers, laser light is demonstrating extraordinary nonlinear phenomena in its interactions with matter. Some of the lasers now under development in the laboratory, such as the tunable and picosecond versions, are showing us that lasers so far have been rather simple devices only because we are just entering the stage of learning why and how to make complicated ones.

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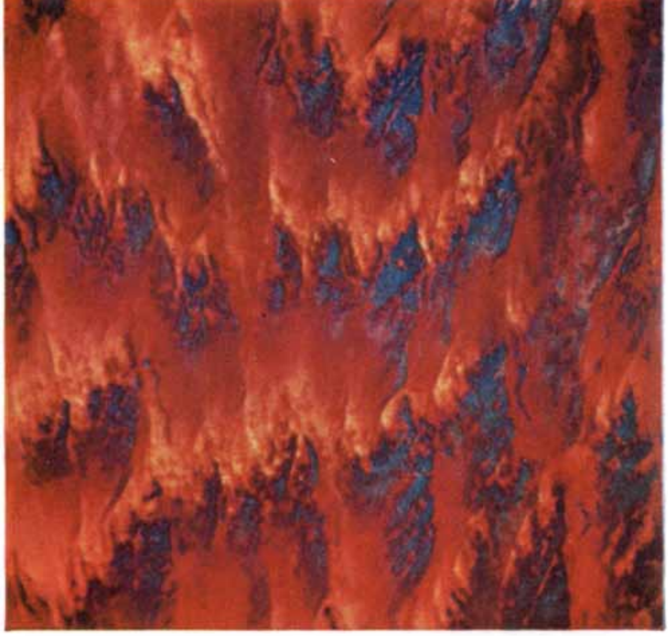

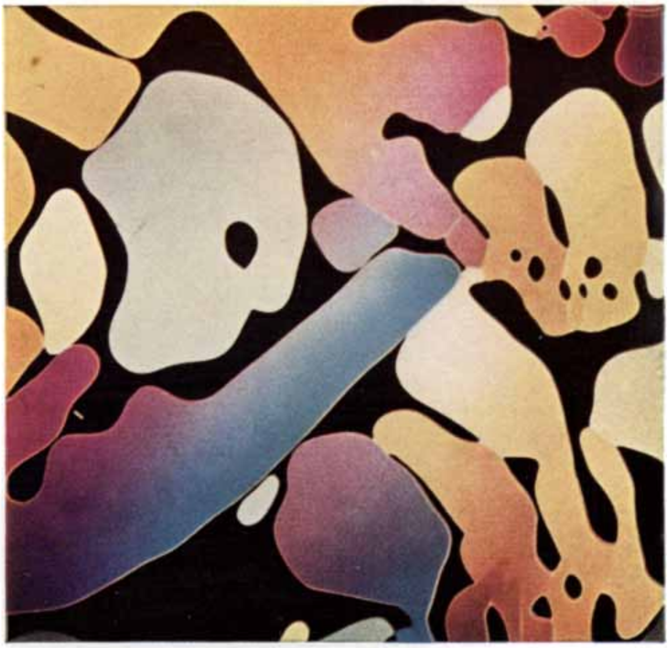

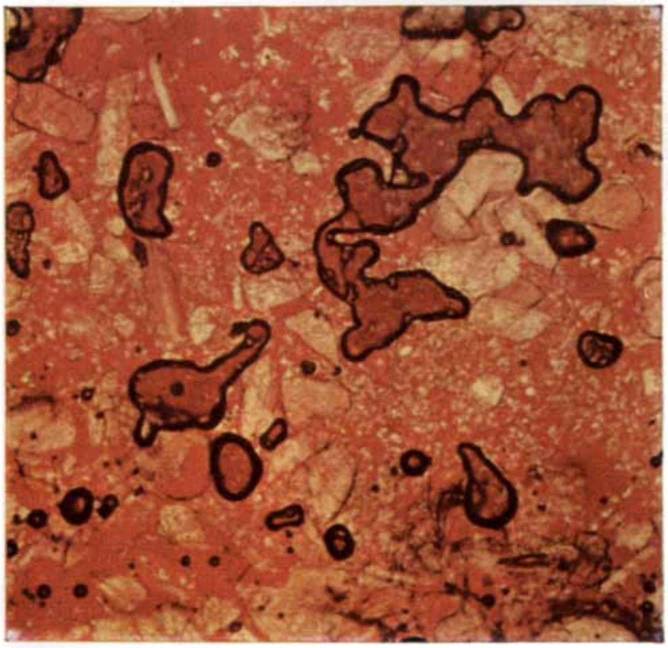

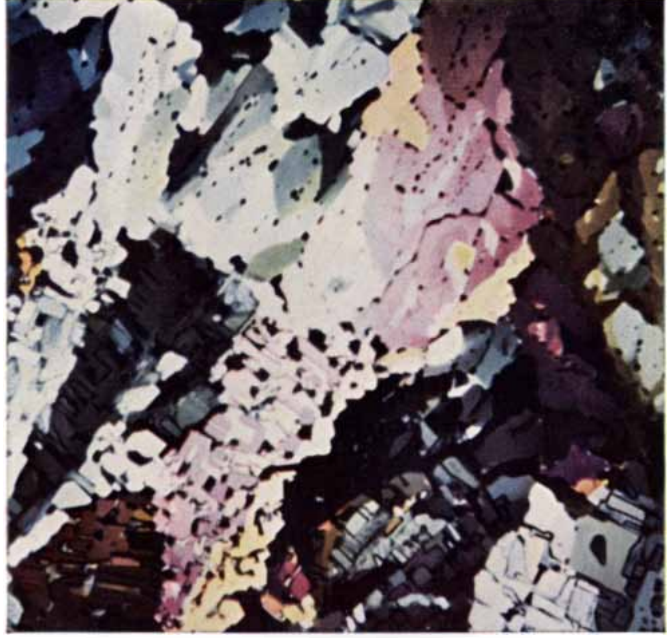

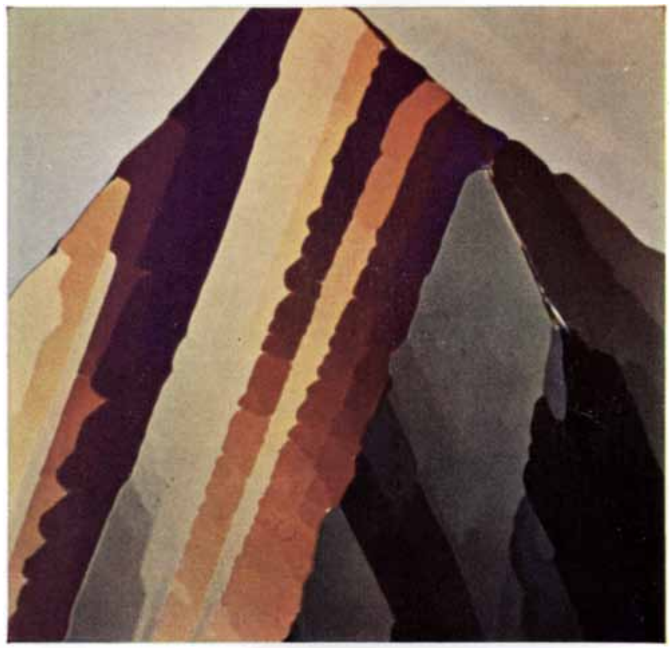

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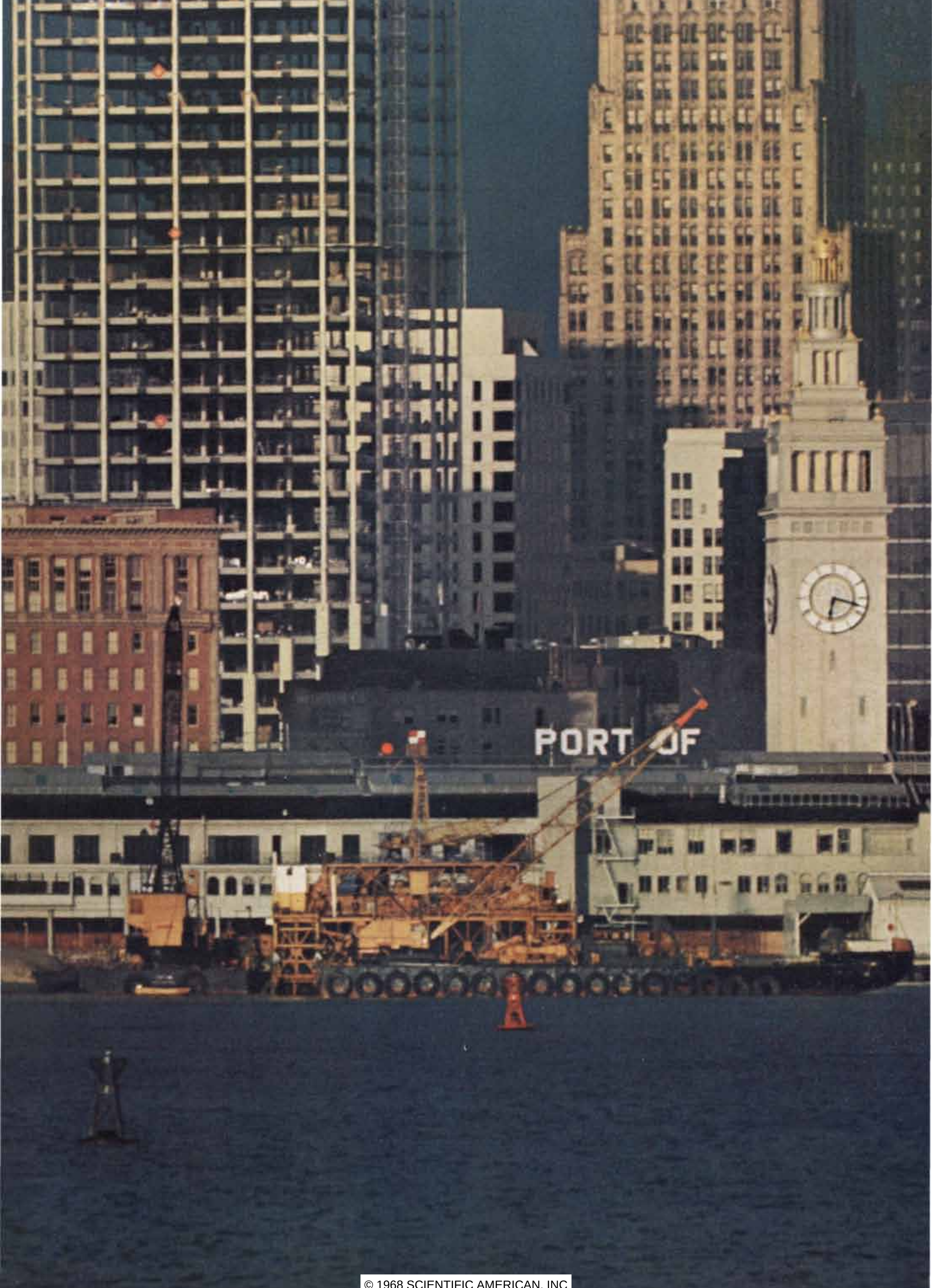

PORT OF

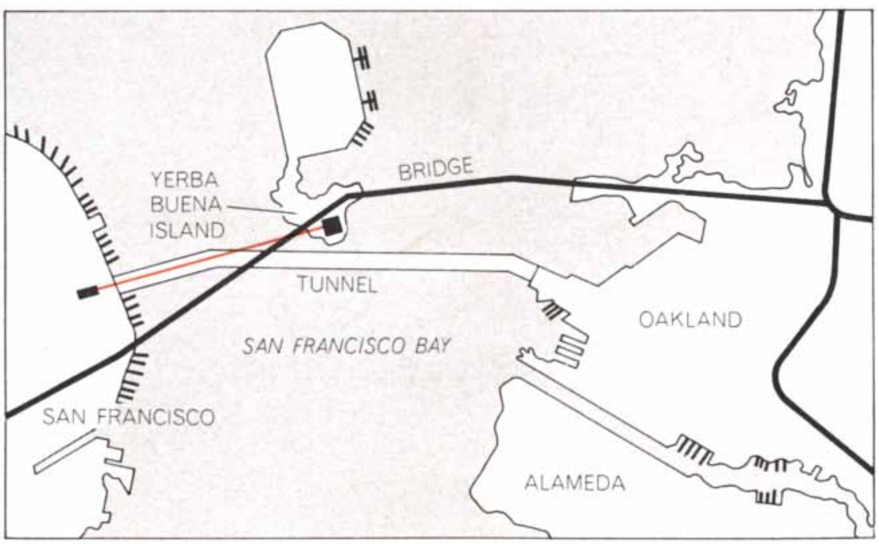
Applications of Laser Light

They range from the straightforward (such as surveying and welding) to the sophisticated (such as optical communication and holography), and it may be that more interesting applications are still to come

by Donald R. Herriott

Predicting what will eventually be done with lasers is risky. The prospects of the laser are qualitatively different, for example, from those of the transistor at the time of its invention 20 years ago. The transistor was, after all, essentially an improved device for performing existing functions, and its evolution was comparatively straightforward. The laser, on the other hand, produces light that is different in both quality and intensity from the light generated by any other source. As a result some of the more obvious uses of lasers in existing systems, such as conventional interferometers, may turn out to be less important than the development of new systems that take advantage of the unique characteristics of laser light to perform tasks either thought to be impossible or not even imagined.

The prime example of such an unpredictable development has been the recent burst of activity in the branch of interferometry known as holography, or photography by wave-front reconstruction. Here the advent of the laser, combined with a few critical refinements of an existing idea, has provided a completely new and unexpected capability.



USE OF THE LASER in technology is symbolized by the photograph on the opposite page. The bright red spot near the center of the photograph was made by a helium-neon gas laser mounted on a surveyor's transit on the roof of the Ferry Building in downtown San Francisco. The laser is one of about a dozen used to align a fleet of dredging barges and other floating equipment being employed in the construction of the subway tube between San Francisco and Oakland, a major link in the projected Bay Area Rapid Transit system (BART). The photograph was made from Yerba Buena Island along one of the straight stretches of underwater trench being prepared for the tube (*see map above*). The laser beam is visible only to an observer standing directly in the path of the beam. The beam was about two inches wide at the laser and spread to a width of about nine inches by the time it reached the camera, approximately a mile and a half away. The square object with alternating red and white quadrants next to the laser on the roof is a target for another laser.

Another aspect of this unpredictability is manifested by the fact that the use of laser light as the carrier wave for a long-distance communication system—a concept recognized quite early as one of the most important of the potential applications of the laser—is still a long way from being commercially implemented on a large scale. This is not for lack of a sound basis for this application but rather because of the broad range of auxiliary techniques required, and because of the existing high level of development in the competing technology.

In the meantime, as more and more people have become aware of this extraordinary new light source, a host of suggestions have been made for more prosaic applications of laser light, in fields as diverse as welding and surveying. A surprising number of these applications appear to be immediately feasible. Indeed, it is quite possible that some of the less sophisticated uses of the laser will in the long run prove to be among the most important, at least from an economic point of view. Here I shall outline the major areas in which applications of laser light can be grouped and describe some typical examples in each area.

There is a large class of laser applications that depend not so much on coherence or monochromaticity per se but rather on the unprecedented brightness, or energy per unit area, that can be obtained by focusing a laser beam with a lens. This brightness, which is a by-product of the beam's coherence, is a unique feature of laser light and can be many orders of magnitude greater than the brightest light produced by conventional sources. To understand why this is so it is necessary to review briefly a few of the basic differences between the incoherent light produced by an ordinary bright source and the coherent light produced by a laser.

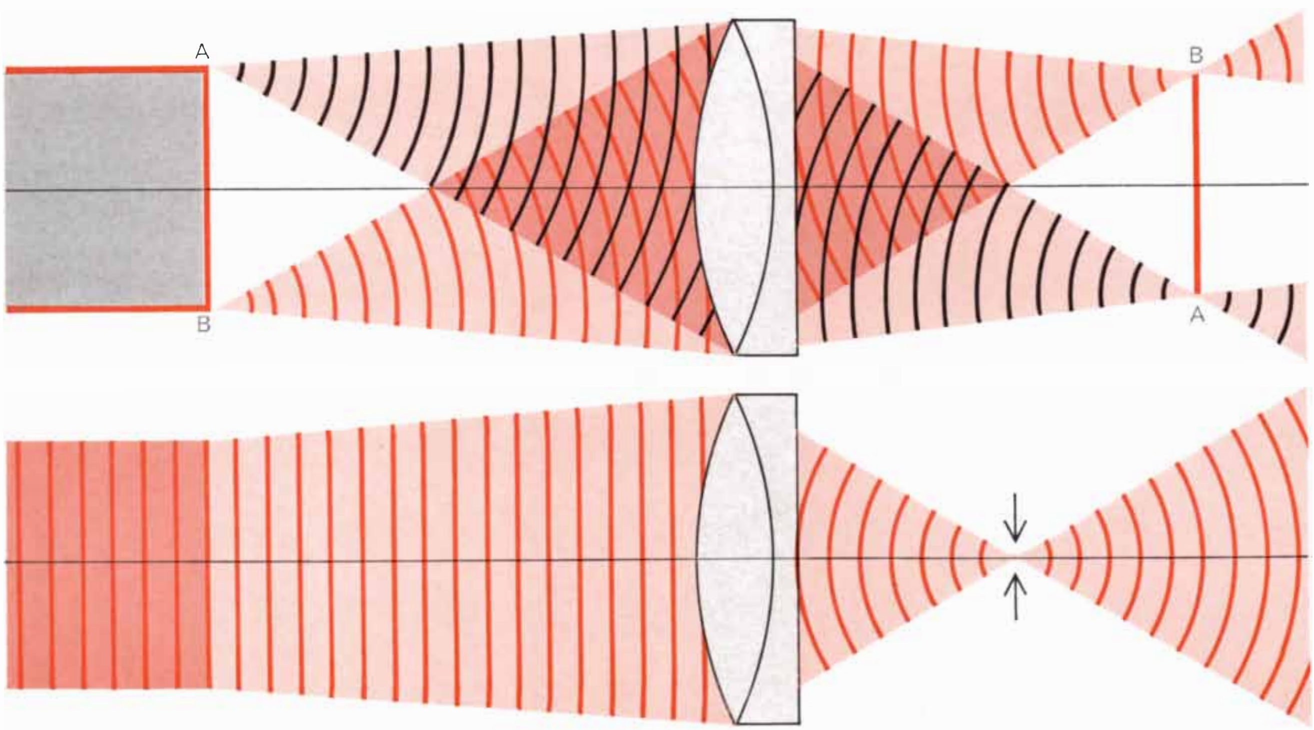
In a conventional light source the atoms of a solid or a gas are agitated either thermally or electrically to higher energy states. When these atoms return spontaneously to their lower energy levels, they radiate some of their excess energy as light. Since each atom behaves independently at this stage, its emission is at a random time and in a random direction with a random polarization.

It follows that the light radiated in a single direction is the complex sum of all the light from the individual atoms. The phases of any two atoms will tend to cancel their radiation in some directions and enhance it in others. The total energy of the source will on the average be radiated uniformly in all accessible directions, and the amount of energy observed in a given direction will be proportional to the solid angle subtended by the observing device. The maximum total energy that can be radiated by a given source depends on two factors: the surface area of the source and the maximum temperature to which the source can be heated without melting (in the case of a solid) or the maximum pressure and temperature that can be sustained in a discharge lamp (in the case of a gas). Thus in practice the only way to increase the power output from an ordinary source beyond the limitations imposed by the source material is to increase the area of the source.

Power output, however, is only half the story. For many applications brightness, or concentrated power, is much more important than power itself. A 40-watt fluorescent lamp, for example, produces more light than a 40-watt incandescent lamp, but it would not make nearly as good a light source for a spotlight. It is therefore not surprising that students of optics have tried for centuries to get a brighter light source by reducing the size of a large source with a lens. They have discovered that the brightness of the source cannot be increased in this way, because even under ideal conditions the reduced area of the image just makes up for the reduced collection angle that the lens intercepts from the source [*see illustration below*]. In other words, with a conventional source one cannot produce an image that is brighter than the source. The brightness can at best match that of the source, neglecting losses due to surface reflection, scattering and absorption by the lens elements.

In the case of a source that is smaller than the resolution limit of the lens, the size of the image is determined by the aperture and aberrations of the lens. For example, when a star is photographed through a telescope, the size of the image does not depend on the size of the object. Since the star is actually smaller than the size indicated by the image, the brightness of the image must always be less than the surface brightness of the star.

Now, in a laser light is also emitted when atoms drop from a higher energy level to a lower one, but in this case the atoms are triggered to emit in unison by the standing wave in the laser cavity. Enough of the light previously generat-

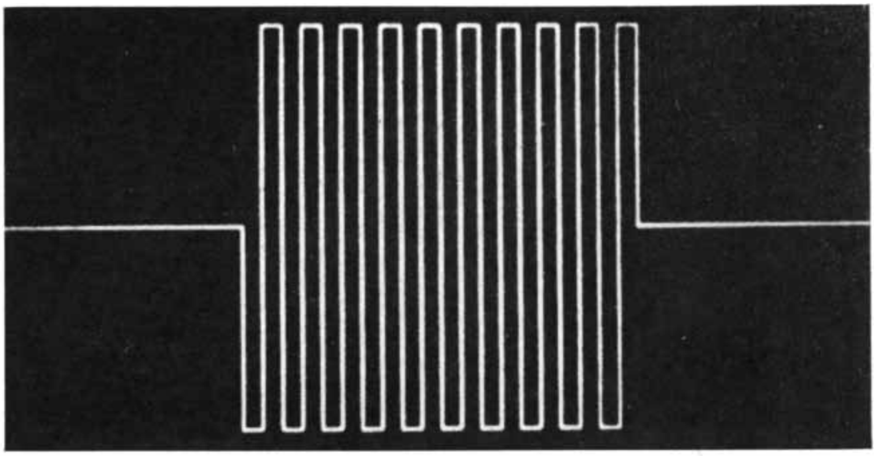


ADVANTAGE OF LASER LIGHT over ordinary light in forming an image with a high brightness, or energy per unit area, arises from the basic differences between the coherent light produced by the laser and the incoherent light produced by an ordinary source. In an ordinary source (*top*) light is emitted independently by each atom, so that the emissions from all the atoms of the source will be at random times and in random directions with random polarizations. As a result the total energy of the source will on the average be radiated uniformly in all accessible directions, and the amount of energy in any given direction will be proportional to the solid angle subtended by the observing device. Any attempt to increase the brightness of an image over the brightness of the source by reducing the size of the source with a lens cannot succeed, because even under ideal conditions the reduced area of the image just makes up for the reduced collection angle that the lens intercepts from the source. In contrast, the coherent light produced by a laser (*bottom*) is generated over a sizable volume with the proper phase, so that when it is focused by a lens, all the individual contributions by the atoms in the laser medium are in the correct phase to add up. In a typical laser the directionality of the beam is limited only by diffraction by the laser aperture. Accordingly with a suitable lens all the energy of the laser can be concentrated into a diffraction-limited image that is only one micron in diameter, resulting in much greater energy density than the density of the source.

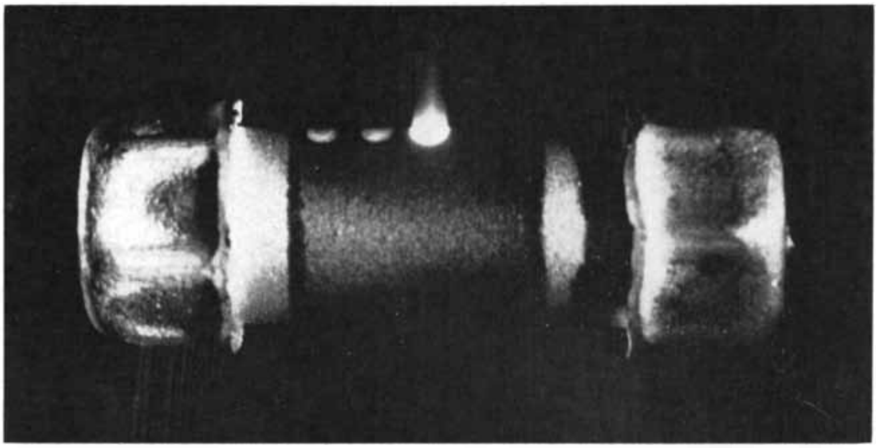
ed is retained in the reflective cavity to keep the new emission in the proper phase, polarization and direction. This standing wave interacts with the excited atoms and causes most of them to emit their excess energy in phase with the stimulating wave before they have a chance to emit it randomly. As a result the laser generates only light that travels in the direction of the standing wave. In a typical laser this directionality is limited only by the diffraction of the emerging beam by the laser aperture. It is important to realize that the laser does not violate the materials limitations of ordinary light sources; it simply concentrates all its energy into a single, diffraction-limited beam.

In effect the beam from a laser is the same as one from a distant small source, such as a star. When the beam is focused by a lens, its diameter at the point of sharpest focus depends only on the resolution limit of the lens. With a suitable lens all the energy from a typical laser can be concentrated into a diffraction-limited image that is only one micron in diameter, regardless of the size of the laser! This results in a tremendous energy density, one that is far greater than the energy density of the source. The key point is that inside the laser the radiation is generated over a sizable volume with the proper phase, so that when the radiation is focused by the lens, all the individual contributions are in the correct phase to add up.

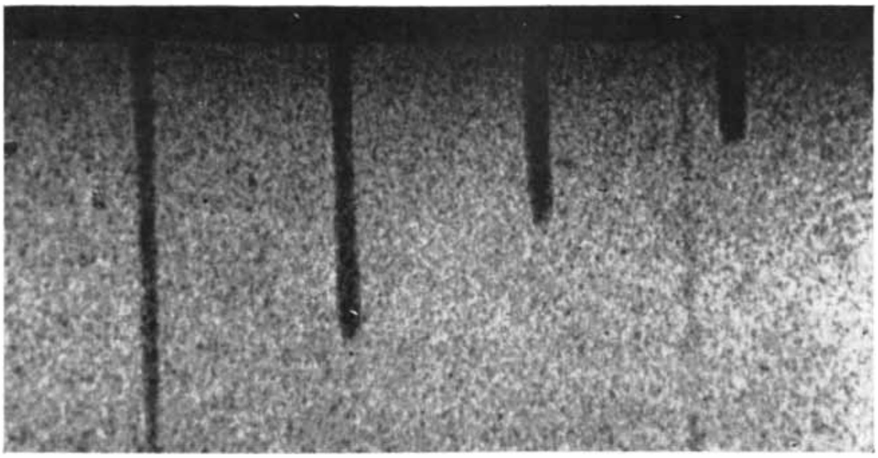
The energy density of the image formed by a lens in a laser beam can be used to heat, melt or even vaporize small areas of any material. This capability promises to find wide use in the field of microelectronics. The main advantages here are the very small size of the focused image, the absence of contamination of the very pure materials required in such circuits and the precise control of the amount of energy used. For example, the image of the laser can be used to cut a narrow gap through a vapor-deposited film; by cutting such a gap along a meander path through a conducting film one can easily form a capacitor [*see top illustration at right*]. In the fabrication of integrated circuits the laser beam can also be used to weld connections between parts of the circuit, or to cut through connections and thereby tailor a general circuit to perform one of a variety of functions. This discretionary wiring can also be used to compensate for a small percentage of defective components and thus increase reliability. Discrete components such as a precision resistor can be adjusted in a



MICROCAPACITOR was made by using a beam from a solid-state laser to cut a meander path through a .3-micron-thick gold conducting film vapor-deposited on a sapphire substrate. The cut is six microns wide. The main advantages of laser light in the field of microelectronics are the very small size of the focused image, the absence of contamination of the very pure materials required in such circuits and the precise control of the energy used.



PRECISION RESISTOR is adjusted in value by means of a completely automatic machine that measures the resistance and pulses a laser to vaporize conductive material until the desired resistance is obtained. This photograph was made at the Western Electric Company.



PENETRATING POWER of the focused light beam from a pulsed ruby laser is demonstrated by this X-ray photograph, which shows a number of holes drilled by such a laser in an alumina ceramic .062 inch thick. The diameter of the holes varies between .0015 inch and .003 inch. Twenty-four pulses each with an energy of a tenth of a joule were required to pierce a hole all the way through the ceramic. The reason narrow holes can be drilled to a depth greater than the depth of focus of the laser has not been adequately explained. This photograph and the one at top of the page were made at the Bell Telephone Laboratories.

completely automatic machine that measures the resistance and pulses the laser to vaporize conductive material until the desired resistance is obtained [*see middle illustration on preceding page*].

In a related application a pulsed laser has been used to pierce holes in diamond chips used in dies for drawing wire. A number of laser pulses are used to make the hole and to rough it into shape. The hole is then polished with olive oil and diamond dust to its final shape and finish.

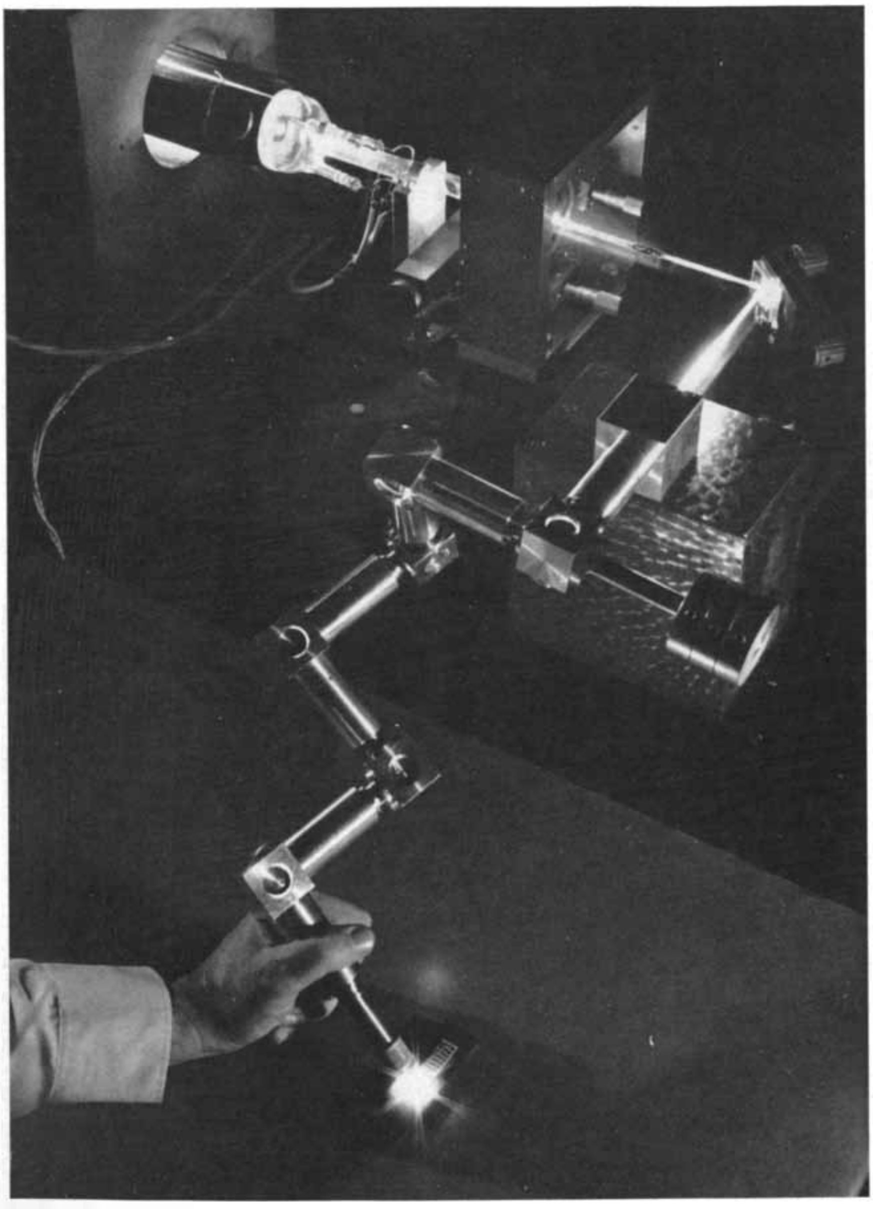
Another interesting application that has already been demonstrated is the use of a pulsed laser to balance high-speed gyroscope motors as they run. Vibration sensors determine the amount and the exact orientation of the errors in balance, and the laser source is automatically pulsed to remove material at the proper places until balance is achieved. In fact, it is conceivable that high-power lasers will someday be used routinely to cut a wide range of materials, including wood, cloth and paper. The combustion of the adjacent material is usually not a problem because the heated material vaporizes almost instantaneously and hence dissipates heat rapidly.

The high intensity and directionality of a laser beam has made surveying one of the most direct and practical applications of the laser. The laser beam can be focused through a telescope to have the same width at any distance as the resolution of the telescope. Thus when the light beam formed in the telescope is measured at the target, the accuracy is the same as when, in conventional surveying, the image of the target is observed in the telescope. The principal advantage of the laser system is in saving labor and communications. In a typical surveying application a laser beam is positioned along the intended route for a pipeline. It is important in laying pipeline that the trench be dug to just the bottom of the pipe, since soil disturbed below this level will later settle and may rupture the line. As the shovel digs, its depth can be regularly measured with a stick. The stick is simply placed at the bottom of the cut and the height of the laser beam falling on the stick is read directly. The same technique can be used by the men cleaning up the trench to fit the actual shape of the pipe. Accuracies of a fraction of an inch are easy to maintain in this way. In the present procedure a telescope is set up in a similar manner, but then a man must stay at the telescope, take all the measurements and communicate them to the group doing the digging. This requires both an additional man at the telescope and communication of the results to the digging crew.

When property lines or power lines are being laid out through wooded land, it is common to clear broad rights-of-way along the entire path. With a laser surveying instrument the laser beam can be set up on the proper line and the beam can be observed as it falls on each obstruction. A man can then walk from the laser to the target, see immediately each branch or tree that the beam hits and remove only actual obstructions.

The high intensity and directionality of a laser beam can also be used to align jigs for mechanical tooling by photoelectric centering of a target. The person viewing a target through a telescope can resolve or distinguish two objects separated by the diffraction limit of the telescope (approximately one second of arc per inch of diameter). He can center a dark cross hair in the telescope on a white line on a suitable target pattern to three or five times that accuracy. A laser beam can be projected through the same telescope with a half-power width that is also about the same as the diffraction limit. By balancing the light in the two sides of the beam, the center of the beam can be found to better than a tenth of the half-power width. Under the best conditions a hundredth of this width would be possible.

Laser alignment systems are now be-



LASER "KNIFE" developed at Bell Laboratories has an articulated arm that allows the beam from a stationary laser to be moved freely for use in surgery, microcircuit fabrication or many other applications. The "elbows" of the hollow arm contain prisms that reflect the beam down the center of each section in spite of the free rotation of each joint.

RECENT FINDINGS

RESEARCH LABORATORIES

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On the way to a better understanding of lasers and the optical properties of surfaces.

Through a study of second harmonic light generated at surfaces, we may one day have a better understanding of the properties of surfaces.

Second harmonic generation (SHG) of light is a process in which a light beam, in passing through a substance, generates another light beam whose frequency is twice the original. This means *red* light (i.e., from a ruby laser) would be converted into *blue* light. Simple geometrical considerations demand that the process occur only in regions of space which are not symmetric under inversion. Piezoelectric crystals provide macroscopic volumes which satisfy this condition, and with them Ford Motor Company scientists first demonstrated 20% optical second harmonic conversion. Thus, using SHG, intense coherent light beams are available at new, higher frequencies. At the other end of the scale, they are now studying cases in which only one part of 10^{17} of the incident light is harmonically converted. That so weak an interaction

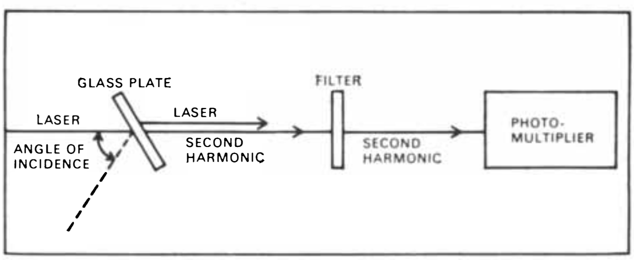

FIGURE 1

can be detected rests, among other things, on filters which strongly absorb the fundamental radiation and yet transmit the harmonic light. The second important ingredient is the availability of sophisticated multi-megawatt lasers, designed and engineered by Ford scientists, which pulse once a second for half a million seconds without maintenance and which are equipped with automated photodetection systems capable of recording single photoelectrons at noise levels of only one event in 500 laser shots. Thus it is that SHG may be studied at surfaces, spatial regions only a few angstroms deep which lack inversion symmetry. It is found that surface SHG can originate not only from otherwise unmeasurable properties of the bulk material

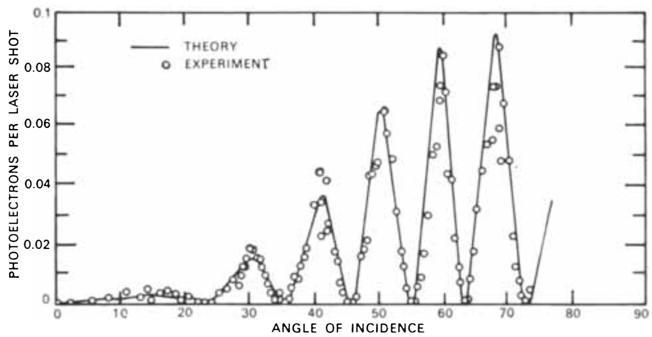

FIGURE 2

but also can yield important information on pure surface properties.

Figure 1 shows a typical experimental arrangement and Figure 2 summarizes results obtained using a ruby laser and a thin glass platelet. As indicated by the ordinate the second harmonic signal was indeed very weak. The oscillatory behavior of the second harmonic intensity results from interference of the second harmonic waves generated at the front and back faces of the platelet. The angular spacing between successive maxima is determined by the platelet's thickness and by the difference in its refractive index for the laser and harmonic frequencies.

This study is typical of the work being undertaken in Ford Motor Company laboratories to obtain a better understanding of the properties of materials. Ford scientists are actively investigating many fields in the conviction that greater knowledge leads to improved technology and better products.

PROBING DEEPER FOR BETTER IDEAS

Ford

ing used, and indeed are needed, for the alignment of jigs in the new large second-generation jet aircraft, where tolerances of a hundredth of an inch over distances in excess of 200 feet are involved. One or more laser sources can be set up in alignment along the length of the jig and each critical point can be measured with respect to the laser beams. This can be done over short distances without people at the laser sources. Detectors of the quadrant type, with servo drives that automatically center the detector on the beam both horizontally and vertically, are frequently employed.

If a laser beam is directed to scan an object, and a viewing telescope is made to track the intersection of the laser beam and the object from a different direction, the combination can survey the object in three dimensions. Angular readings can be taken from such an instrument to convey to a computer the form of an object such as an automobile model so that the computer can define the shape of the dies necessary to make the automobile body parts. It could also scan an aircraft to determine if its form properly agrees with the plans.

In the area of remote sampling it has been suggested that laser beams could be used to map the distribution and motion of pollutants. The idea here is to pulse a short burst of light from a laser through the atmosphere and observe the light scattered back to a receiving telescope, much as radar is used to observe clouds and rain. It will take a predictable amount of time for the light to travel to a particular sampled region and return. The signal observed at a given time after the laser pulse is dispatched will be a measure of the transmittance of the air along the path and the backscatter of the pollutant at the specific distance along the beam. It should be possible to analyze the returned beam to determine the concentration of a variety of pollutants at each point along the path of the beam. Thus one observing point in a large area could monitor pollution levels and identify the specific sources of pollutants.

So far we have considered the group of applications that are principally based on the high brightness of the laser source, which is an indirect result of the coherence of the light from the source. We shall now consider applications that directly exploit the spatial and temporal coherence of a laser source to extend the capability of a system beyond what can be done with coherent light from conventional sources.

The principal application of coherent light before the advent of the laser was in interferometry. Here two or more light beams are made to follow different paths through an optical system. The light is then combined so that interference can be observed. If the two beams are in phase when they recombine, the square of the sum of their amplitudes will be the observed intensity; if the beams are out of phase, the square of the difference of their amplitudes will be observed. In some interferometers these intensities will be observed as alternate light and dark fringes across a field of view, each indicating a half-wavelength shift in path length between the two paths through the interferometer. In other interferometers fringes caused by light traveling at various angles through the instrument are observed in angular space. In still others a single fringe covers the entire field, and changes in intensity of the field are caused by variation of phase between the beams with time. This last type of interferometer is commonly used with photoelectric detectors and records phase shift as a function of time.

In none of these conventional methods of interferometry is it mandatory that the two light beams come from a single source. The trouble is that if they do not come from a single source, their frequencies will vary with time, causing the fringes to shift so rapidly that they cannot be observed. Lasers have now provided sources whose frequency can be controlled so that interference between light from different sources is practical.

With two beams from a conventional source the light following the different paths must meet so that light from the same point on the source is superposed, and so that light emitted at the same time is recombined. Both the position and the time must be close enough so that the phases of the two effective sources are coherent. The distance along the beam between two points that have correlation adequate to give useful contrast will depend on the width of the spectral lines of the source. High-pressure mercury lamps require that the two paths be matched to within a fraction of a millimeter. Low-pressure isotope lamps can be used at a path difference of a good part of a meter. Laser sources, in contrast, are narrow enough in line width to be used over hundreds of miles. The importance of this lies in the fact that it frees one from the need to worry about the matching of path lengths. In making measurements on a 200-inch telescope with an interferometer one path of which is 50 feet long, for example, it is now possible to use a reference path of a few inches instead of having to build a reference path of the same 50-foot length as the path to the mirror.

The long coherence length afforded

LASER ERASER invented by Arthur L. Schawlow of Stanford University is capable of vaporizing ink from paper without appreciably heating the paper. The heating of the black ink, which absorbs the laser pulse and becomes incandescent, is so rapid that the ink vapor carries away the heat before it can penetrate below the surface by conduction. The dark ring is a shadow of the end of the laser, produced by stray light from the laser flash lamp.

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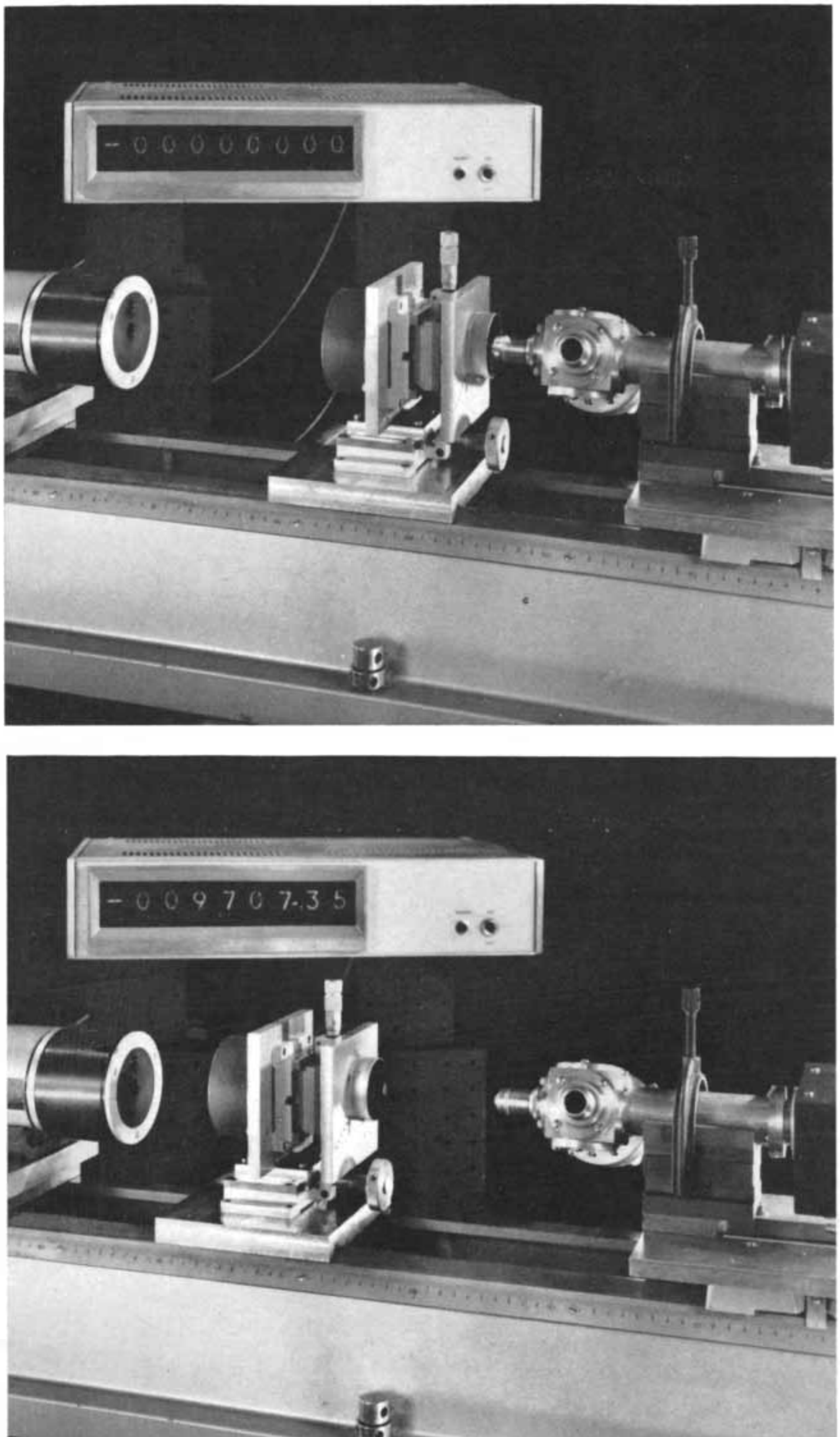

TWO LASER INTERFEROMETERS in the author's laboratory at Bell Laboratories are used to test polished lens surfaces for sphericity and to measure their radius of curvature. In this demonstration of the system's extreme sensitivity the laser interferometer at right is being used to position the slide carrying the lens, so that the focal point of the microscope objective at the end of the interferometer coincides first with the surface of the lens (*top*) and then with the center of curvature of the lens (*bottom*). In both of these situations one observes through the viewer attached to this interferometer a straight-line pattern of interference fringes rather than the usual curved pattern of such fringes. The laser interferometer at left is used independently to measure the displacement of the slide along the optical bench by counting automatically the number of interference fringes shifted in going from the position at top to the position at bottom. This fringe shift is in turn translated into a measurement of the lens's radius of curvature in units of eighths of a wavelength; the results are displayed on the face of the electronic counter above the optical bench.

by the laser has eliminated one of the routine requirements that have generally limited the practical applications of interferometry. For instance, a spherical test interferometer has been constructed in which a polished lens surface can be tested for sphericity without making a test glass of identical radius, a costly and time-consuming job [*see illustration at left*]. In a similar instrument constructed prior to the introduction of the laser, light from a low-pressure mercury-isotope lamp was converged at right angles to the surface of a reference glass and then to the surface being tested. The light reflected from the two surfaces was combined to give interference fringes that showed the regularity of the sample. The spacing between the reference glass and the surface of the lens was limited to two inches in order for adequate contrast to be observed. This required a separate interchangeable reference surface for every two inches of range of the instrument. The faint light from the low-pressure lamp required that the observer adapt his eyes to the dark for several minutes for adequate visibility. A laser source in the same instrument would provide all the light needed and allow a single reference surface to be used with the full range of lens radii. This would change an instrument used under only the most favorable conditions in the laboratory into one with everyday application in the optical shop.

The freedom from the need for path compensation in interferometers with laser sources has made many long-path interferometric measurements practical. Flexure in dams, drift along geologic faults and long-wave, low-frequency oscillations in the earth's crust can now be studied by this method.

To expand on just one of these examples, a dam should be an elastic structure; in other words, it should deflect in proportion to the water level behind it. If a dam shows hysteresis in its deflections (that is, if it remains partly deflected), or if it is slowly shifting, this is an indication that it will ultimately fail. A laser interferometer can be used to measure and record motions of points on a dam to fractions of a wavelength of light. This kind of information should help civil engineers to study such structures and determine their safety.

In one of the earliest determinations of a standard of length by means of interferometry A. A. Michelson manually counted the fringes in an "etalon" a tenth of a meter long and stepped this unit along repeatedly to cover a meter;

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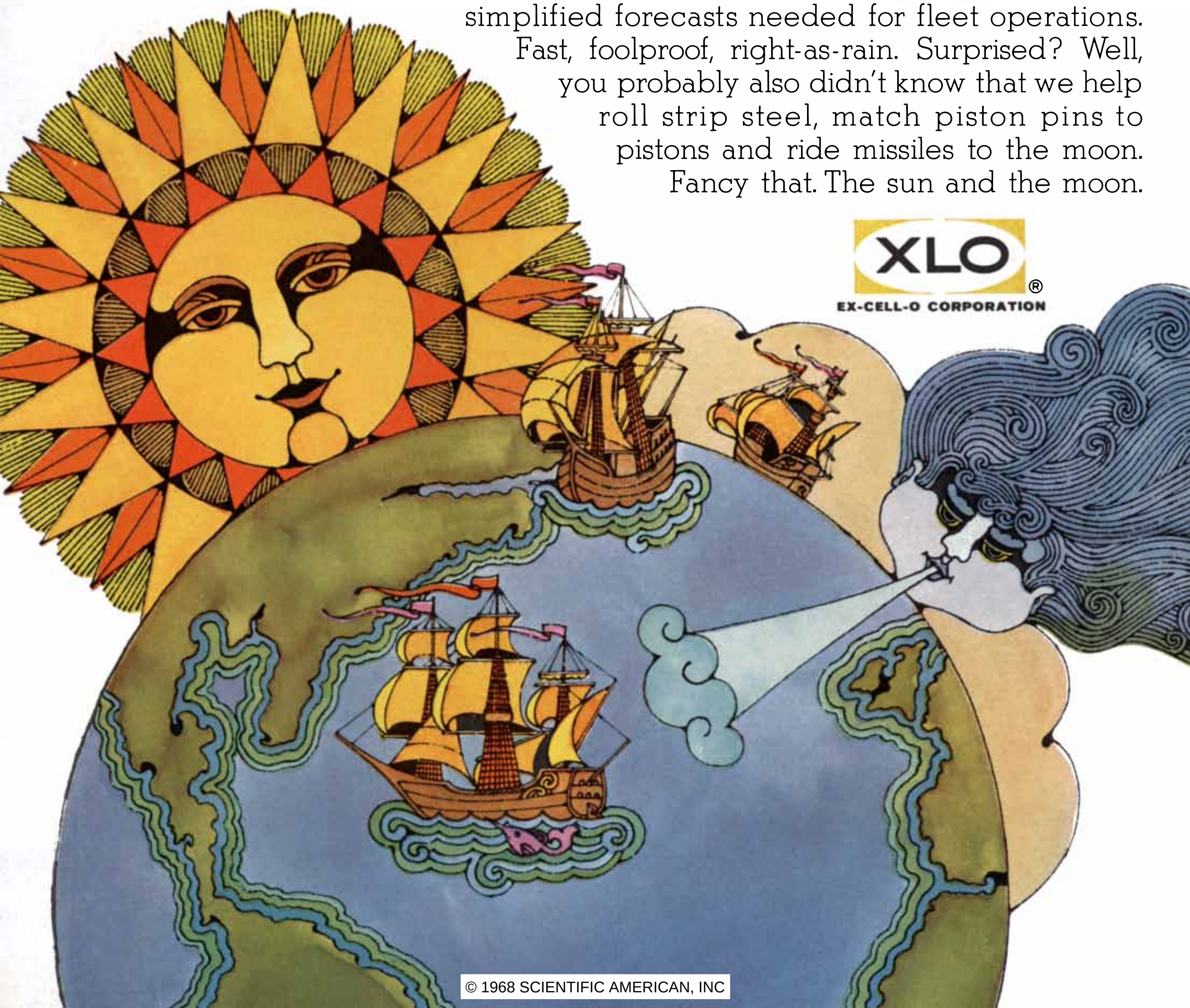

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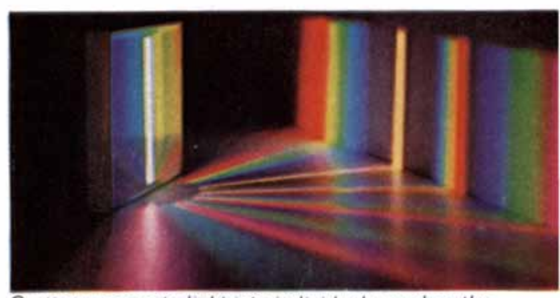

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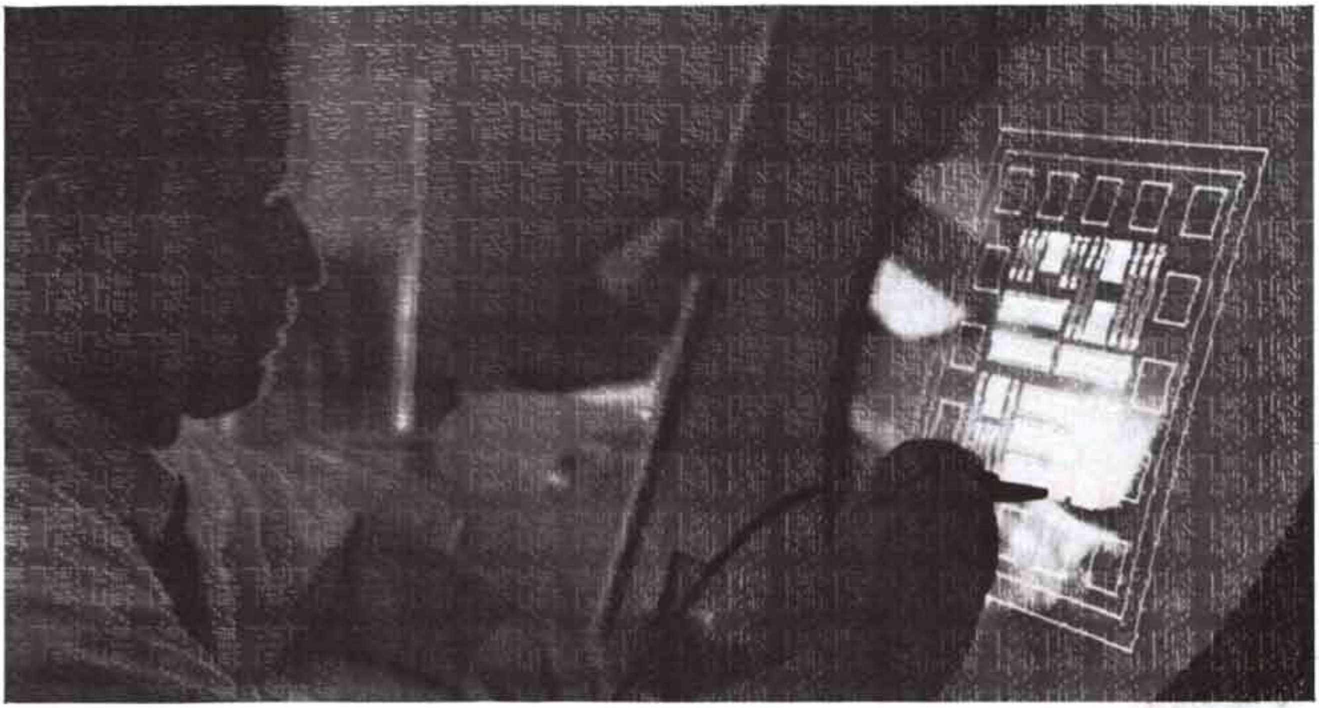

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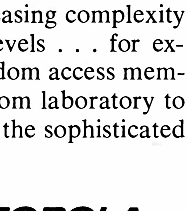

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in this way he succeeded in determining the length of the meter in wavelengths of the red line of a cadmium discharge lamp. Automatic fringe-counting techniques have since eliminated the counting chore, but the low intensity of conventional light sources limits the counting rate, and the breadth of their spectral lines limits the range of measurement to inches. The laser removes both limitations. A fringe-counting interferometer can now count the fringes directly as a mirror is moved over distances of 20 meters or more at a velocity of many inches per second. This measurement is made in terms of the wavelength of the laser source and is therefore limited only by the stability of the laser.

It is well known that fringe-counting can be used to measure the velocity of one of the interferometer mirrors by means of the Doppler effect. With a laser as a light source, however, light scattered from a moving sheet of paper, a moving liquid or even a gas moving in a pipe or in the open atmosphere can be made to interfere with the original light to obtain beat frequencies that are an accurate measure of the velocity of the scattering target. The application of this new capability to the control of industrial processes will almost certainly be significant.

Let us turn now to the two principal applications of laser light that could not have been achieved without the brightness and the coherence of laser sources: optical communications and holography.

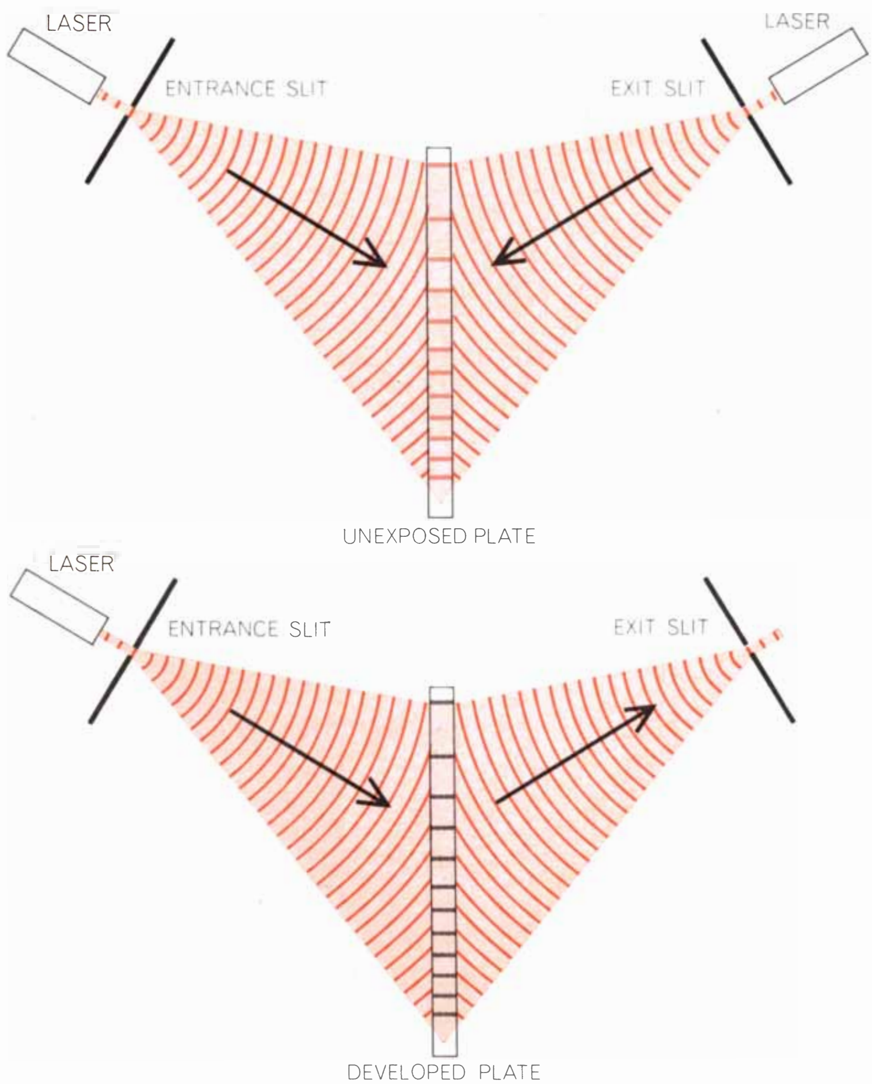
Communication with laser light is based both on the high brightness of the source and on the narrowness of its spectral lines. A suitable antenna system for optical communications consists of two identical large-aperture telescopes facing each other. The receiving telescope sees, from each part of its aperture, the aperture of the transmitting telescope with a uniform brightness equal to that of the source. Thus it is the high source brightness of the laser that is necessary to transmit enough energy to define broad-band information. This type of antenna system may be quite useful for communication in space, but on the earth atmospheric turbulence, smog, snow, airplanes, birds and so on jeopardize reliability. As a result major efforts are being made to devise a light conductor that can be installed (with a reasonable number of bends) for communication purposes. Lenses spaced periodically along a pipe would correct for some degree of misalignment. Gas lenses promise similar guidance without the loss due to reflectance.

The monochromaticity of the laser beam is chiefly important in assembling and recovering the messages from the laser beam. Information modulated on a light beam should be at a frequency higher than the range of frequencies over which the carrier wave may wander, so that after mixing with a local source at the receiving end to retrieve the original signal the carrier-wave noise can be filtered from the signal. Laser beams have frequencies that are high enough and stable enough for this purpose.

Although at first laser communications will be confined to outer space or other special instances, lasers will probably fill a real need when the growing demand for communication facilities cannot be easily satisfied with lower-frequency systems and when better modulators, detectors and enclosed light guides are developed [see "Communication by Laser," by Stewart E. Miller; Scientific American, January, 1966].

The basic concept of holography, which is more than 20 years old, is simply that the diffraction pattern of light from an object is a transform, or coded record, of the object. If such a diffraction pattern could be stored, one should be able to reconstruct an image of the object.

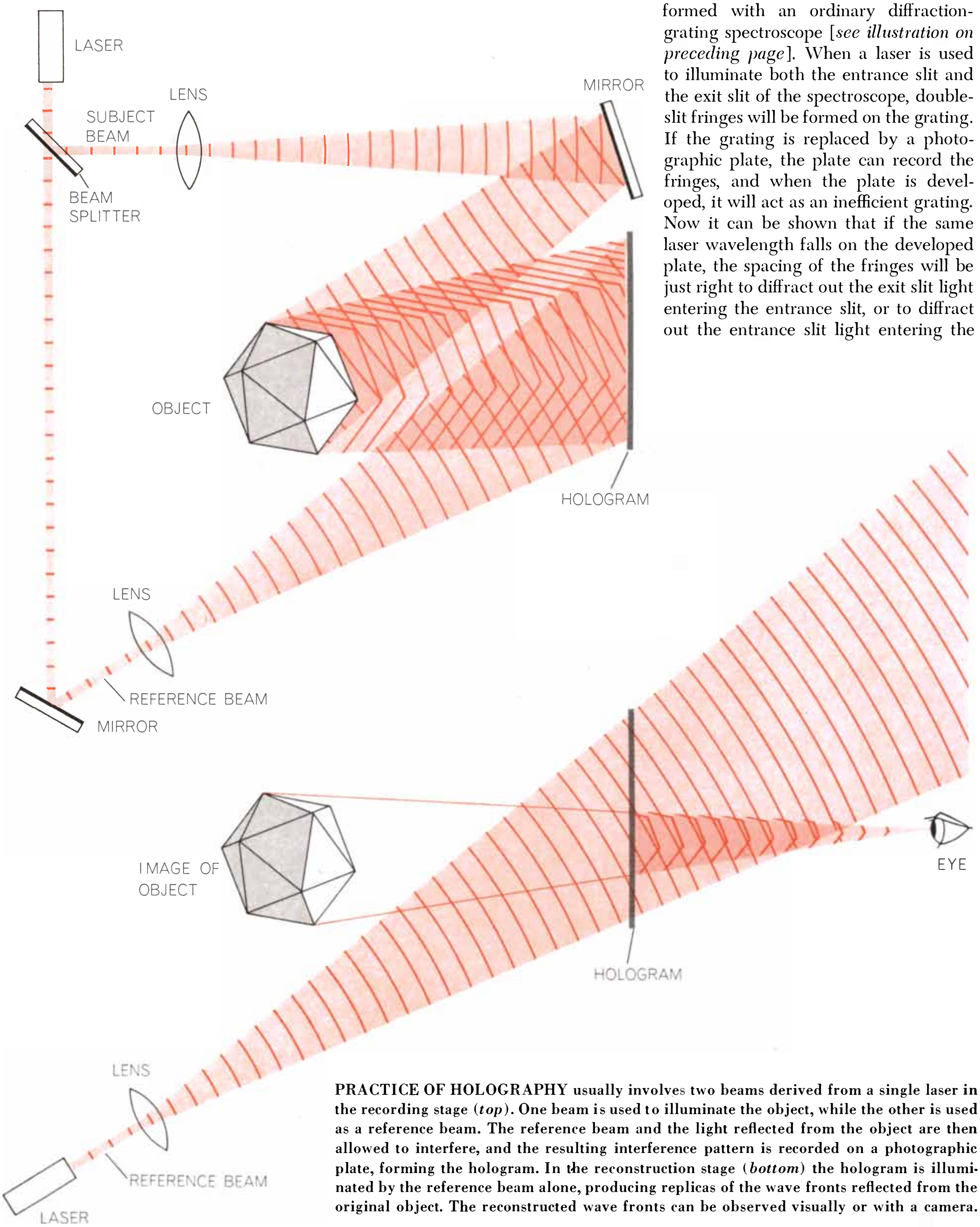
The original problem with holography



PRINCIPLE OF HOLOGRAPHY is elucidated by referring to this simplified diagram of an ordinary diffraction-grating spectroscope in which the grating has been replaced by a photographic plate. When a pair of laser beams are used to illuminate both the entrance and the exit slit of the spectroscope, characteristic double-slit fringes will be formed on the plate (*top*). When the plate is developed, it will then act as an inefficient grating (*bottom*). Using light of the same wavelength, the spacing of the fringes will be just right to diffract out the exit slit light entering the entrance slit, or to diffract out the entrance slit light entering the exit slit. In holography a more complex subject is substituted for one of the original laser beams and a correspondingly more complex fringe pattern results.

was that whereas it is easy to record the square of the amplitude of the diffraction pattern, the phase is usually lost, and without a record of the phase the holographic reconstruction is poor except for very special objects. The critical innovation, which came in 1963, was to have the diffraction pattern interfere with a reference beam of monochromatic laser light at a certain angle. The interference of the reference beam and the "subject" beam now results in a series of interference fringes whose contrast is a measure of the amplitude of the subject beam and whose position is a measure of the phase of the subject beam. When the developed photographic plate that has recorded the interference pattern is later illuminated with a laser beam identical with the reference beam, the diffracted light will have the same amplitude and phase characteristics as the original beam from the subject.

How a hologram works can be clarified by considering an experiment performed with an ordinary diffraction-grating spectroscope [*see illustration on preceding page*]. When a laser is used to illuminate both the entrance slit and the exit slit of the spectroscope, double-slit fringes will be formed on the grating. If the grating is replaced by a photographic plate, the plate can record the fringes, and when the plate is developed, it will act as an inefficient grating. Now it can be shown that if the same laser wavelength falls on the developed plate, the spacing of the fringes will be just right to diffract out the exit slit light entering the entrance slit, or to diffract out the entrance slit light entering the



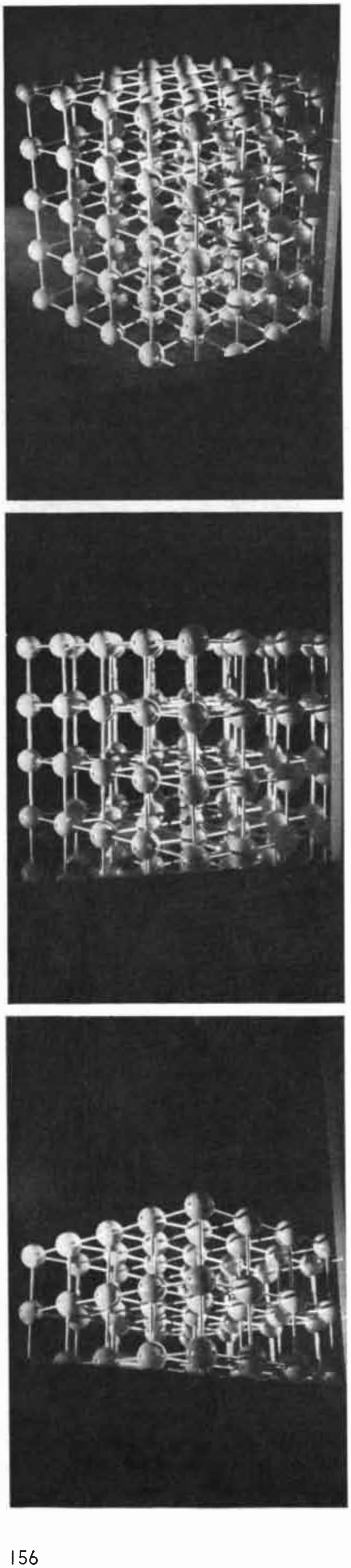
PRACTICE OF HOLOGRAPHY usually involves two beams derived from a single laser in the recording stage (*top*). One beam is used to illuminate the object, while the other is used as a reference beam. The reference beam and the light reflected from the object are then allowed to interfere, and the resulting interference pattern is recorded on a photographic plate, forming the hologram. In the reconstruction stage (*bottom*) the hologram is illuminated by the reference beam alone, producing replicas of the wave fronts reflected from the original object. The reconstructed wave fronts can be observed visually or with a camera.

exit slit. If more than one slit were involved, a series of fringes would be superposed, with each fringe pattern having a contrast corresponding to the intensity of light from one point and a spacing to diffract the light to the correct position. If a more complex subject were used, a correspondingly more complex fringe pattern would result and the photographic plate would be called a hologram.

This storage of the phase and amplitude of light has led to a number of new applications. For example, the information stored in a hologram can be reconstructed at a later time to interfere with the object, now distorted or slightly moved, in the interferometer. Thus accurate interferometric measurements can be made of a casting as it ages or as its temperature changes.

Holograms can also be made between two complex wave forms. Here the reference beam does not have to be a plane wave; the beam from a second object can be used as the reference. When the resulting hologram is illuminated with light from either of the objects, the other object will be seen. More than one such hologram can be superposed in this way on one piece of photographic material. For instance, an *A* can be recorded with a spot of light in one position of the field for one exposure, and a *B* can be stored with the reference-beam spot at another point. Other letters can each be superposed with the reference source in a different position. If one now illuminates the developed hologram with light from one of the letters, only the spot that was used as the reference beam for that letter will appear bright. This can be used to associate the position of a spot of light in a field of view with the shape of a character and promises to be very useful as an "associated memory" system. Unfortunately some letters, such as *E* and *F* or *O* and *Q*, are so similar that both reference beams appear bright at the same time.

Other applications of holography take advantage of the extreme fidelity of the reconstructed holographic image of a scene. This fidelity makes it possible to "see around" objects in the image and to focus at various depths in the image. In fact, the broad range of possible developments in the field of holographic applications recalls the situation in the parent field of laser applications, and is a fascinating subject in its own right [see "Advances in Holography," by Keith S. Pennington; SCIENTIFIC AMERICAN, February].



HOLOGRAM of a ball-and-stick model of the atomic structure of a simple cubic crystal was photographed from three different vertical directions to obtain the three different perspectives shown. Part of the hologram frame is visible in each photograph. The reconstructed three-dimensional holographic image has all the visual properties of the original atomic model, and in fact no known visual test can distinguish the two.

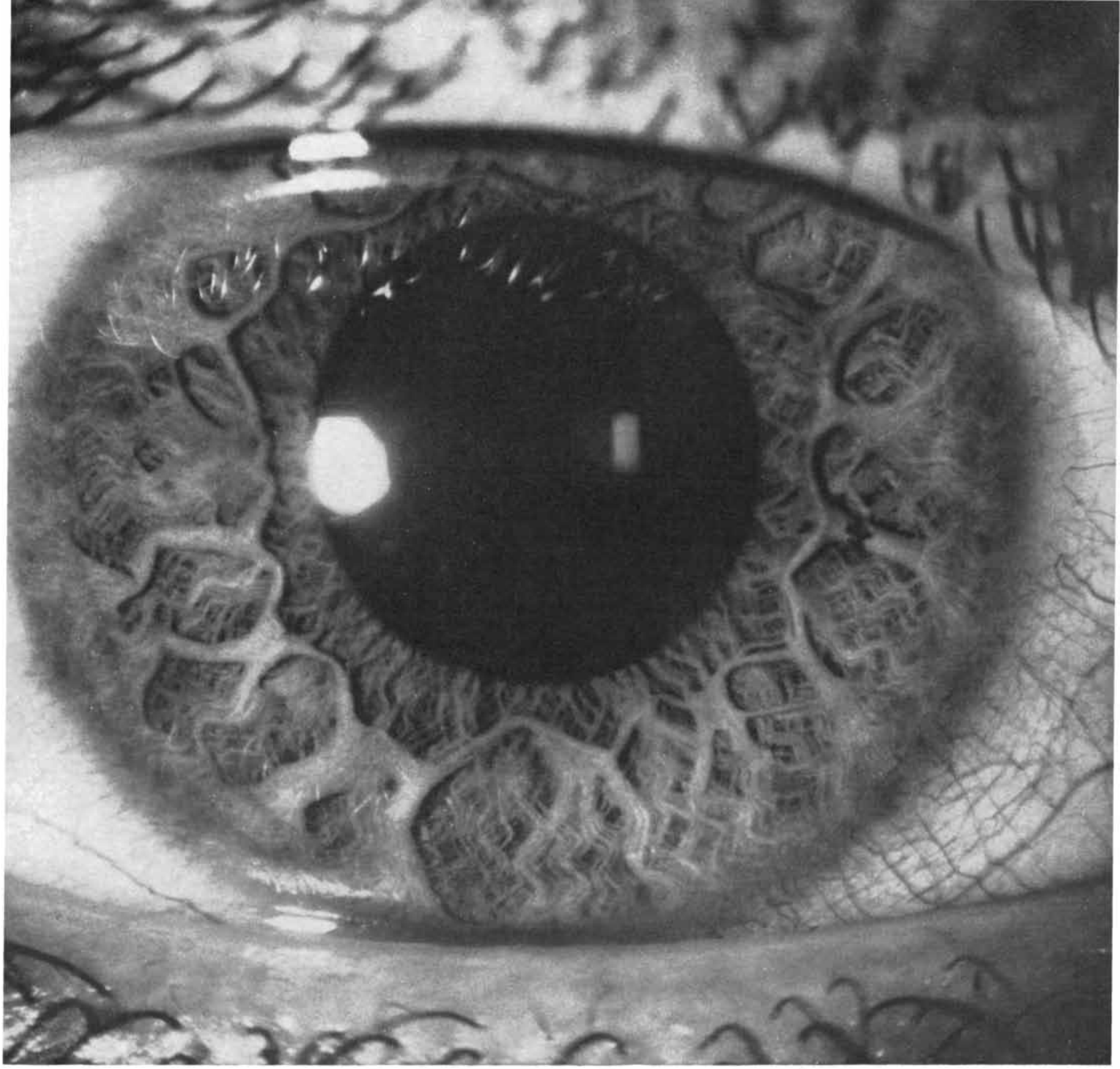
The uses of laser light in spectroscopy straddle the borderline between the scientific and the technological applications of the laser. For instance, extremely small bits of a substance can be vaporized and excited in a laser beam to emit the wavelengths characteristic of the substance's energy levels for spectroscopic analysis. This makes it possible to study smaller samples than one could before, and it eliminates contamination of the substance by the electrodes needed in conventional spectroscopy.

The enormous power that can be generated with laser beams makes it possible to conveniently produce and examine the higher energy states of substances in the laboratory. Such states exist in the sun and the stars, but their effects are obscured over much of the visible spectrum by the earth's atmosphere. Excitation with conventional arcs and plasmas is more cumbersome and is limited in available energy.

Raman spectroscopy in which an intense monochromatic source is used to irradiate a sample has been greatly improved with the polarized, collimated beam from laser sources. The light is scattered so that new spectral lines characteristic of the substance are observed. The substance to be examined can be placed within the laser cavity or in other multiple-reflection arrangements to increase the excitation by 10 to 100 times.

Raman scattering has thus become a more useful tool with laser excitation and continuous recording than would have been possible even with very large conventional light sources or day-long exposures on photographic plates. Raman measurements that are now only scientific studies can be expected to become a standard control procedure in many chemical operations.

It is impossible to predict which of these various applications of laser light will be most important in the long run. Moreover, as I have indicated, the developments in this area so far suggest that what is most predictable about it is its unpredictability.



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The Chemical Effects of Light

Visible light triggers few chemical reactions (except in living cells), but the photons of ultraviolet radiation readily break chemical bonds and produce short-lived molecular fragments with unusual properties

by Gerald Oster

Our everyday world endures because most substances, organic as well as inorganic, are stable in the presence of visible light. Only a few complex molecules produced by living organisms have the specific property of responding to light in such a way as to initiate or participate in chemical reactions [see "How Light Interacts with Living Matter," by Sterling B. Hendricks, page 174]. Outside of living systems only a few kinds of molecules are sufficiently activated by visible light to be of interest to the photochemist.

The number of reactive molecules increases sharply, however, if the wavelength of the radiant energy is shifted slightly into the ultraviolet part of the spectrum. To the photochemist that is where the action is. Thus he is primarily concerned with chemical events that are triggered by ultraviolet radiation in the range between 180 and 400 nanometers. These events usually happen so swiftly that ingenious techniques have had to be devised to follow the molecular transformations that take place. It is now routine, for example, to identify molecular species that exist for less than a millisecond. Species with lifetimes measured in microseconds are being studied, and new techniques using laser pulses are pushing into the realm where lifetimes can be measured in nanoseconds and perhaps even picoseconds.

The photochemist is interested in such short-lived species not simply for their own sake but because he suspects that many, if not most, chemical reactions proceed by way of short-lived intermediaries. Only by following chemical reactions step by step in fine detail can he develop plausible models of how chemical reactions proceed in general. From such studies it is often only a short step to the development of chemical processes and products of practical value.

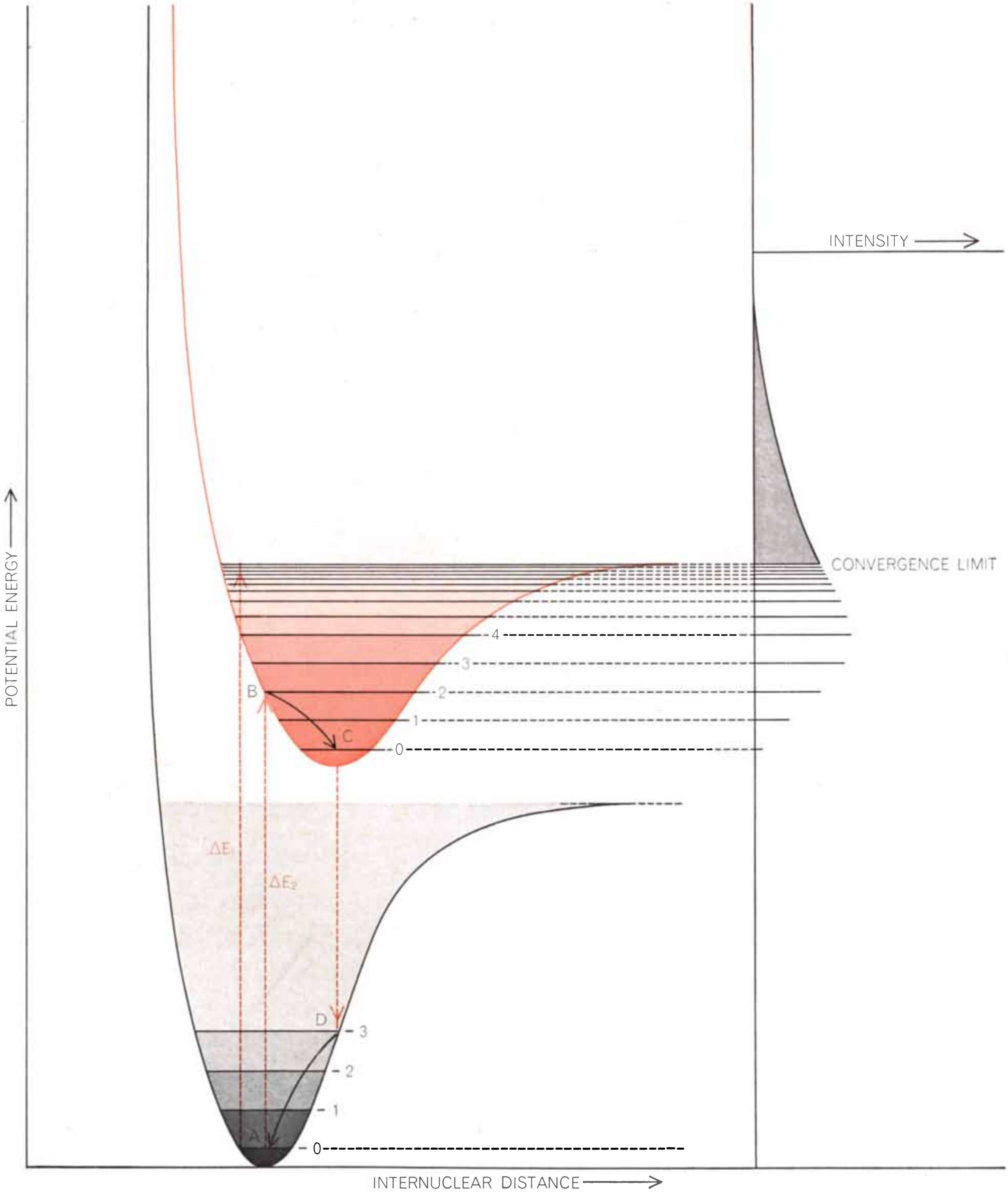
When a quantum of light is absorbed by a molecule, one of the electrons of the molecule is raised to some higher excited state. The excited molecule is then in an unstable condition and will try to rid itself of this excess energy by one means or another. Usually the electronic excitation is converted into vibrational energy (vibration of the atoms of the molecule), which is then passed on to the surroundings as heat. Such is the case, for example, with a tar roof on a sunny day. An alternative pathway is for the excited molecule to fluoresce, that is, to emit radiation whose wavelength is slightly longer than that of the exciting radiation. The bluish appearance of quinine water in the sunlight is an example of fluorescence; the excitation is produced by the invisible ultraviolet radiation of the sun.

The third way an electronically excited molecule can rid itself of energy is the one of principal interest to the photochemist: the excited molecule can undergo a chemical transformation. It is the task of the photochemist to determine the nature of the products made, the amount of product made per quantum absorbed (the quantum yield) and how these results depend on the concentrations of the starting materials. His next step is to combine these data with the known spectroscopic and thermodynamic properties of the molecules involved to make a coherent picture. It must be admitted, however, that only the simplest photochemical reactions are understood in detail.

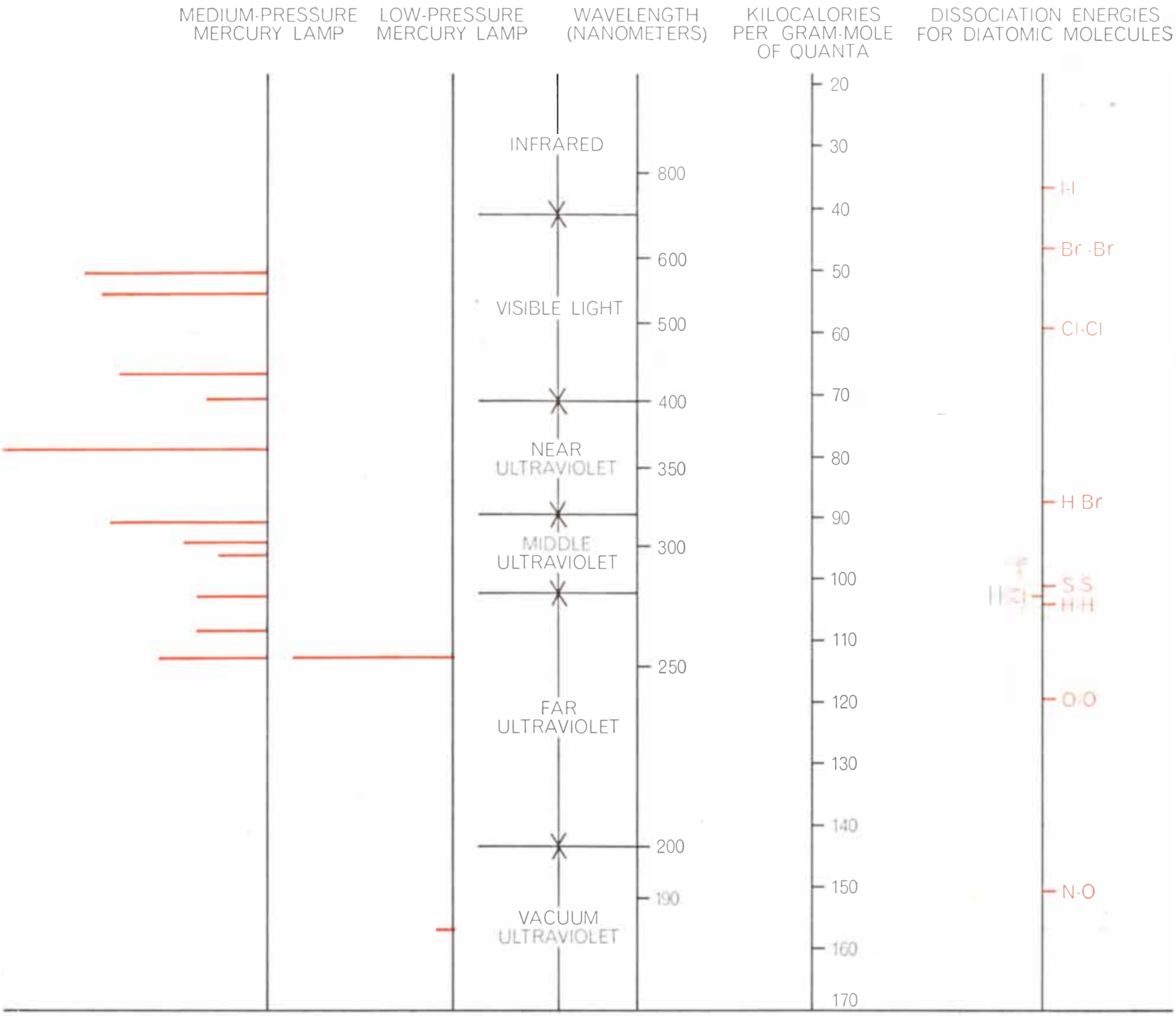
There is also a fourth way an excited molecule can dissipate its energy: the molecule may be torn apart. This is called photolysis. As might be expected, photolysis occurs only if the energy of the absorbed quantum exceeds the energy of the chemical bonds that hold the molecule together. The energy required to photolyse most simple molecules corresponds to light that lies in the ultraviolet region [*see illustration on page 160*]. For example, the chlorine molecule is colored and thus absorbs light in the visible range (at 425 nanometers), but it has a low quantum yield of photolysis when exposed to visible light. When it is exposed to ultraviolet radiation at 330 nanometers, on the other hand, the quantum yield is close to unity: each quantum of radiation absorbed ruptures one molecule.

Albert Einstein proposed in 1905 that one quantum of absorbed light leads to the photolysis of one molecule, but it required the development of quantum mechanics in the late 1920's to explain why the quantum yield should depend on the wavelength of the exciting light. James Franck and Edward U. Condon, who carefully analyzed molecular excitation, pointed out that when a molecule makes a transition from a ground state to an electronically excited state, the transition takes place so rapidly that the interatomic distances in the molecule do not have time to change. The reason is that the time required for transition is much shorter than the period of vibration of the atoms in the molecule.

To understand what happens when a molecule is excited by light it will be helpful to refer to the illustration on the opposite page. The lower curve represents the potential energy of a vibrating diatomic molecule in the ground state. The upper curve represents the potential energy of the excited molecule, which is also vibrating. The horizontal lines in the lower portion of each curve indicate the energy of discrete vibrational levels. If the interatomic distance



RESPONSE OF SIMPLE MOLECULES TO PHOTONS can be followed with the help of potential-energy curves. The lower curve represents the potential energy of a typical diatomic molecule in the ground state; the upper curve represents its potential energy in the first excited electronic state. Because the two atoms of the molecule are constantly vibrating, thus changing the distance between atomic nuclei, the molecule can occupy different but discrete energy levels (*horizontal lines*) within each electronic state. The molecule in the lowest ground state can be dissociated, or photolysed, if it absorbs a photon with an energy equal to or greater than ΔE_1. This is the energy required to carry the molecule to or beyond the "convergence limit." The length of the horizontal lines at the right below that limit represents the probability of transition from the ground electronic state to a particular vibrational level in the excited electronic state. Thus a photon with an energy of ΔE_2 will raise the molecule to the second level (*B*) of that state. There it will vibrate, ultimately lose energy to surrounding molecules and fall to *C*. It can now emit a photon with somewhat less energy than ΔE_2 and fall to *D*. This is called fluorescence. After losing vibrational energy molecule will return to *A*.



DISSOCIATION ENERGIES of most common diatomic molecules are so high that the energy can be supplied only by radiation of ultraviolet wavelengths. The principal exceptions are molecules of chlorine, bromine and iodine, all of which are strongly colored, indicating that they absorb light. The energy carried by a quantum of radiation, or photon, is directly proportional to its frequency, or inversely proportional to its wavelength. There are 6.06×10^{23} photons in a gram-mole of quanta. This is the number required to dissociate a gram-mole of diatomic molecules (6.06×10^{23} molecules) if the quantum yield is unity. A gram-mole is the weight in grams equal to the molecular weight of a molecule, thus a gram-mole of oxygen (O_2) is 32 grams. The principal emission wavelengths of two commonly used types of mercury lamp are identified at the left. Lengths of the bars are proportional to intensity.

becomes large enough in the ground state, the molecule can come apart without ever entering the excited state. The curve for the excited state is displaced to the right of the curve for the ground state, indicating that the average interatomic distance (the minimum in each curve) is somewhat greater in the excited state than it is in the ground state. That is, the excited molecule is somewhat "looser."

The molecule can pass from the ground state to one of the levels of the excited state by absorbing radiation whose photon energy is equal to the energy difference between the ground state and one of the levels of the excited state. Provided that the quantum of radiation is not too energetic the molecule will remain intact and continue to vibrate. After a brief interval it will emit a quantum of fluorescent radiation and drop back to the ground state. Because the emission occurs when the excited molecule is at the lowest vibrational level, the emitted energy is less than the absorbed energy, hence the wavelength of the fluorescent radiation is greater than that of the absorbed radiation.

When the absorbed radiation exceeds a certain threshold value, the molecule comes apart; it is photolysed. At this point the absorption spectrum, shown at the right side of the illustration, becomes continuous, because the molecule is no longer vibrating at discrete energy levels. As long as the molecule is intact only discrete wavelengths of light can be absorbed.

It is possible for the excited state to pass to the ground state without releasing a quantum of radiation, in which case the electronic energy is dissipated as heat. Franck and Condon explained that this was accomplished by an overlapping, or crossing, of the two potential-energy curves, so that the excited molecule slides over, so to speak, to the ground state, leaving the molecule in an abnormally high state of vibration. This vibrational energy is then readily transferred to surrounding molecules.

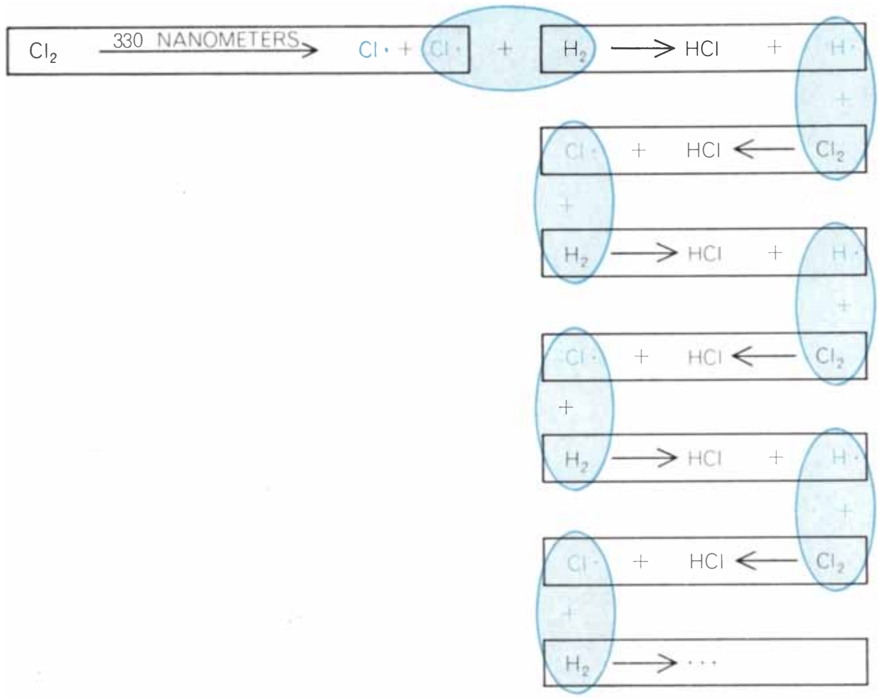
As far as life on the earth is concerned, the most important photolytic reaction in nature is the one that creates a canopy of ozone in the upper atmosphere. Ozone is a faintly bluish gas whose molecules consist of three atoms of oxygen; ordinary oxygen molecules contain two atoms. Ozone absorbs broadly in the middle- and far-ultraviolet regions with a maximum at 255 nanometers. Fortunately ozone filters out just those wavelengths that are fatal to living organisms.

Ozone production begins with the photolysis of oxygen molecules (O_2), which occurs when oxygen strongly absorbs ultraviolet radiation with a wavelength of 190 nanometers. The oxygen atoms released by photolysis may simply recombine or they may react with other oxygen molecules to produce ozone (O_3). When ozone, in turn, absorbs ultraviolet radiation from the sun, it is either photolysed (yielding O_2 and O) or it contributes to the heating of the atmosphere. A dynamic equilibrium is reached in which ozone photolysis balances ozone synthesis.

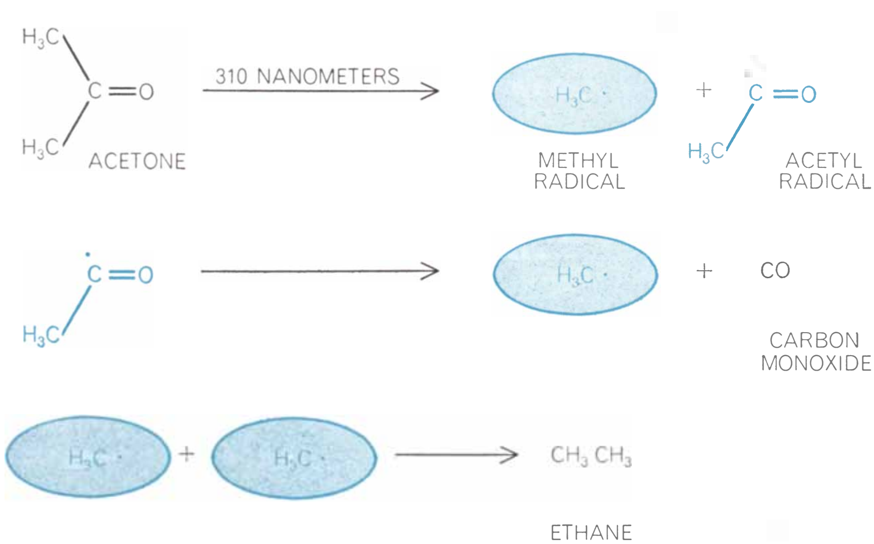
Early in this century physical chemists were presented with a photolytic puzzle. It was observed that when pure chlorine and hydrogen are exposed to ultraviolet radiation, the quantum yield approaches one million, that is, nearly a million molecules of hydrogen chloride (HCl) are produced for each quantum of radiation absorbed. This seemed to contradict Einstein's postulate that the quantum yield should be unity. In 1912 Max Bodenstein explained the puzzle by proposing that a chain reaction is involved [*see upper illustration at right*].

The chain reaction proceeds by means of two reactions, following the initial photolysis of chlorine (Cl_2). The first reaction, which involves the breaking of the fairly strong H-H bond, creates a small energy deficit. The second reaction, which involves the breaking of the weaker Cl-Cl bond, makes up the deficit with energy to spare. Breaking the H-H bond requires 104 kilocalories per gram-mole (the equivalent in grams of the molecular weight of the reactants, in this case H_2). Breaking the Cl-Cl bond requires only 58 kilocalories per gram-mole. In both of the reactions that break these bonds HCl is produced, yielding 103 kilocalories per gram-mole. Consequently the first reaction has a deficit of one kilocalorie per gram-mole and the second a surplus of 45 (103 – 58) kilocalories per gram-mole. The two reactions together provide a net of 44 kilocalories per gram-mole. Thus the chain reaction is fueled, once ultraviolet radiation provides the initial breaking of Cl-Cl bonds.

The chain continues until two chlorine atoms happen to encounter each other to form chlorine molecules. This takes place mainly at the walls of the reaction vessel, which can dissipate some of the excess electronic excitation energy of the chlorine atoms and allow chlorine mole-



CHAIN REACTION is produced when pure chlorine and hydrogen are exposed to ultraviolet radiation. A wavelength of 330 nanometers is particularly effective. Such radiation is energetic enough to dissociate chlorine molecules, which requires only 58 kilocalories per gram-mole, but it is too weak to dissociate hydrogen molecules, which requires 104 kilocalories per gram-mole. The formation of HCl in the subsequent reactions provides 103 kilocalories per gram-mole. Since 104 kilocalories are needed for breaking the H-H bond, the reaction of atomic chlorine (Cl·) and H_2 involves a net deficit of one kilocalorie per gram-mole. However, the next reaction in the chain, involving H· and Cl_2, provides a surplus of 45 kilocalories (103 – 58). This energy surplus keeps the chain reaction going.



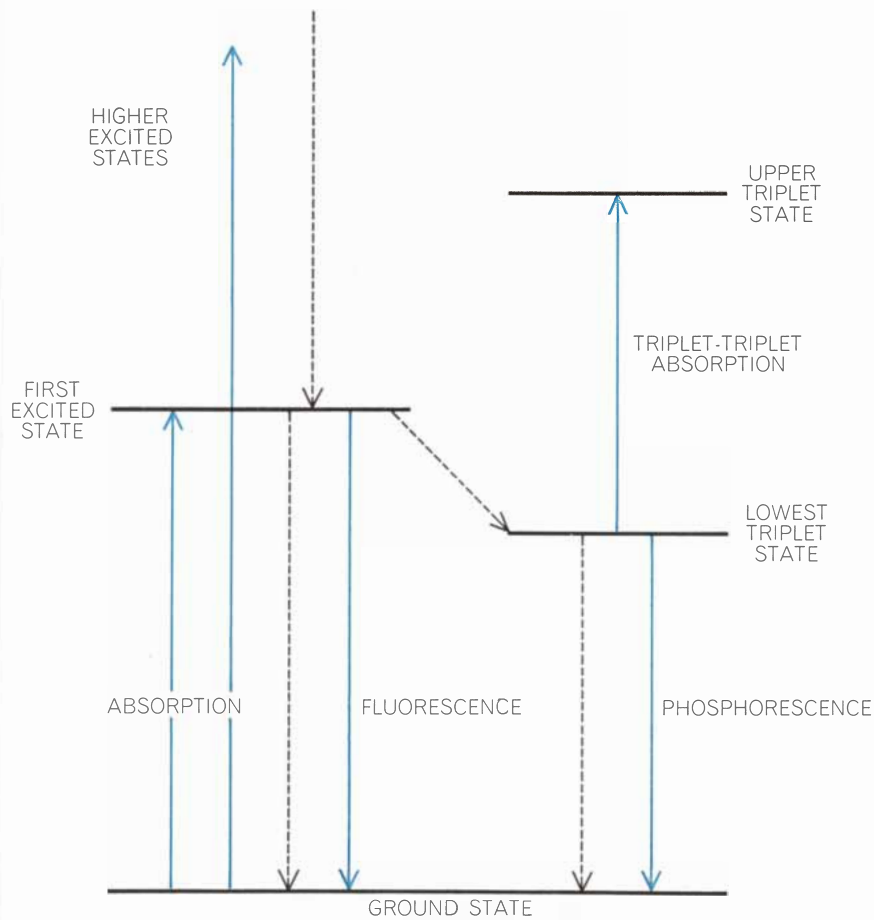
PHOTOLYSIS OF ACETONE, which yields primarily ethane and carbon monoxide, is a much studied photochemical reaction. It was finally understood by postulating the existence of short-lived free radicals, fragments that contain unsatisfied valence electrons.

cules to form. The free atoms may also be removed by impurities in the system.

Bromine molecules will likewise undergo a photochemical reaction with hydrogen to yield hydrogen bromide. The quantum yield is lower than in the chlorine-hydrogen reaction because atomic bromine reacts less vigorously with hydrogen than atomic chlorine does. Bromine atoms react readily, however, with olefins (linear or branched hydrocarbon molecules that contain one double bond). Each double bond is replaced by two bromine atoms. This is the basis of the industrial photobromination of hydrocarbons. Bromination can also be carried out by heating the reactants in the presence of a catalyst, but the product itself may be decomposed by such treatment. The advantage of the photochemical process is that the products formed are not affected by ultraviolet radiation.

An important industrial photochlorination process has been developed by the B. F. Goodrich Company. There it was discovered that when polyvinyl chloride is exposed to chlorine in the presence of ultraviolet radiation, the resulting plastic withstands a heat-distortion temperature 50 degrees Celsius higher than the untreated plastic does. As a result this inexpensive plastic can now be used as piping for hot-water plumbing systems.

A much studied photolytic reaction is one involving acetone (C_2H_6CO). When it is exposed to ultraviolet radiation, acetone gives rise to ethane (C_2H_6) with a quantum yield near unity, together with carbon monoxide and a variety of minor products, depending on the wavelength of excitation. The results can be explained by schemes that involve free radicals—fragments of molecules that have unsatisfied valence elec-



TRIPLET STATE has become an important concept in understanding the photochemical reactions of many organic molecules. Like all molecules, they can be raised to an excited state by absorption of radiation. They can also return to the ground state by normal fluorescence: reemission of a photon. Alternatively, they can drop to the triplet state without emission of radiation. (Broken lines indicate nonradiative transitions.) The existence of this state can be inferred from the wavelength of the radiation it is then able to absorb in passing to a higher triplet state. The triplet state arises when the spins of paired electrons point in the same direction rather than in the opposite direction, as they ordinarily do.

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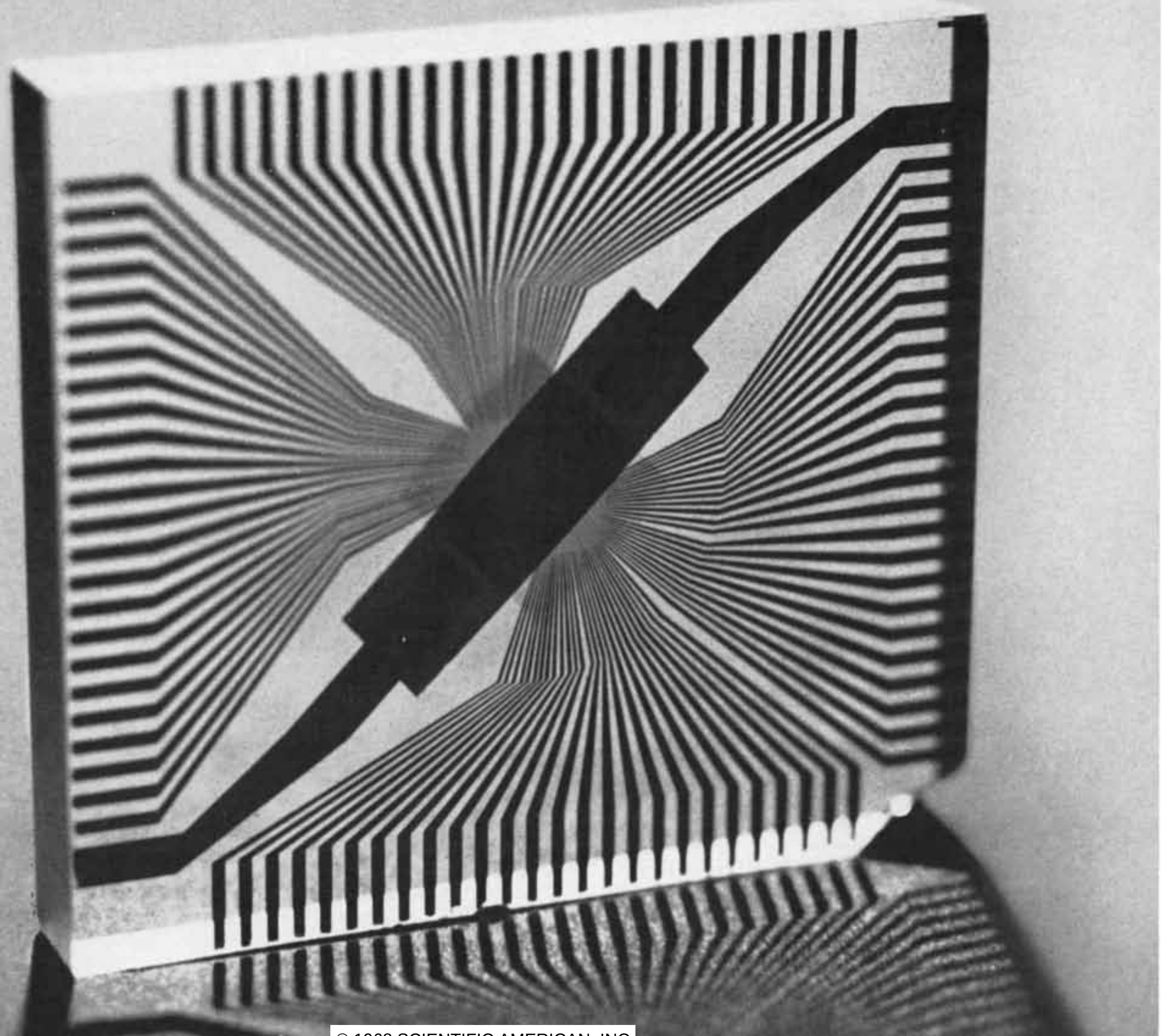


trons. Photolysis of acetone produces the methyl radical (CH_3) and the acetyl radical (CH_3CO). Two methyl radicals combine to form ethane [*see lower illustration on page 161*].

W. A. Noyes, Jr., of the University of Rochester and others assumed the existence of these free radicals in order to explain the end products of the photolysis. Because the lifetime of free radicals may be only a ten-thousandth of a second, they cannot be isolated for study. Since the end of World War II, however, the technique of flash spectroscopy has been developed for recording their existence during their brief lifetime.

Flash spectroscopy was devised at the University of Cambridge by R. G. W. Norrish and his student George Porter, who is now director of the Royal Institution. They designed an apparatus [*see illustration below*] in which a sample is illuminated with an intense burst of ultraviolet to create the photolytic products. A small fraction of a second later weaker light is beamed into the reaction chamber; at the far end of the chamber the light enters a spectrograph, which records whatever wavelengths have not been absorbed. The absorbed wavelengths provide clues to the nature of the short-lived species produced by photolysis. In 1967 Norrish and Porter shared the Nobel prize in chemistry with Manfred Eigen of the University of Göttingen, who had also developed techniques for studying fast reactions.

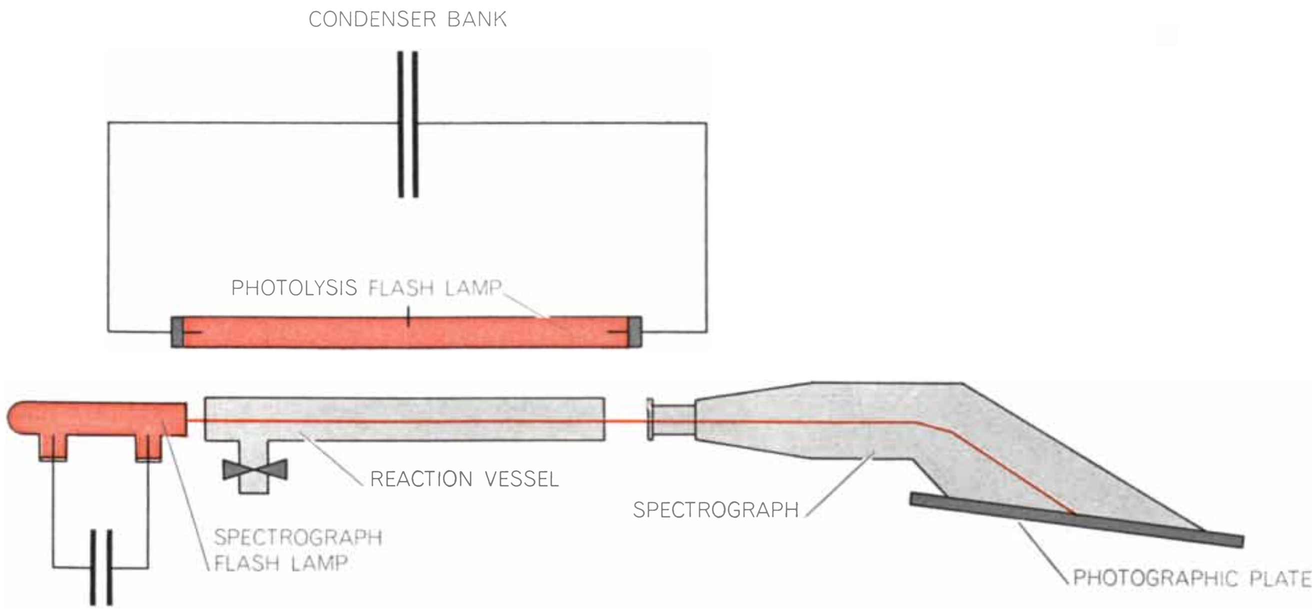
Flash spectroscopy has greatly increased chemists' knowledge about the "triplet state," an excited state that involves the pairs of electrons that form chemical bonds in organic molecules. Normally the spins of the paired electrons are antiparallel, or opposite to each other. When exposed to ultraviolet radiation, the molecules are raised to the first excited state and then undergo a nonradiative transition to an intermediate state in which the spins of two electrons in the same state are parallel to each other. This is the triplet state. If it is again exposed to ultraviolet or visible radiation, the triplet state exhibits its own absorption spectrum, which lies at a longer wavelength than the absorption spectrum of the normal ground state, or state of lowest energy [*see illustration on page 162*].

The concept of the triplet state in organic molecules is due mainly to the work of G. N. Lewis and his collaborators at the University of California at Berkeley in the late 1930's and early 1940's. These workers found that when dyes (notably fluorescein) are dissolved in a rigid medium such as glass and are exposed to a strong light, the dyes change color. When the light is removed, the dyes revert to their normal color after a second or so. This general phenomenon is called photochromism. Lewis deduced the existence of the triplet state and ascribed its fairly long duration to the time required for the parallel-spin electrons to become uncoupled and to revert to their normal antiparallel arrangement.

In 1952 Porter and M. W. Windsor used flash spectroscopy to search for the triplet state in the spectra of organic molecules in ordinary fluid solvents. They were almost immediately successful. They found that under such conditions the triplet state has a lifetime of about a millisecond.

In his Nobel prize lecture Porter said: "Any discussion of mechanism in organic photochemistry immediately involves the triplet state, and questions about this state are most directly answered by means of flash photolysis. It is now known that many of the most important photochemical reactions in solution, such as those of ketones and quinones, proceed almost exclusively via the triplet state, and the properties of this state therefore become of prime importance."

While studying the photochemistry of dyes in solution, my student Albert H. Adelman and I, working at the Polytechnic Institute of Brooklyn, demonstrated that the chemically reactive species is the triplet state of the dye. Specifically, when certain dyes are excited by light in the presence of electron-donating substances, the dyes are rapidly changed into the colorless ("reduced") form. Our studies showed that the reactive state of the dye—the triplet state—has a lifetime of about a tenth of a milli-



APPARATUS FOR FLASH PHOTOLYSIS was devised by R. G. W. Norrish and George Porter at the University of Cambridge. With it they discovered the short-lived triplet state that follows the photolysis of various kinds of molecules, organic as well as inorganic. The initial dissociation is triggered by the photolysis flash lamp, which produces an intense burst of ultraviolet radiation. A millisecond or less later another flash lamp sends a beam of ultraviolet radiation through the reaction vessel. Free radicals in the triplet state absorb various wavelengths ("triplet-triplet" absorption) and the resulting spectrum is recorded by the spectrograph.

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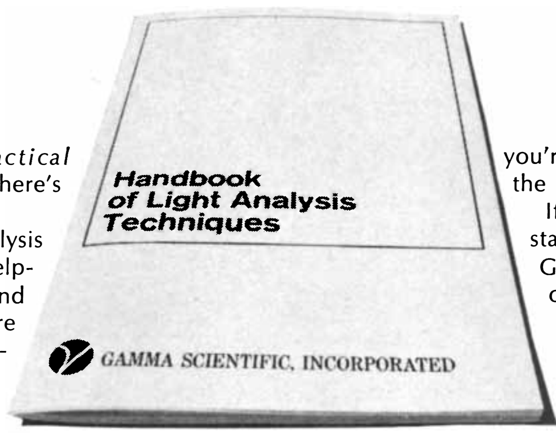

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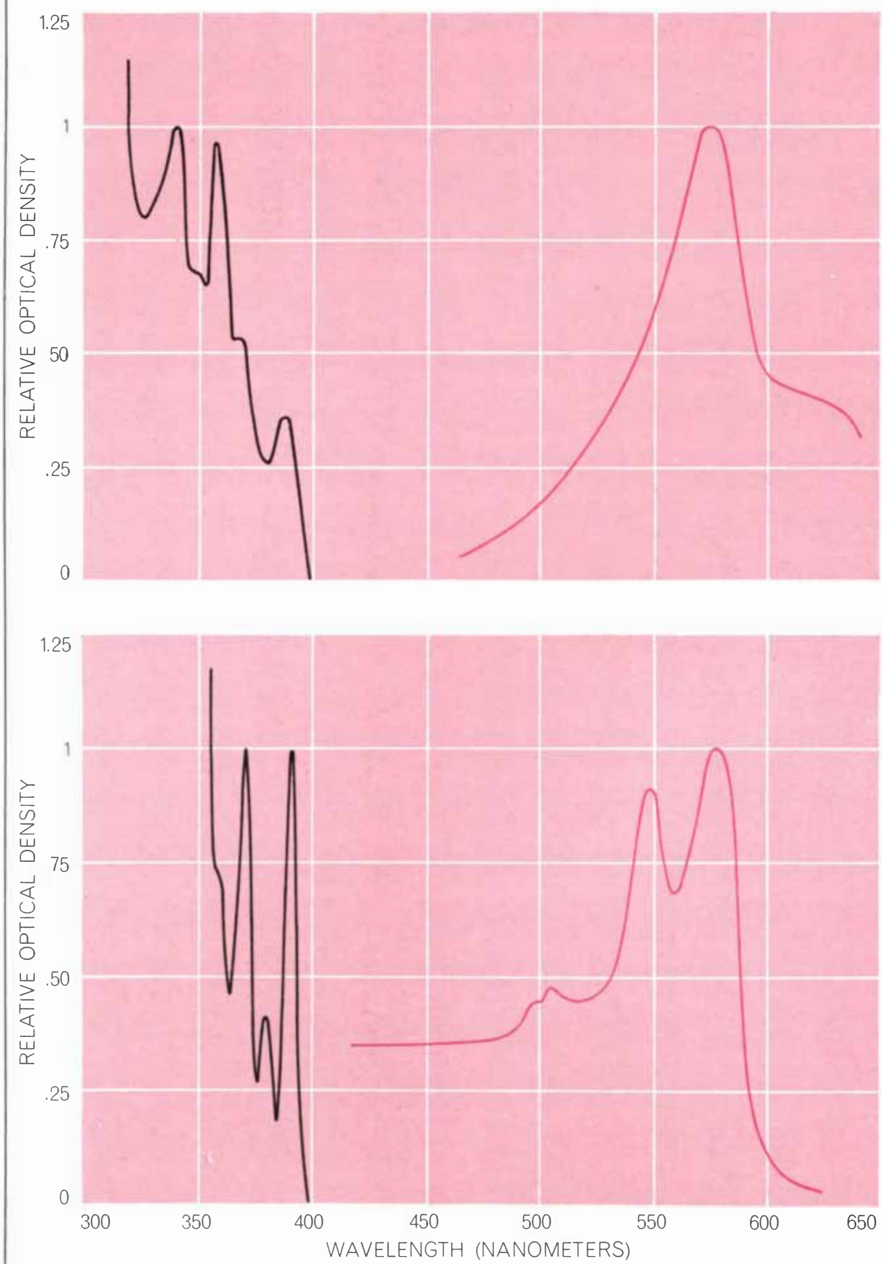
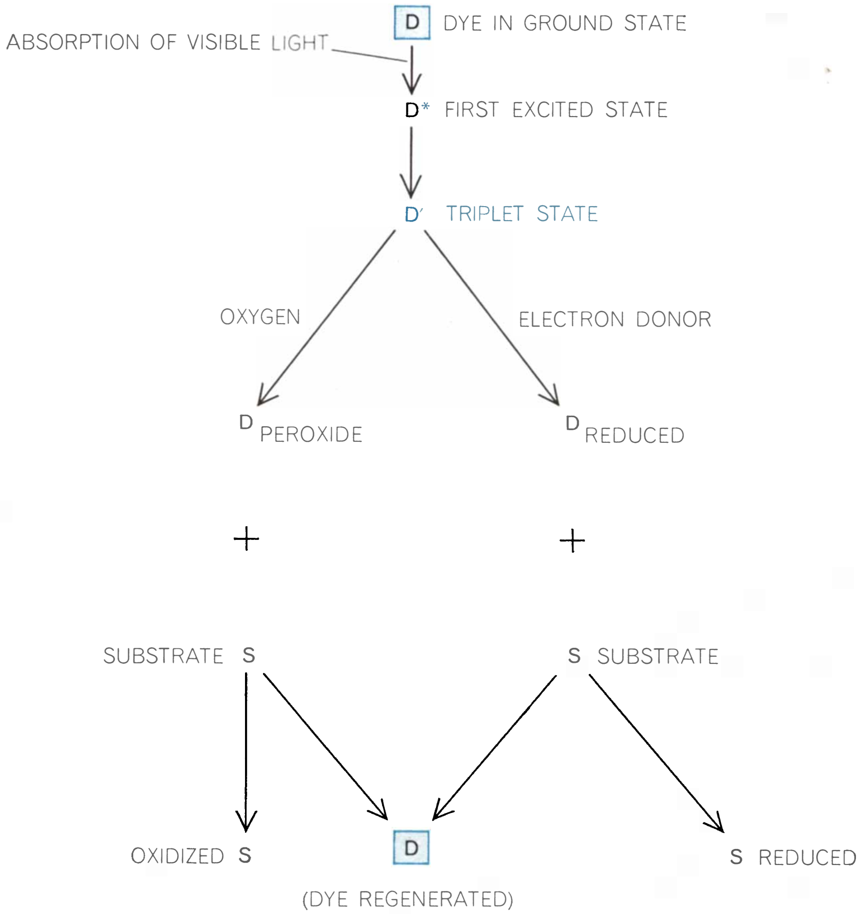
second. The dye is now a powerful reducing agent and will donate electrons to other substances, with the dye being returned to its oxidized state [*see illustration on page 168*]. In other words, the dye is a photosensitizer for chemical reductions; visible light provides the energy for getting the reaction started.

In the course of these studies I discovered that free radicals are created when dyes are photoreduced. The free radicals make their presence known by causing vinyl monomers to link up into polymers. The use of free radicals for bringing about polymerization of monomers is well known in industry. It occurred to me that adding suitable dyes to monomer solutions would provide the basis for a new kind of photography. In such a solution the concentration of free radicals



TRIPLET-TRIPLET ABSORPTION OF VISIBLE LIGHT has been observed in the author's laboratory at the Polytechnic Institute of Brooklyn. His equipment sends a beam of ultraviolet radiation into samples embedded in a plastic matrix in one direction and visible light at right angles to the ultraviolet radiation. The visible absorption spectra are then recorded in the presence of ultraviolet radiation. The black curves at the left in these two examples show the absorption of the electronic ground state. The colored curves at the right show the absorption of visible wavelengths that raises the excited molecule from the lowest triplet state to upper triplet states. The top spectra were produced by chrysene, the lower spectra by 1,2,5,6-dibenzanthracene. Both are aromatic coal-tar hydrocarbons.



UNUSUAL PROPERTIES OF TRIPLET STATE have been explored by the author. Certain dyes in the triplet state can act either as strong oxidizing or as strong reducing agents, depending on the conditions to which the triplet state itself is exposed. In the presence of a substance that donates electrons (i.e., a reducing agent), the dye is reduced and can then donate electrons to some other substance (*substrate S*). In the presence of an oxidizing agent, the dye becomes highly oxidized and can then oxidize, or remove electrons from, a substrate. In both cases the dye is regenerated and returns to its normal state. The author's studies show that the reactive state of the dye lives only about .1 millisecond.

would be proportional to the intensity of the visible light and thus the degree of polymerization would be controlled by light. It has turned out that very accurate three-dimensional topographical maps can be produced in plastic by this method.

The use of dyes as photosensitizing agents is, of course, fundamental to photography. In 1873 Hermann Wilhelm Vogel found that by adding dyes to silver halide emulsions he could make photographic plates that were sensitive to visible light. At first such plates responded only to light at the blue end of the spectrum. Later new dyes were found that extended the sensitivity farther and farther toward the red end of the spectrum, making possible panchromatic emulsions. Photographic firms continue to synthesize new dyes in a search for sensitizers that will act efficiently in the infrared part of the spectrum. The nature of the action of sensitizers in silver halide photography is still obscure, nearly 100 years after the effect was first demonstrated. The effect seems to depend on the state of aggregation of the dye absorbed to the silver halide crystals.

The reverse of photoreduction—photooxidation—can also be mediated by dyes, as we have found in our laboratory. Here again the reactive species of the dye is the dye in the triplet state. We have found that the only dyes that will serve as sensitizers for photooxidation are those that can be reduced in the presence of light.

The oxidized dye—the dye peroxide—is a powerful oxidizing agent. In the process of oxidizing other substances the dye is regenerated [*see illustration above*]. My student Judith S. Bellin and I have demonstrated this phenomenon, and we have employed dye-sensi-

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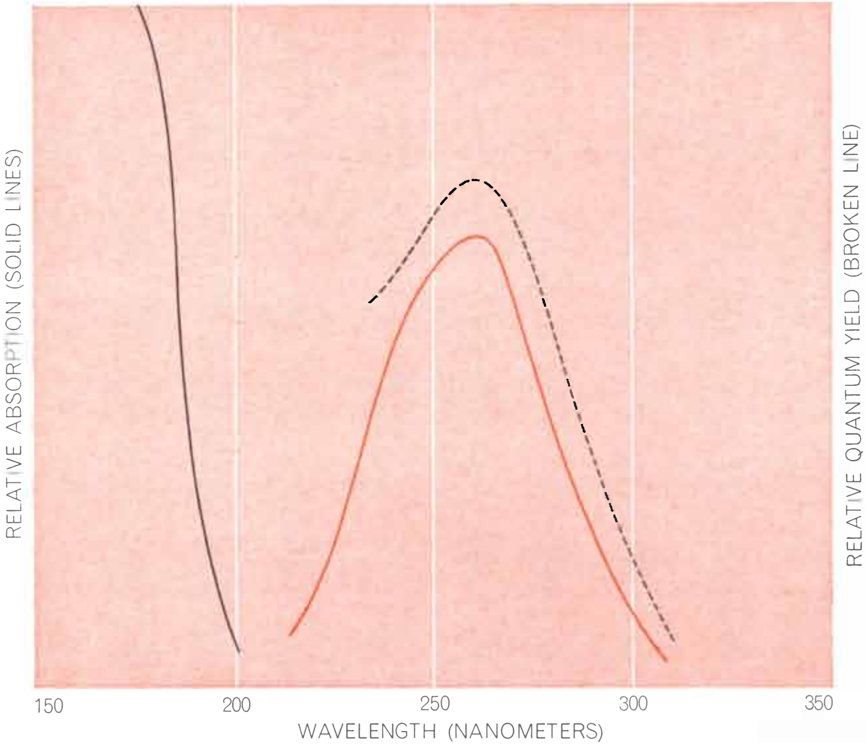

ABSORPTION SPECTRUM OF OZONE (*solid curve in color*) **peaks at about 250 nanometers in the ultraviolet. As a happy consequence, the canopy of ozone in the upper atmosphere removes the portion of the sun's radiation that would be most harmful to life. The biocidal effectiveness of ultraviolet radiation is shown by the broken black line. The solid black curve is the absorption spectrum of molecular oxygen. For reasons not well understood, ultraviolet radiation of 200 nanometers does not penetrate the atmosphere.**

tized photooxidation to inactivate some biological systems. These systems include viruses, DNA and ascites tumor cells. That dyes are visible-light sensitizers for biological inactivation was first demonstrated in 1900 by O. Raab, who observed that a dye that did not kill a culture of protozoa did so when the culture was placed near a window.

The inactivation that results from dye sensitization is different from the inactivation that results when biological systems are exposed to ultraviolet radiation. Here the inactivation often seems to result from the production of dimers: the cross-linking of two identical or similar chemical subunits. Photodimerization is implicated, for example, in the bactericidal action of ultraviolet radiation. It has long been known that the bactericidal action spectrum (the extent of killing as a function of wavelength) closely parallels the absorption spectrum of DNA, the genetic material. If dried-down films of DNA are irradiated with ultraviolet, they become cross-linked. According to one view the cross-linking occurs by means of the dimerization of thymine, one of the constituent groups of DNA.

Although this may well be the mode of action of ultraviolet radiation, my own feeling is that insufficient consideration has been given to the photolysis of the disulfide bonds of the proteins in bacteria. This bond is readily cleaved by ultraviolet radiation and has an absorption spectrum resembling that of DNA. Disulfide bonds are vital in maintaining the structure and activity of proteins; their destruction by ultraviolet radiation could also account for the death of bacteria.

In using dyes as sensitizers for initiating chemical reactions we are taking our first tentative steps into a realm where nature has learned to work with consummate finesse. Carbon dioxide and water are completely stable in the presence of visible light. Inside the leaves of plants, however, the green dye chlorophyll, when acted on by light, mediates a sequence of chemical reactions that dissociates carbon dioxide and water and reassembles their constituents into sugars and starches. A dream of photochemists is to find a dye, or sensitizer, that will bring about the same reactions in a nonliving system. There is reason to hope that such a system could be a good deal simpler than a living cell.

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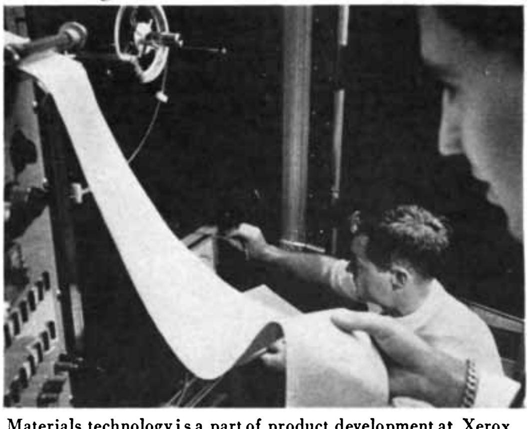

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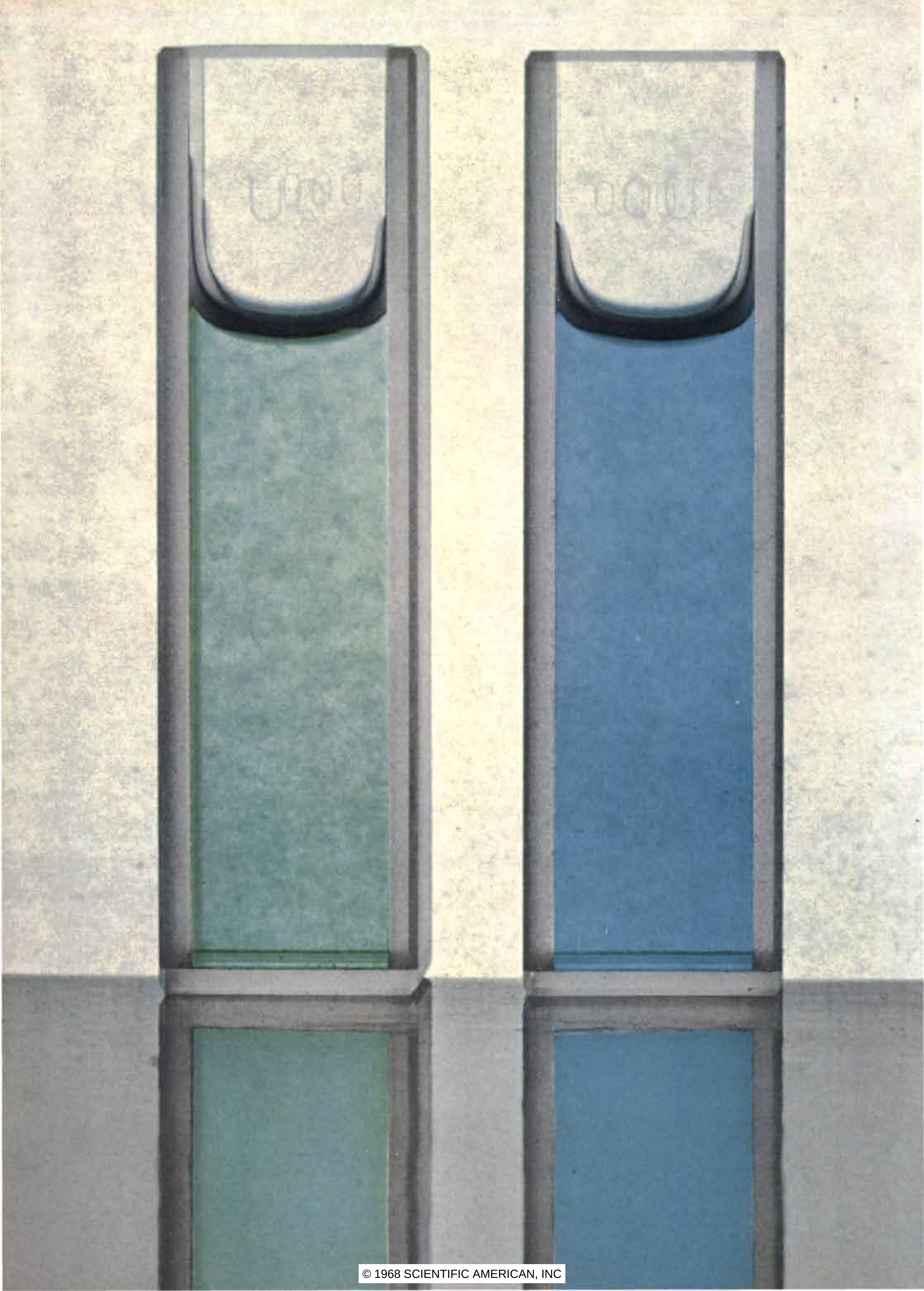


How Light Interacts with Living Matter

Light activates three key processes of life: photosynthesis, vision and photoperiodism (the response of plants and animals to the cycle of night and day). Such activation is mediated by specific pigments

by Sterling B. Hendricks

Life is believed to have arisen in a primordial broth formed by sunlight acting on simple molecules at the surface of the cooling earth. It could have been sustained by the broth for aeons, but eventually, with the arrival of photosynthesis, some living things came to use sunlight more directly. So it remains today, with photosynthesis by plants serving to capture sunlight for the energy needs of all forms of life.

As various kinds of animals evolved, the ones that were best able to sense their surroundings were favored to survive. Because light acts over considerable distances it is well suited to sensing. To exploit light the animals needed some kind of detector: a tissue, an eyespot or an eye. The detector had to be coupled to a responding system: a ganglion or a brain. Signals from the system controlled locomotion toward food or away from danger.

Photosynthesis and vision do not exhaust the potential of the luminous environment. Both plants and animals have evolved mechanisms to respond to the changing daily cycle of light and dark. It is this photoperiodism that provides the seasonal schedule for, among other things, the flowering of plants, the pupation of insects and the nesting of birds.

To understand these phenomena one must ask how light acts in life. Part of the answer is very simple: it acts by exciting certain absorbing molecules. What happens to the molecules in the course of absorption is more difficult to describe, but many details of the processes are now reasonably well known. On the other hand, our ideas about how the molecular events are coupled to the responses of plants and animals are still quite tentative.

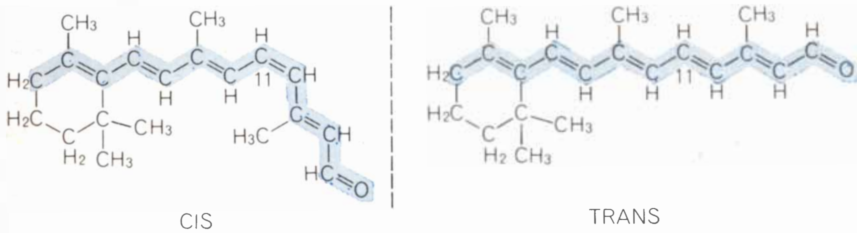
In discussing the present state of knowledge about light and life I shall treat vision first because this phenomenon has some features in common with both photosynthesis and photoperiodism. In all three processes light acts through absorption by a small, colored molecule—a chromophore—that is associated with a large molecule of protein. In the case of vision the light-sensitive molecules are responsible for the pink and purplish color of the retina. In the retina of the human eye there are some 100 million thin rod-shaped cells and five million slightly cone-shaped ones. Each is connected through a synapse, or junction, to a nerve fiber leading to the brain. Electron micrographs show that the outer end of both rods and cones is packed with thin membranous sacs, and with these sacs are associated the light-absorbing chromophores. (Vision and photosynthesis share this association of a chromophore with a membrane.) Excitation of the chromophore by light causes some kind of change in the membrane, and this change gives rise to a signal in the nerve fiber.

In vision the nature of the receiving chromophore and the manner of its excitation by light are well understood. Both have much in common with light reception in photoperiodism. As George Wald of Harvard University established, the receiving chromophore is vitamin-A aldehyde (in structural terms 11-*cis* retinal). The chromophore is found in association with a protein, opsin. The opsins are fatty proteins; thus they have an affinity for the sac membranes, which consist largely of lipid—that is, fatty—material. There are four types of opsin, one in the rods and three in the cones. Combined with 11-*cis* retinal, they respectively form rhodopsin and three kinds of iodopsin. On excitation by light all four opsins change in the same way.

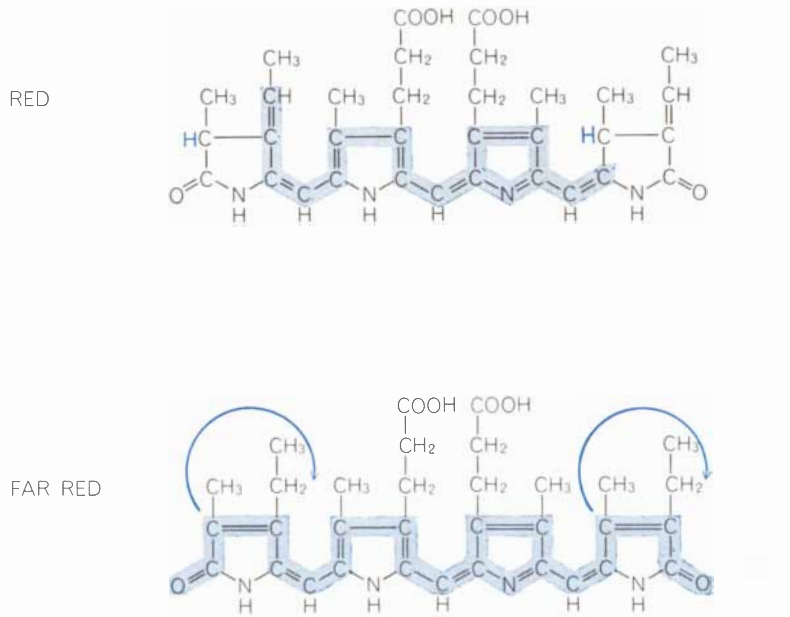
In vision, photosynthesis and photoperiodism alike the chromophore molecule is notable for its alternating single and double chemical bonds. Known to chemists as conjugated systems, molecules of this kind are structurally quite stable because the groups of atoms attached by double bonds cannot rotate around the bonds. Each conjugated system, if it is adequately extended, has a rather low energy state that can be excited by visible light. When the system is excited, its double-bond character is somewhat relaxed, so that a *cis* configuration can change to a *trans* one [*see top illustration on next page*]. This ability to change form is a key element in vision and photoperiodism. In photosynthesis, however, no change of form takes place because the change is constrained by the ring structures of the chlorophyll chromophores.

The effects of light in vision and photoperiodism are determined by measur-

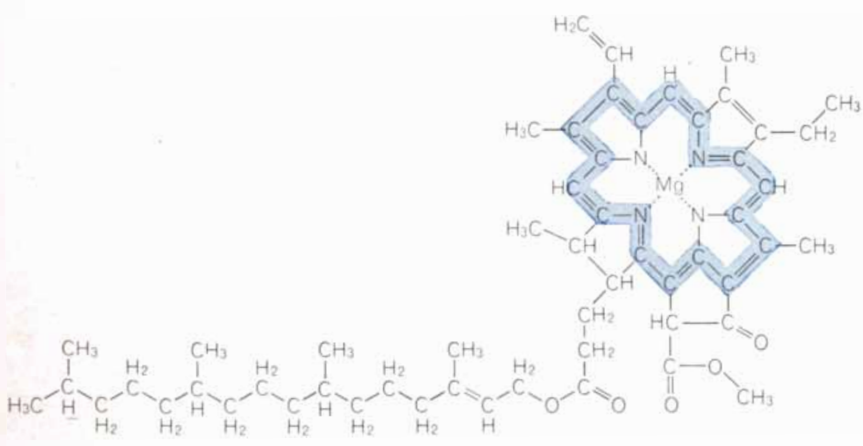
LIGHT-SENSITIVE PIGMENT that triggers photoperiodic responses in plants is shown in its two states in the photograph on the opposite page. Called phytochrome, the pigment, which is seen here in a .2 percent solution, is instrumental in a number of seasonal occurrences such as plants flowering and seeds germinating. In one state (*left*) phytochrome is excitable by far-red light, in the other (*right*) by red light. Alternating exposures to these colors change the pigment from one state to the other and back again. The phytochrome shown here was extracted from oat seedlings in the laboratory of F. E. Mumford and E. L. Jenner in the Central Research Department of E. I. du Pont de Nemours & Co. It is contained in square quartz cells designed for studies of light absorption. The faint numerals near the top indicates the length of the light path through the cell: 1.000 centimeter.



VISION depends on a light-sensitive chromophore molecule, 11-*cis* retinal (*left*), which has alternating single and double bonds (*color*). When light excites the molecule, its configuration changes from *cis* to the *trans* form (*right*), thereby setting in train a series of complex changes in the structure of the proteins with which the retinal chromophore is associated.



PHOTOPERIODISM in plants depends on phytochrome, another molecule that is sensitive to light. Like the retinal molecule, phytochrome has alternating single and double bonds (*color*). When excited by light, it changes from a configuration sensitive to red light (*top*) to one sensitive to far-red light, probably because two hydrogen atoms shift (*bottom*).



PHOTOSYNTHESIS depends on the light-sensitive chromophore molecules of several kinds of chlorophylls that have differing side groups. The molecule shown here is chlorophyll *a*. Like the vision and photoperiodism chromophores, chlorophyll molecules include singly and doubly bonded atoms, but these form a closed loop within the chlorophyllin portion of the molecule (*color*). When excited by light, chlorophylls forward the energy they receive to centers where it induces chemical changes (*see illustrations on page 183*).

ing the molecular changes produced by light excitation. Some of these changes are very rapid: they may occur in less than a millionth of a second. Changes as fast as this can be followed only if they are excited in an even shorter time, for instance by a very brief but intense flash of light. The measurement of the change also must be made quite rapidly. The method employed is flash excitation at room temperature or lower, followed by photoanalysis—the technique for which George Porter and R. G. W. Norrish shared (with Manfred Eigen) last year's Nobel prize in chemistry [see "The Chemical Effects of Light," by Gerald Oster, page 158]. Low temperatures slow down the molecular changes and make them more amenable to measurement.

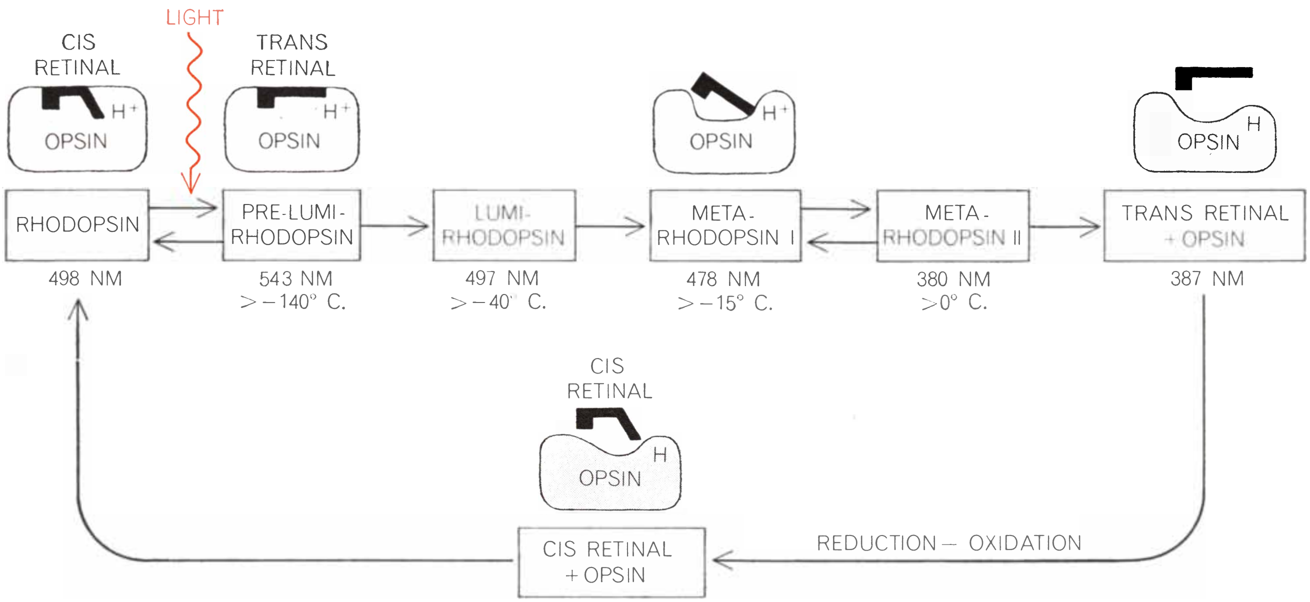
When the vision chromophore is excited by light, it changes from the *cis* to the *trans* form. The result is the conversion of rhodopsin into prelumirhodopsin with an all-*trans* chromophore. The production of this single change is the one and only role that light plays in vision. The change is followed by several rapid shifts in the structure of the opsin and also changes in the relation of the chromophore to the opsin. To judge by the time it takes for a retinal-cell signal to arrive at a nerve ending, the signal is induced by the shifts that take place in the first thousandth of a second.

The course of the molecular changes can be traced by studying rhodopsin in solution. Prelumirhodopsin, identifiable by its maximum absorption of light at a wavelength of 543 nanometers, can be held at temperatures below −140 degrees Celsius and reversibly changed back into rhodopsin. When the prelumirhodopsin is warmed to −40 degrees C., it is converted into lumirhodopsin. The same conversion probably occurs at body temperature but much more rapidly. This change and subsequent ones, including the formation of metarhodopsins, involve shifts in the molecular configuration of opsin. Among vertebrates the changes finally lead to the dissociation of the chromophore from the protein. The released all-*trans* retinal then has to be reduced to the alcohol form and oxidized back to the aldehyde form to regenerate 11-*cis* retinal. Once the *cis* retinal is regenerated it spontaneously recombines with opsin to form rhodopsin again.

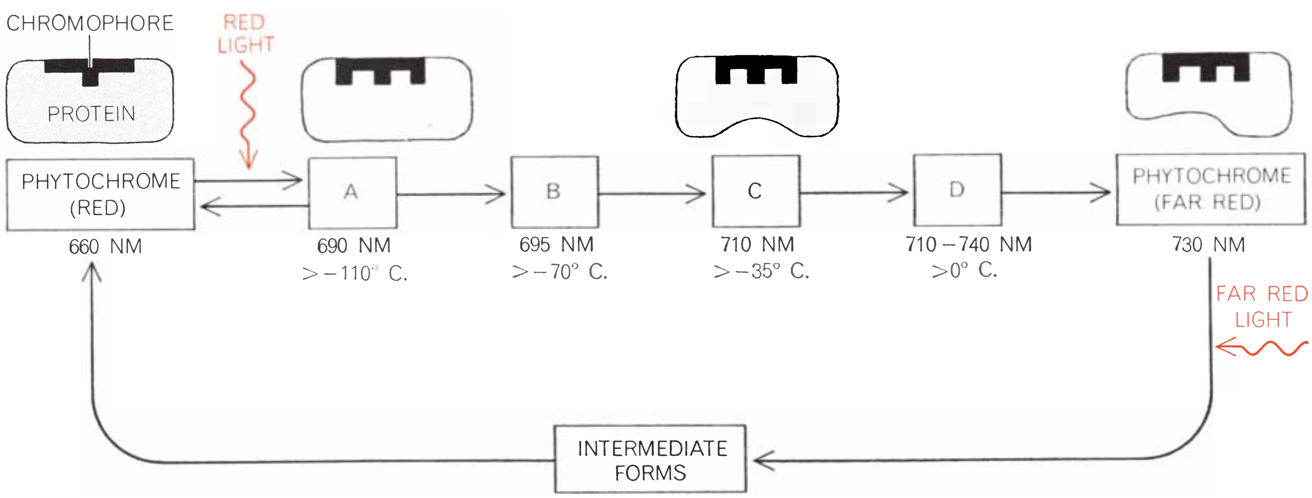
Analysis of the changes in electric potential that occur simultaneously with these molecular changes shows that a potential appears within 25 millionths of a second after a flash of light. The potential is positive with respect to the cornea in a circuit that includes neighboring tissues and the retina. The positive potential is followed in a thousandth of a second by a growing signal of the opposite sign. These events take place during the period when prelumirhodopsin and lumirhodopsin are present. The first potential probably accompanies the change of rhodopsin to prelumirhodopsin. The second depends markedly on the temperature at some distance from the place of light action, probably in the outer membrane of the rod or cone. Currently there is much interest in the possible identification of these changes in potential as early steps in the eventual excitation of the nerve fiber. Another view is that nerve excitation is associated with the transitions involving metarhodopsin I and metarhodopsin II [*see upper illustration below*].

Color vision depends on the three opsins, each found in a different cone cell. Their absorption spectra have been measured, and curves were found with peaks at wavelengths of 450, 525 and 555 nanometers (respectively in the blue, green and yellow regions of the visible spectrum). Activation by light leads to the same sequence of molecular changes described for rhodopsin. The singularity of the nerve associations with the rod and cone cells preserves the retinal detail, or register, in the transmission of the visual signal; the differences in absorption among the three kinds of cone retain the color pattern of the image.

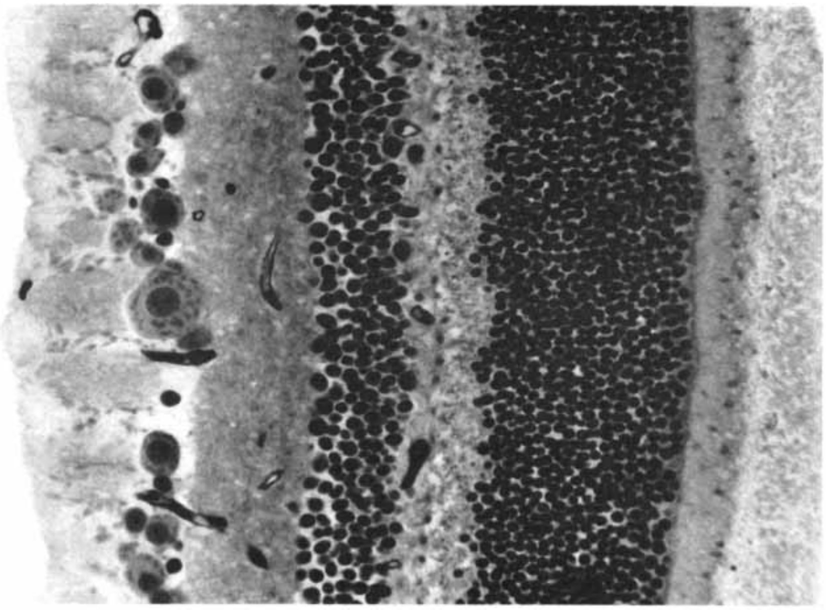
The responses of plants to variations in the length of day and night involve light-induced molecular changes that closely parallel those involved in vision. Because photoperiodic responses are not as well known as visual ones I shall present some illustrative examples. Chrysanthemums and many other plants flower in response to the increasing length of the nights as fall approaches. If the long nights are experimentally inter-



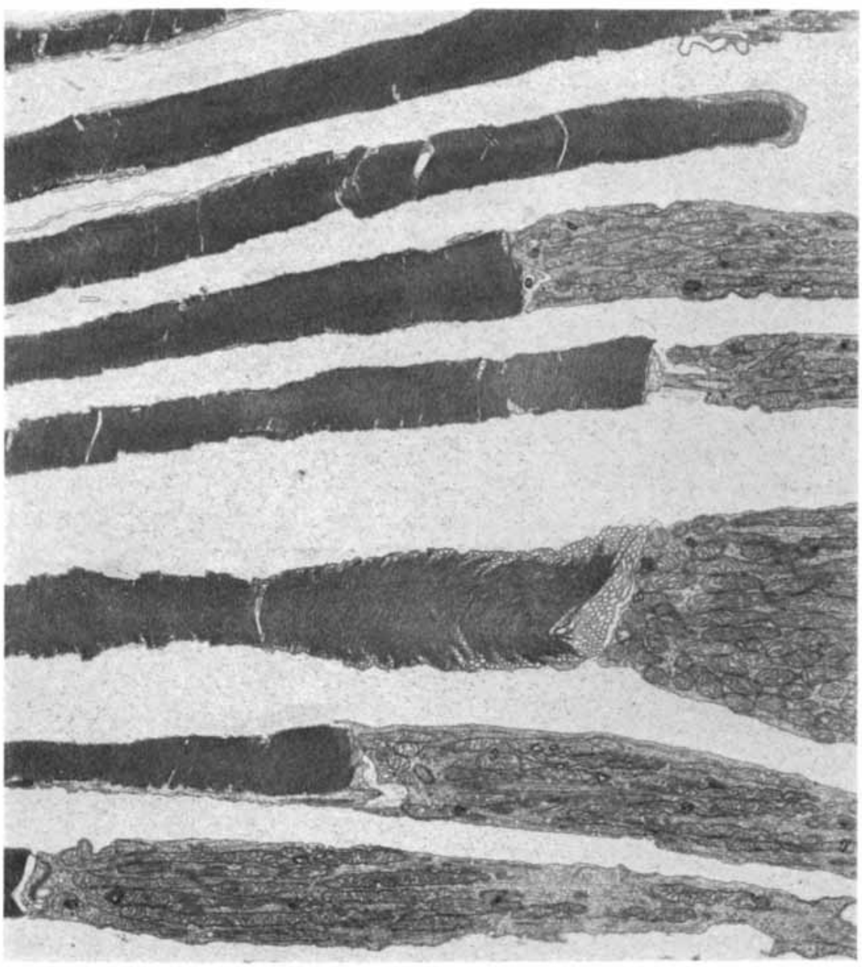
CHANGES IN RHODOPSIN, the visual pigment contained in the rod cells of the vertebrate eye, can be traced in the laboratory at low temperatures. Four successive forms of the pigment appear (*rectangles*) as the retinal molecule (*black*) first attains its *trans* configuration and then dissociates from the protein opsin. When it becomes *cis* retinal again, it recombines and completes the cycle.



CHANGES IN PHYTOCHROME, the plant-photoperiodism chromophore, can also be traced at low temperature. As with rhodopsin, intermediate forms with characteristic light-absorption peaks appear before the initial red-absorbing form of the pigment is turned into the far-red-absorbing form. Unlike retinal, the chromophore (*black*) remains associated with its protein throughout the cycle.



CAT RETINA is seen in cross section, enlarged 670 times. The nerve-fiber layer (*left*) is the part of the retina that lies in contact with the eye's vitreous body. The entering light must penetrate this and five additional layers of retinal tissue before reaching rods and cones (*right*). The micrograph was made by A. J. Ladman of the University of New Mexico.



HUMAN RODS AND CONES, enlarged 7,200 times, are seen in an electron micrograph of retina. The visual pigments are concentrated in platelike layers of membrane called lamellae. The micrograph was made by Toichiro Kuwabara of the Harvard Medical School.

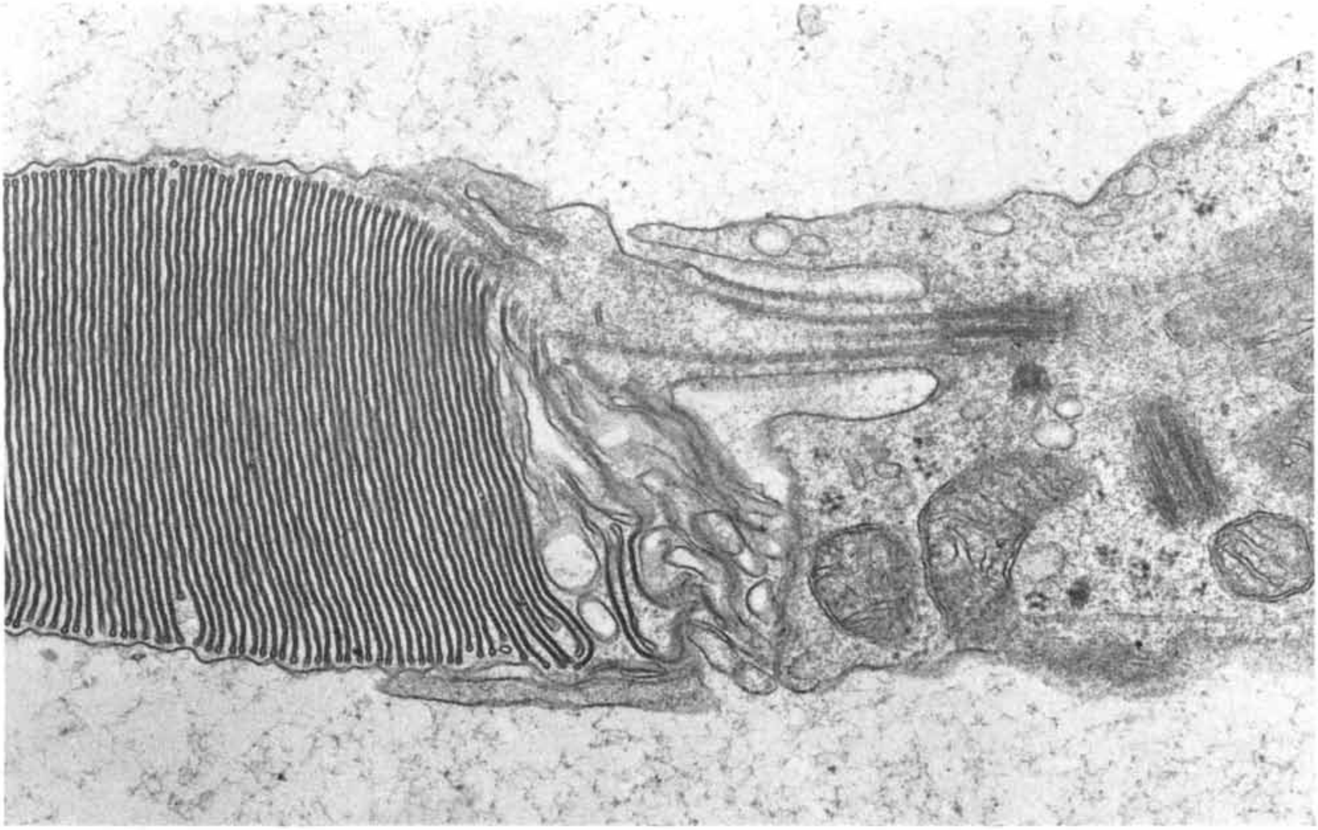
rupted by exposing the plants to short periods of light near midnight, the plants will not flower. Red light with an absorption maximum at a wavelength of 660 nanometers is most effective in preventing flower formation. Thus we anticipate that the light-receiving pigment in the plant is blue—the complementary color to the absorbed red. If shortly after exposure to red light the plants are exposed to light near the limit of vision in the far red (730 nanometers), they will flower.

The ornamental plant kalanchoe clearly illustrates the reversible response. The red light evidently converts the photoreversible pigment to a far-red-absorbing form. This changes the plant from the flowering state to the nonflowering one. The far-red light returns the pigment to its red-absorbing form, which enables flowering to proceed. Control of flowering by length of night is a very important factor in determining what varieties of soybean, wheat and other commercial crops are best suited for being grown in various latitudes with different periods of light and darkness.

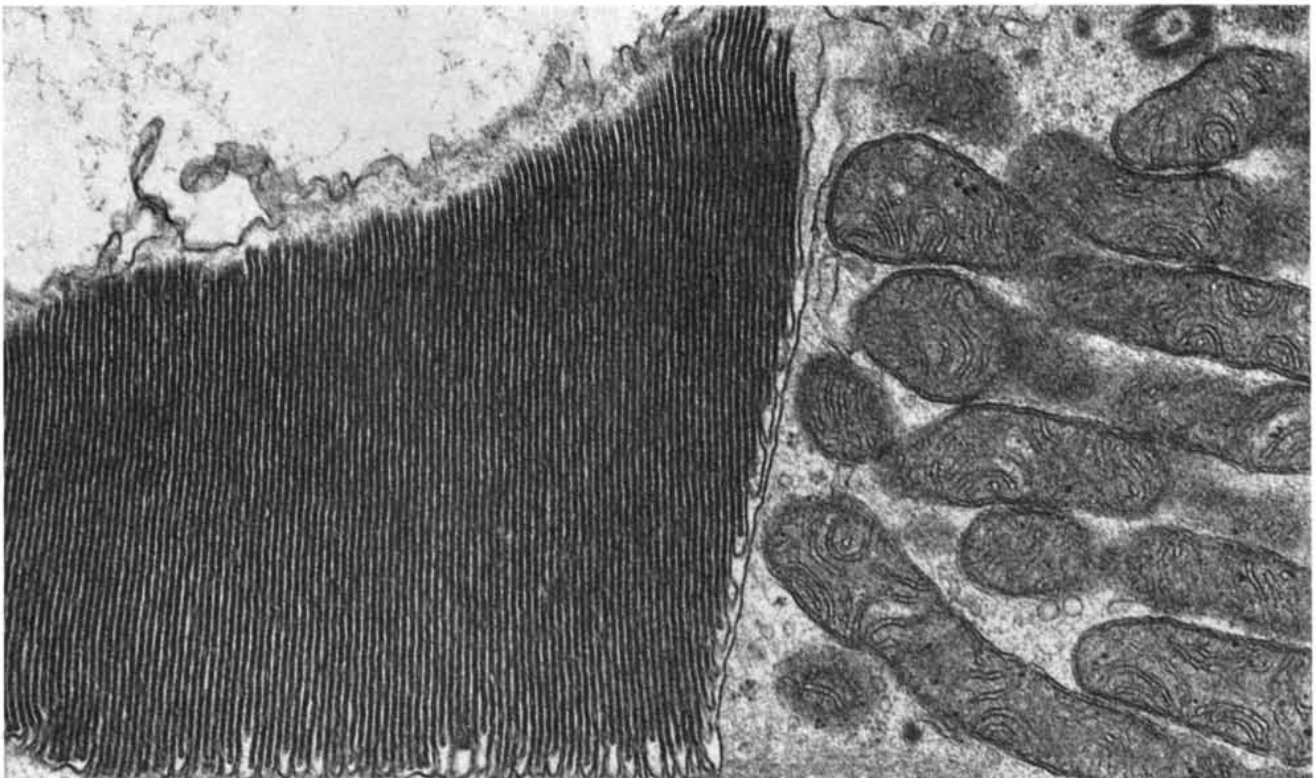
Many kinds of seeds will germinate only if the photoreversible pigment has been activated. The seeds of some pine and lettuce species, for example, will not germinate in the laboratory unless they are briefly exposed to red light (or, to be sure, light containing red light). If the red-light activation of the seeds is followed by a short exposure to far-red light before the seeds are returned to darkness, the seeds remain dormant. The activation-reversal cycle can be repeated many times; germination or continued dormancy depends on the last exposure in the sequence.

The requirement of light for seed germination is a major cause of the persistence of weeds in cultivated crops. A seed that is dormant when it first falls to the ground is usually covered by soil in the course of the winter. As the seed lies buried the pigment that controls its germination changes into the red-absorbing form; now the seed will not germinate until it is again exposed to sunlight by cultivation or some other disturbance of the soil. When it is exposed, the sunlight converts some of the red-absorbing pigment back to the far-red-absorbing form, and germination begins. Seeds of one common weed, lamb's-quarters, are known to have lain buried for 1,700 years and then to have germinated on exposure to light.

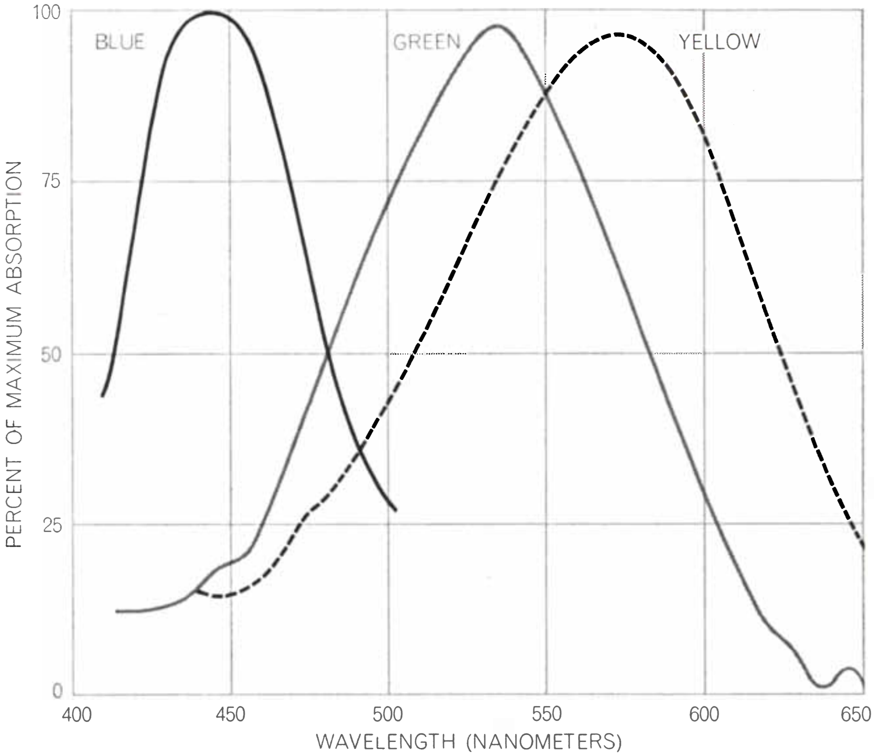
The activation of the photoreversible pigment also controls the growth of trees and many common flowering plants. If



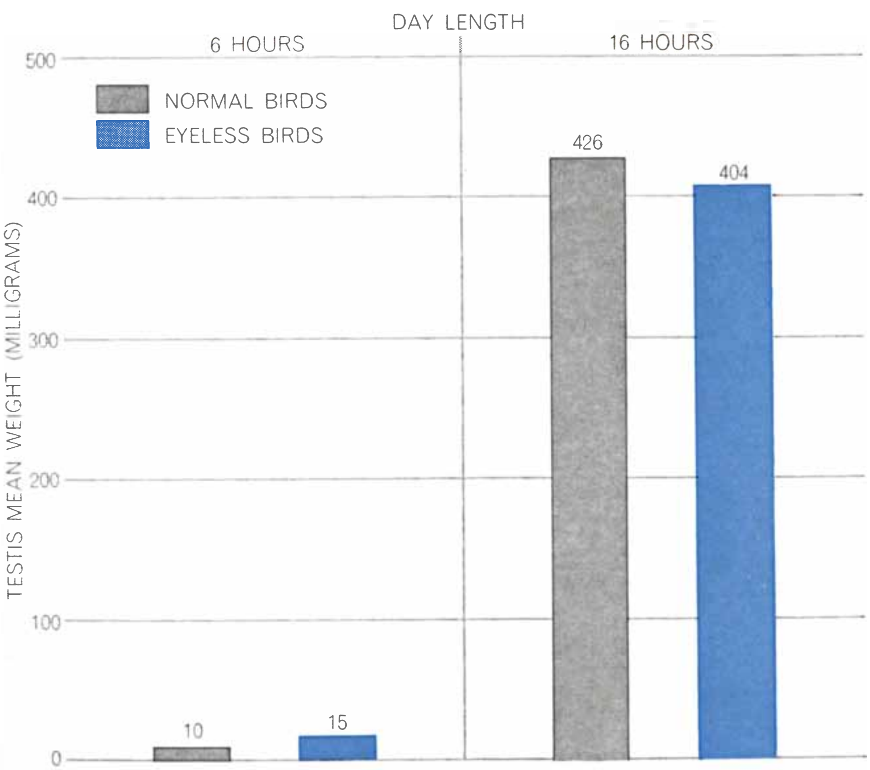
PART OF HUMAN ROD is magnified 44,000 times in electron micrograph. The outer segment of the rod *(left)* is filled with the membrane of the lamellae. The inner segment *(right)* is less complex in structure. This micrograph was also made by Kuwabara.



PART OF HUMAN CONE is magnified 44,000 times in another micrograph by Kuwabara that emphasizes the area connecting the structure's inner and outer segments. The lamellae differ from rod lamellae in being "packaged," some singly and some in groups.



COLOR PERCEPTION in humans arises from the combination of retinal with three dissimilar opsins in the cones of the retina. The three different iodopsin pigments formed thereby absorb the greatest amount of visible light at three different wavelengths. The differences between the signals from each group of cones reflect the color pattern of the image.



PHOTOPERIODISM IN SPARROWS has been shown to involve some light receptor other than the eye. The testis weight of both eyeless and normal sparrows remained low when their cages were lighted to simulate short days and long nights over a two-month period (*left*). When eyeless and normal birds instead underwent two months of long days and short nights, their testis weight showed a nearly identical increase (*right*). The experiment was conducted by Michael Menaker and Henry Keatts of the University of Texas.

such plants are to continue growing, they must have long periods of daylight. As the days become short growth stops and the plants' buds go into a dormant state that protects them against the low temperatures of winter.

The photoreversible pigment of plants has been named phytochrome. It is invisible in plant tissue because of its low concentration. It was isolated by methods widely used in the preparation of enzymes and other proteins. The pigment is indeed blue [*see illustration on page 174*]. Its photoreversibility is exactly what was expected on the basis of plant responses to light.

The chemical structure of the phytochrome molecule shows that it is related to the greenish-yellow pigments of human bile and the blue pigments of blue-green algae. The molecule comprises an open group of atoms that is closely related to the rings in the chlorophyll molecule. It has two side groups that can change from the *cis* form to the *trans* when they are excited by light. A more probable excitation change, however, is a shift in the position of the molecule's hydrogen atoms.

The changes in the phytochrome molecule following excitation by a flash of light are similar to those in rhodopsin. The first excitation response takes place in a few millionths of a second and gives rise to a form of the molecule that is analogous to prelumirhodopsin. The change stops at this point if the temperature is below −110 degrees C. At these low temperatures the molecule can be reconverted into its initial red-absorbing form by the action of light. At temperatures higher than −110 degrees several more intermediate phytochromes are formed before the final far-red-absorbing molecule appears. These intermediate stages also involve alterations in the molecular form of the protein associated with phytochrome, just as there are alterations in the form of opsin, the protein of rhodopsin. In its final form phytochrome differs from rhodopsin in that the molecule of phytochrome remains linked to the protein rather than being dissociated from it. Far-red light will reverse the process and convert the final form of phytochrome back to its initial red-absorbing form, although a different series of intermediate molecular forms is involved.

Flowering, seed germination and most other plant responses follow slowly on the excitation of phytochrome. Unlike vision, in which the response follows the rapid appearance of intermediate molecules, the photoperiodic response of plants depends on the presence of the final, far-red-absorbing form of phytochrome. Little is known about how the far-red-absorbing molecule does its work. One view is that it regulates enzyme production by controlling the genetic material in cell nuclei. Another view is that the molecule's lipid solubility results in its being attached to membranes in the cell, such as the cell wall and the membrane of the nucleus. Changes in the form of the phytochrome molecule would then affect the permeability of the membranes and therefore the functioning of the cell.

The continuous exposure of plants to blue and far-red wavelengths in the visible spectrum opposes the action of the far-red-absorbing form of the phytochrome molecule. It may be that excitation by far-red light causes a continuous displacement of the far-red-absorbing molecules from cell membranes. Continuous excitation of this kind is what happens, for example, during the long light periods that so markedly influence the growth of Douglas firs. If the trees are exposed to 12-hour days and 12-hour nights, they remain dormant. If the length of the day increases, however, they grow continuously.

Photoperiodism is not confined to the plant kingdom: animals also respond to changes in the length of the day. The migration and reproduction of many birds, the activity cycles of numerous mammals and the diapause (suspended animation) of insects are controlled in

LONG LIGHT PERIODS markedly influence the growth of Douglas fir. When exposed to short days, or days and nights of equal length, the tree will remain dormant (*left*). Excitation by additional light produces continuous growth. One tree (*center*) received an hour of dim illumination during its 12-hour night; the other (*right*) had its 12-hour day extended by eight hours of dim light.

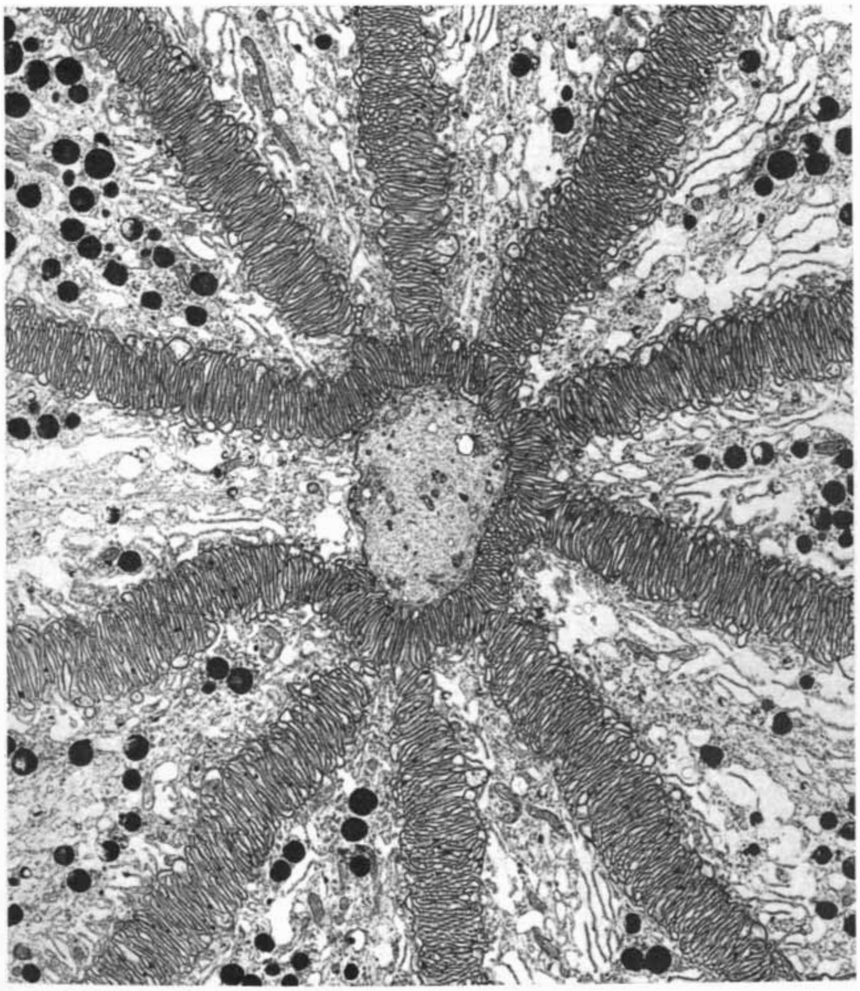
this way. These examples of photoperiodism (and some less clear-cut responses in man) depend on the action of several hormones working in sequence. Such sequences of hormone action can have a regular rhythm. They provide a basis for the circadian (meaning about one day) rhythms of "biological clocks." The 24-hour cycle of such clocks is established by light.

The diapause of insects illustrates one form of the interplay of hormone action and light. Some silkworms and the larva of the codling moth, for example, go into a dormant form when the days are short. In this state, which helps the insects to survive the winter, the release of a hormone from a group of cells in the central part of the brain is suspended. The unreleased hormone is the first in a series that leads to a final hormone, ecdysone, that controls the metamorphosis of the pupa into an adult moth. When the brain cells of the dormant pupa are exposed to light for long days, the brain hormone is released and triggers the metamorphosis. Ecdysone injected into a resting pupa brings on metamorphosis even when the days are short.

Here the sole action of the light is the release of a brain hormone. The pigment in the brain cells that absorbs the light has not yet been identified, but current work in the U.S. Department of Agriculture on the response to light by codling moths in diapause promises an answer. The blue-green part of the spectrum (between 500 and 560 nanometers), and probably shorter wavelengths as well, appears to be most effective for breaking diapause. The pigment is possibly of the porphyrin type, with a central structure resembling the ring system of chlorophyll.

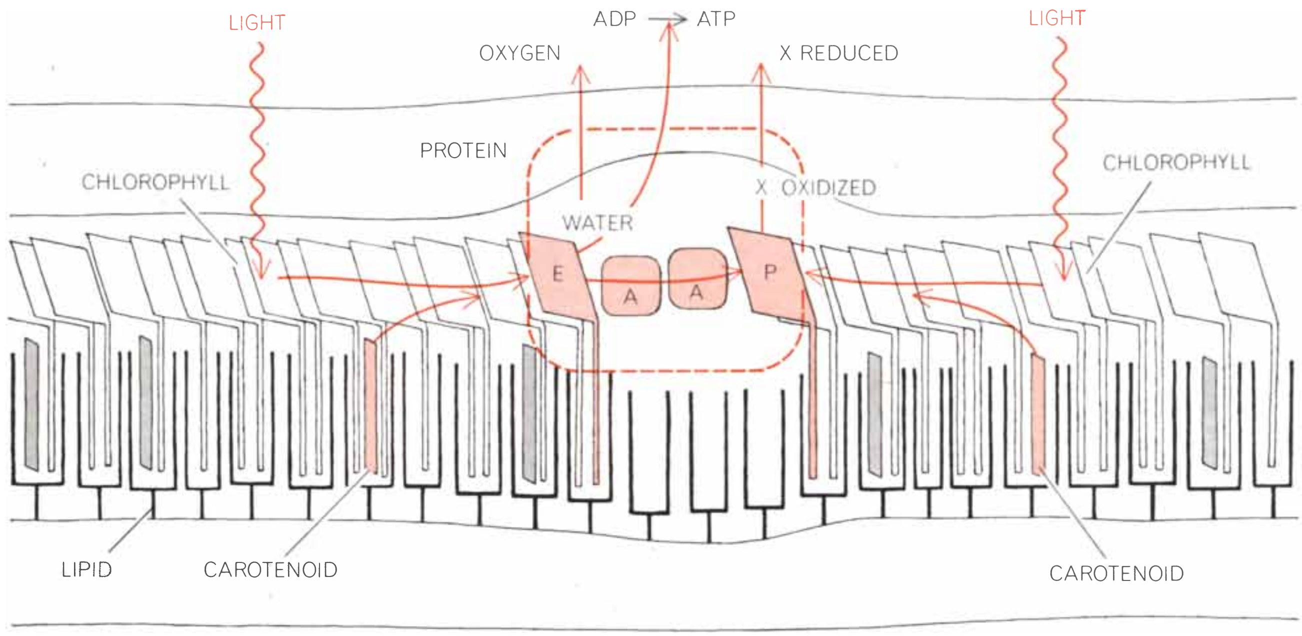
Man's dependence on a biological clock is apparent in the unease he feels when the relation of his circadian rhythm to the actual cycle of day and night is quickly disrupted, as it is when he travels by air for distances measured in many degrees of longitude. His hormonal controls are disturbed or out of phase. Deer mice and other small mammals also display cyclic periods of activity such as running that seem to be regulated by light.

Involved at an early stage in the release of the hormones that trigger activity cycles is the region of the brain known as the hypothalamus. Whether this region contains a pigment receptor for the small amount of light that might penetrate the skull or whether it is stimulated by a signal from the eye, or the region of the eye, is unknown. The hypothalamus also controls the pituitary, hormones from which affect the reproductive organs, the cortex of the adrenal gland and other target organs. At present, however, the existence of a pigment responsible for vertebrate photoperiodism, its physical location and the nature of its action on the molecular level remain to be established.

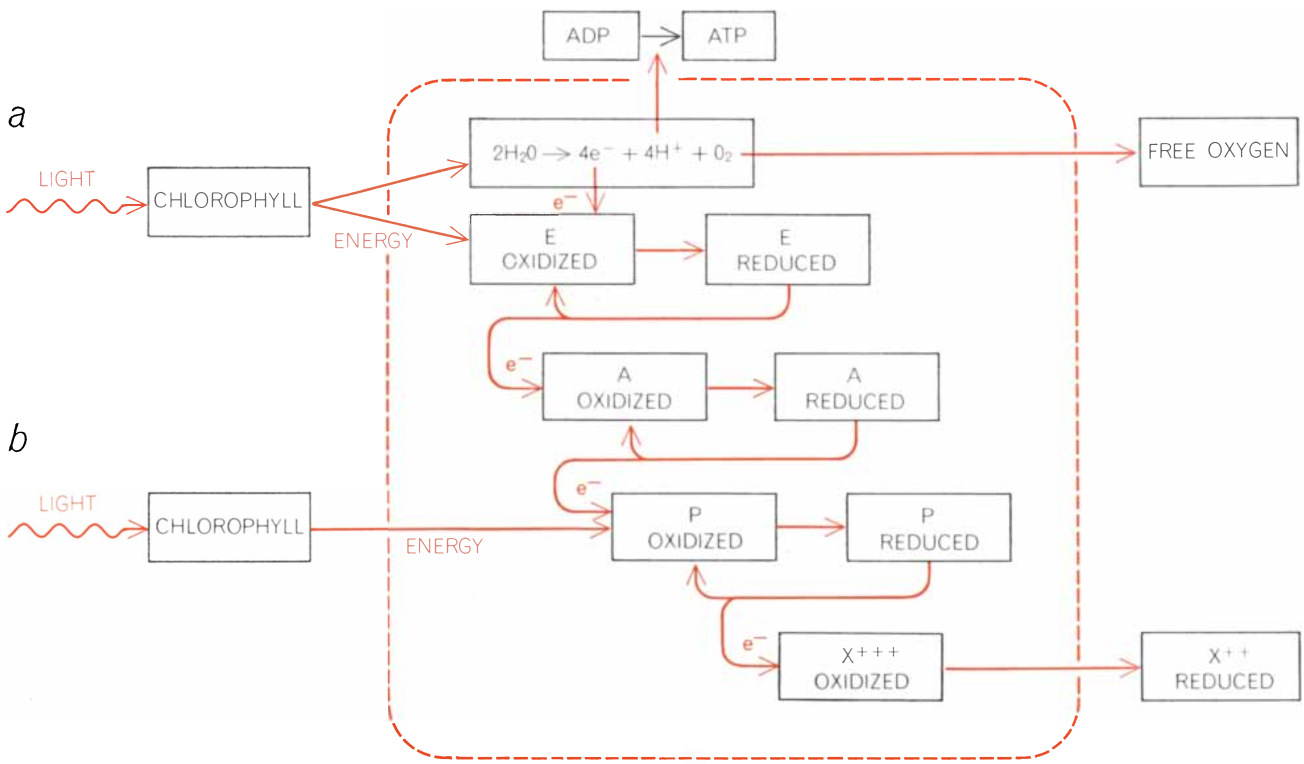


LIGHT-RECEPTOR ORGAN of an invertebrate is enlarged 8,000 times in an electron micrograph. Called an ommatidium, it is one of about 1,000 such units that comprise a horseshoe crab's compound eye. The spokelike arrays and the central ring are photosensitive. William H. Miller of the Yale University School of Medicine made the micrograph.

By exciting a chromophore light acts as a trigger both in vision and in photoperiodism, initiating processes that depend for their energy on the organism's own metabolism. In the third major area of light's interaction with living matter—photosynthesis—the opposite is true: the energy of light is utilized to manufacture the fuels that support life. For this to happen there must be (1) a system to receive the light, (2) an arrangement to transfer energy between molecules and (3) some means of coupling light energy to chemical change. Chlorophyll molecules (or rather the molecules of several chlorophylls that differ in their side groups) constitute the principal receiving system. An electron in the chlorophyll molecule is excited from its normal energy level to a higher level by the impact of visible light. The excited electron reverts to its normal state in less than a hundred-millionth of a second. This reversion might be accomplished by the reemission of visible light, but that, of course, would not advance the photosynthetic process. Instead the reversion proceeds in several steps during which the energy necessary for photosynthesis is transferred along a chain of molecules. A small part of the energy released by the reversion is reemitted as light of a longer wavelength, and hence of lower energy, than the light that was absorbed. (This is the dark red light characteristically emitted by chlorophyll when it is excited to fluorescence.) The remainder of the energy is transferred by way of other chlorophyll molecules to an ultimate recipient, a molecule that receives the energy and effects the chemi-



PLANT PHOTORECEPTORS contain molecular arrays, shown here in schematic form. Within the chloroplast, chlorophyll molecules are held together both by their mutual attraction and by the affinity of each molecule's phytol "tail" for lipids and its main body for proteins. Other molecules of pigment, such as carotenoids, are also embedded in the array. For each 500 or so chlorophyll molecules is found a specialized energy-transfer center, comprising two energy sinks, *E* and *P* (*color, center*), linked by a system for transferring electrons, represented here by units labeled *A*. The electron-cascade system by means of which this array of molecules turns energy from light (*colored inward arrows*) into chemical energy (*outward arrows*) is seen in detail in the illustration below.



ELECTRON CASCADE that is responsible for the main action of photosynthesis, the use of energy from light to reduce carbon dioxide to sugar, is shown schematically here. Within a zone that contains two energy sinks, *E* and *P*, water and its components (*top rectangle*) are in a state of equilibrium until several chlorophyll molecules pass the energy received from light (*a*) to the first energy sink, *E*. This event starts the cascade; *E*, driven to a higher state of excitation by the energy it receives, seizes an electron (*colored arrow*) from a water component. Next *E* falls back to its lower state; the seized electron is released and cascades onward via the transfer system *A*. It arrives at the second energy sink, *P*, soon after that sink has received energy from other light-excited chlorophyll molecules (*b*). The cascade ends when *P* falls back to its lower state, passing both electron and energy to *X*, an electron-rich compound. The event energizes *X* sufficiently to let it power the carbon dioxide reduction process (*arrow, lower right*); this is the main photosynthetic action. Two other events, however, are also consequences of the cascade. Hydrogen ions (*top arrow*) provide the energy gradient needed to transform adenosine diphosphate (ADP) into adenosine triphosphate (ATP). Similarly, the ion neutralized by the electron loss that initiated the cascade joins with other components to form water, thereby freeing oxygen (*arrow, upper right*).

cal synthesis. For these energy transfers to be efficient the molecules in the chain must meet two criteria. First, they must be physically close together. Second, there must be a close match between the amount of energy available from the donor molecule and the amount acceptable by the recipient.

The plastids of plant cells, the microscopic bodies that contain the chlorophyll pigments, are made up of layered structures known as lamellae that have a high content of protein and lipid [*see top illustration on preceding page*]. The chlorophyll molecule has one end (the phytol end) that is soluble in lipid and a main body (the chlorophyllin end) that has an affinity for protein. These affinities give rise to a structural system in which the chlorophyll molecules are closely packed.

The lamellae also contain other molecules with conjugated bonds. These include carotenoids that are similar in structural arrangement to retinal, and phycocyanin, which has a chromophore closely related to the chromophore of phytochrome. These accessory molecules also absorb radiant energy and transfer it to the chlorophyll molecules.

The accumulated energy is finally transferred from the chlorophyll molecules to a relatively few molecules that act as energy-trapping "sinks." In each lamella there is about one sink for every 500 chlorophyll molecules. This small number, whereas it effects a desirable parsimony in the systems required for the chemical steps of photosynthesis, constitutes a bottleneck insofar as energy transfer is concerned. When light reach-

PART OF PHOTOSYNTHETIC ORGAN, a chloroplast of the alga *Nitella*, is seen enlarged 133,000 times in an electron micrograph made by Myron C. Ledbetter of the Brookhaven National Laboratory. Chlorophylls and other pigments involved in the process of photosynthesis are associated with the many lamellae scattered throughout the chloroplast.

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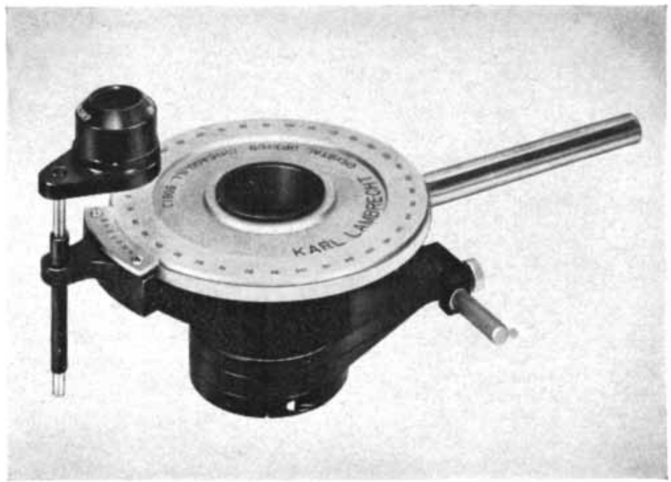

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SPECIFICATIONS

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Length of support rod	6 inches
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Micrometer screw range	13 mm readable by vernier drum to .005 mm
Weight of support rod & collar	1/2 pound
Diameter of support rod	1/2 inch
Weight of circle	3 pounds
Weight of micrometer box	1/2 pound
Aperture size (Babinet)	Diaphragmed to clear aperture of 10 mm (removable)
(Babinet-Soleil)	Diaphragmed to clear aperture of 13 mm (removable)

Circle dividing (0-180) in one degree intervals each tenth degree numbered. Readable by single vernier to zero degrees six minutes (0.1 degree).

*Also available: Babinet Compensator (Ramsden Eyepiece)

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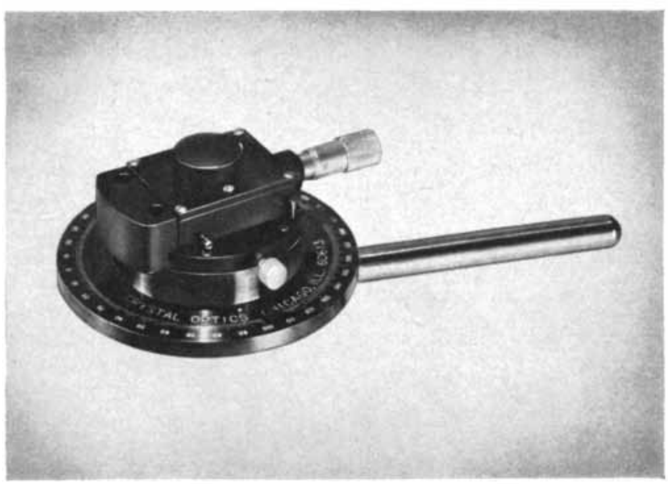

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es a level of intensity about a fifth the intensity of full sunlight, energy arrives at the sinks faster than it can be utilized. Saturation at this level of intensity is nonetheless a good compromise because the average plant leaf is somewhat shaded and seldom receives energy much above the one-fifth level.

The energy accumulated by the sink molecules is ultimately applied to split water molecules into hydrogen and oxygen and to yield an electron-rich compound, which here I shall call "X," that acts as a final electron-acceptor. An oxidized material (that is, one that has given up electrons) is formed as a waste product. In green plants this material is oxygen. It is as a result of this aspect of photosynthesis that the earth's atmosphere contains the oxygen essential to all animal life.

Measured in terms of its products, the effectiveness of the photosynthetic chemical system decreases as the wavelength of the light being absorbed becomes longer. Absorption in the far-red region of the visible spectrum can be made effective, however, if supplementary light of shorter wavelength is also present. This suggests that two steps are involved in electron transfer rather than one; perhaps two energy sinks work together in some kind of booster action. The processes associated with each type of sink are a subject of current investigation, as is the manner in which electron flow might be coordinated between the two steps.

The electron-transport system, as it is now conceived, can be represented schematically [*see illustrations on page 183*]. Trapping centers are indicated as points *E* and *P*. An electron is thought to be transferred from *P* to *X* by one act of light absorption (*b*): the electron loss leaves *P* oxidized, whereupon *X*, the electron-acceptor, becomes an electron-rich, or reduced, compound. In close order a second act of light absorption (*a*) transfers an electron from water to point *E*, leaving *E* electron-rich and leading eventually to free oxygen as the oxidized substance in green plants. The scheme is completed by electron transfer from reduced *E* to oxidized *P*. Functioning of the electron transport steps from water to *X* again requires close association of the necessary parts in the lipid-rich lamellae of the plastids.

The bare skeleton of the scheme serves the purpose of exposition as far as the "photo" part of photosynthesis is concerned, but it leaves much to be told about the "synthesis" part. "Synthesis" implies an output that can be used in a life process. Oxygen, although it is an oxidized waste product of the scheme, eventually closes back on the electron-rich compound *X* through the process of respiration. *X* is an immediately useful product for reactions outside the lamellae. It serves as the chief energy-transferring agent in the reduction of carbon dioxide to sugar. A further reaction transforms *X* through intermediates, along with carbon dioxide and water, into electron-poor, or oxidized, *X* and phosphorus-containing sugars. The reaction needs more energy than can be supplied by *X* alone. This energy, as well as the needed phosphate, comes from adenosine triphosphate (ATP). ATP is formed by the removal of water from adenosine diphosphate (ADP) and the addition of a phosphate molecule. Energy for the transformation of *X* is available when the added phosphate of ATP is transferred to some other molecule or is split from ATP by water.

Returning to our illustration of the scheme, it appears that the energy difference in the electron transfer from *E* to *P* is adequate to make ATP. This until recently was thought to be the most likely way at least part of a plant's supply of ATP was produced. A view that is now being vigorously debated suggests that hydrogen ions appear inside the lamella in the electron transfer that follows light absorption. The enhanced acidity with respect to the outside of the retaining membrane that the ions inside the membrane provide would give an energy gradient adequate for the formation of ATP. With regard to the first action of light (*b*), electrons excited by that event can also be transferred through *X* back to the starting point *P* with coupling to ATP along the way—a process known as cyclic phosphorylation.

This broad outline of energy transfer in photosynthesis has been developed chiefly during the past 10 years. There is still much to be learned about the molecular details of oxygen liberation, the formation of ATP and the coordination of electron flow in various parts of the process. New discoveries may well alter some of today's concepts of photosynthesis at the most basic level. The situation is much the same with regard to our present understanding of vision and photoperiodism. Examination of the immediate changes after light absorption has proved to be a more fruitful realm of study than the search for the ensuing steps that lead to the responses of sight, growth and biological rhythm.

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The Control of the Luminous Environment

Architecture, which for millenniums was dependent on natural sources of light, has in the past century increasingly turned to artificial sources. In the long run it must perfect the integrated use of both

by James Marston Fitch

We live in a luminous environment that is radically new for mankind. Until the 19th century life for most people was geared to the daily period of natural light between sunup and sundown. In George Washington's day 95 percent of Americans were farmers; daylight sufficed for their work, and they went to bed early not only because their hard labor made them sleepy but also because artificial lighting was primitive and expensive, illiteracy was general, books were few and the darkness of night still held much of its primordial menace. A symbolic illustration of the poverty of the luminous environment in the agricultural era is the picture of Abraham Lincoln heroically studying by the flickering light of an open fire.

The industrial revolution changed all of that. It created both the necessity and the means for a new order of artificial illumination. Machines could, and for efficient use should, be run around the clock. It became necessary not only to light up the nighttime but also to provide controlled illumination for the close and precise vision to which man now had to adapt himself—for operating machines and instruments, for reading and for the universal education that became an economic as well as a social and political necessity.

Today the majority of us work and spend most of our time in buildings, where the proper handling of daylight and the provision of artificial lighting are a *sine qua non*. In response to such needs artificial lighting, for both indoor and outdoor purposes, has been developed into a large and imaginative industry. Yet it cannot be said that many of the lighting systems are particularly well suited to the requirements of the job or to the health and comfort of the human eye. For one thing, they are often designed for appearance or for economy rather than for the utilitarian functions they are supposed to serve. For another thing, all too little study has been given to the psychology and physiology of vision in relation to illumination.

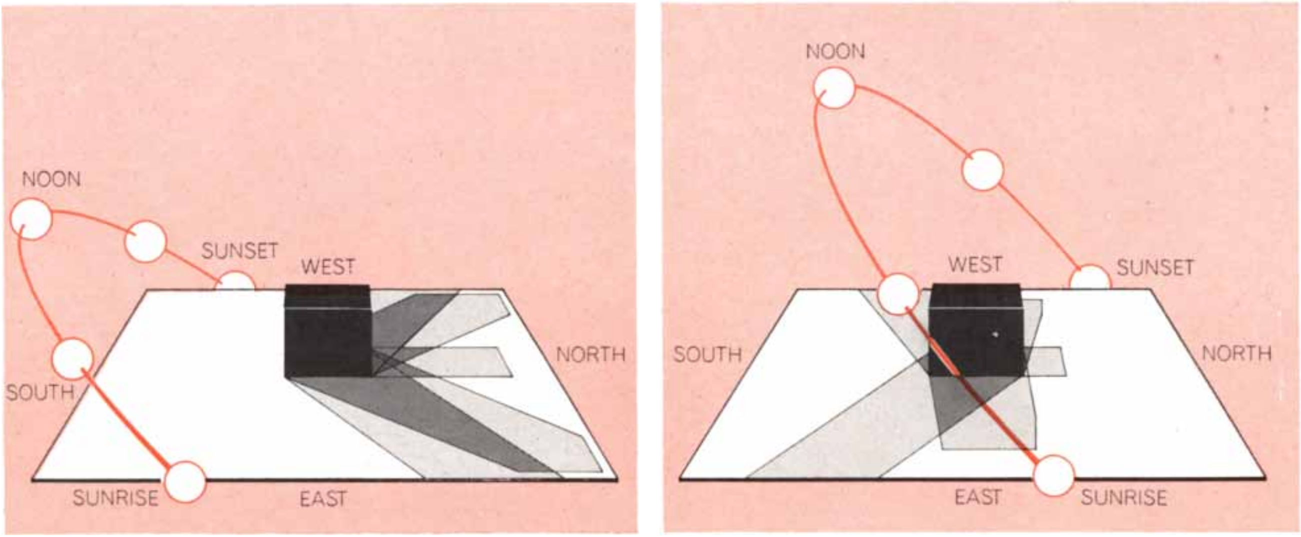
Within the visible portion of the spectrum the human eye is most sensitive to the yellow-green wavelengths at about 570 nanometers. The range of energies to which it responds is remarkable: the unaided eye can detect a lighted candle at a distance of 14 miles and at the other extreme is able to resolve the details of a landscape flooded by 8,000 foot-candles of sunshine. (The amount of light falling on a surface is measured in foot-candles; the reflected light, or brightness, of the surface is measured in foot-lamberts.) These figures refer to the responses of the normal eye under ordinary conditions; the actual performance of the visual system will vary, of course, according to external and internal circumstances, including stresses on the eye or fatigue. The causes and mechanism of visual fatigue are not entirely clear, but it is known that the fatigue rate rises in direct proportion to the dimming of the visual field; in other words, the brighter the illumination, the less the eye tires. The fatigue rate is also affected, however, by other factors, such as the distribution, direction and color of the light.

Generally speaking, the eye is most comfortable when the visual field has no great contrasts. This does not mean that it responds well to a field of uniform brightness; objects seen under diffuse light, for example, are difficult to make out. For optimal eye comfort the visual stimuli should vary somewhat in space and time but not strongly enough to produce stress. For tasks requiring fairly fine vision (such as proofreading, sewing or watch-repairing) the work should be illuminated by 100 to 150 foot-candles, and the surrounding surfaces should have a brightness of at least one-third of this value (35 to 45 foot-candles). Of course, many tasks require far higher levels of illumination: a surgeon at the operating table, for example, may need 1,000 foot-candles.

Apart from miscellaneous items of information such as these, the architect and the designer of illumination systems have little in the way of research findings on visual requirements to guide them in the creation of luminous environments for present-day needs. The questions that still need answers are numerous and important. It would be useful to know, for instance, if illumination should be increased as the day goes on and workers' eyes tire. What are the most effective forms of lighting for particular tasks? What is the optimal mix of natural and artificial illumination in the modern urban environment?

Illumination engineers tend to favor establishing complete control over the

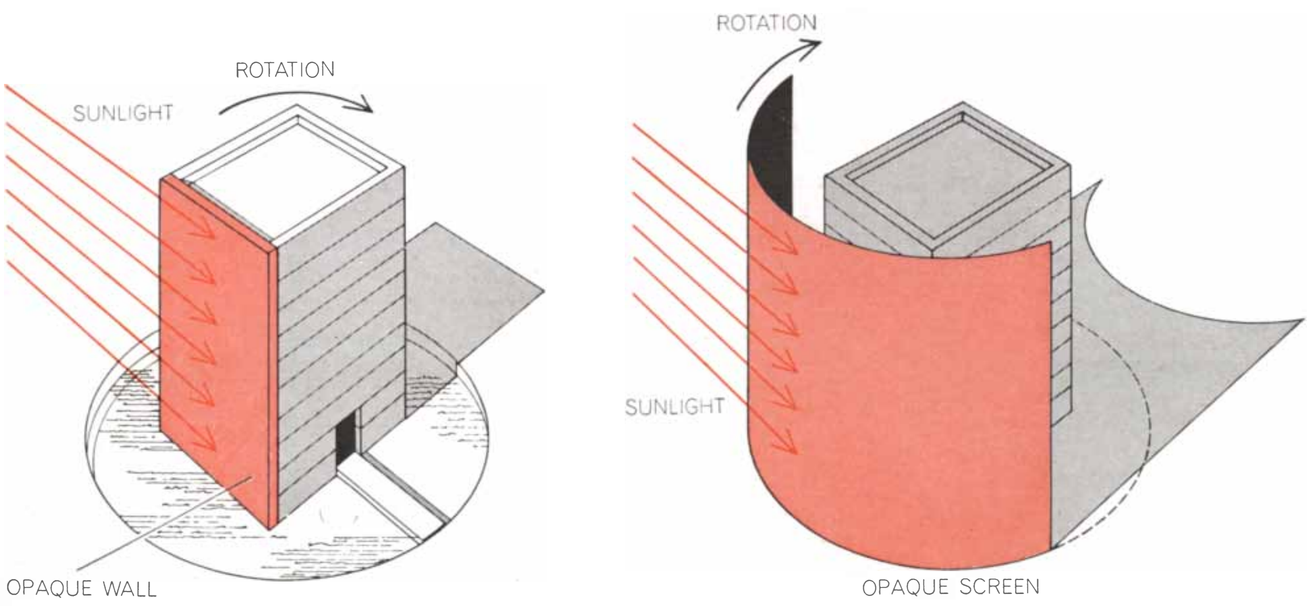
FOUR PANES OF GLASS that modify daylight in different ways frame part of the midtown Manhattan skyline in the photograph on the opposite page. At top left is water-white glass; it absorbs no colors and transmits nearly 90 percent of the outdoor light. The other panes are examples of the wide range of "environmental" glasses available to architects today. The bronze-tinted glass (*top right*) transmits 51 percent of the light, the neutral gray glass (*bottom left*) 42 percent and the blue-green glass (*bottom right*) 75 percent. Environmental glasses also reject a large percentage of solar heat, thereby reducing the load on interior cooling systems. The glasses seen in the photograph are made by PPG Industries, Inc.



MOVEMENT OF THE SUN across the sky differs in azimuth and elevation with the seasons. The examples shown are summer (*left*) and winter (*right*) at 40 degrees north latitude. The seasonal variations alter the amount of solar energy that impinges on buildings.

luminous environment by employing fully artificial lighting in windowless buildings. For some functions this is obviously appropriate and essential. An outstanding example is the assembly tower at Cape Kennedy where the vehicle for the moon mission is to be constructed. In this structure (the world's largest building) the necessity for absolute control of all the environmental conditions is such that the enclosure must be hermetically sealed. For most purposes, however, the windowless building seems not only impracticable but also undesirable. Apart from the question of cost (involving the expense of the lighting system and the cooling needed to remove the waste heat it produces), people do not relish being cooped up in a windowless building. Human vision and well-being apparently suffer when vision is restricted to the shallow frame of man-made perspectives and is denied the deep views of nature. The eye wants variety in the optical conditions and freedom for occasional idle scanning of a visual field broader than the work at hand. In the home and at work people hunger for view windows, if only to "see what the weather is like outside." And in many activities windows serve an essential function, for looking out or in or for both; one need only mention stores, banks, lobbies and airport control towers. Although artificial lighting will inevitably come into increasing use, the windowless building will certainly remain a special case.

Let us begin, then, with the first consideration in the illumination of a building interior: the appropriate use of sunlight. For this an architect now has a large variety of devices at his command. The first step, of course, is suitable orientation of the building toward the sun, so that sunlight will be admitted through transparent walls where it is wanted or excluded by opaque walls where it is not wanted, and a maximum of indirect daylight can be obtained throughout the day in parts of the building where direct



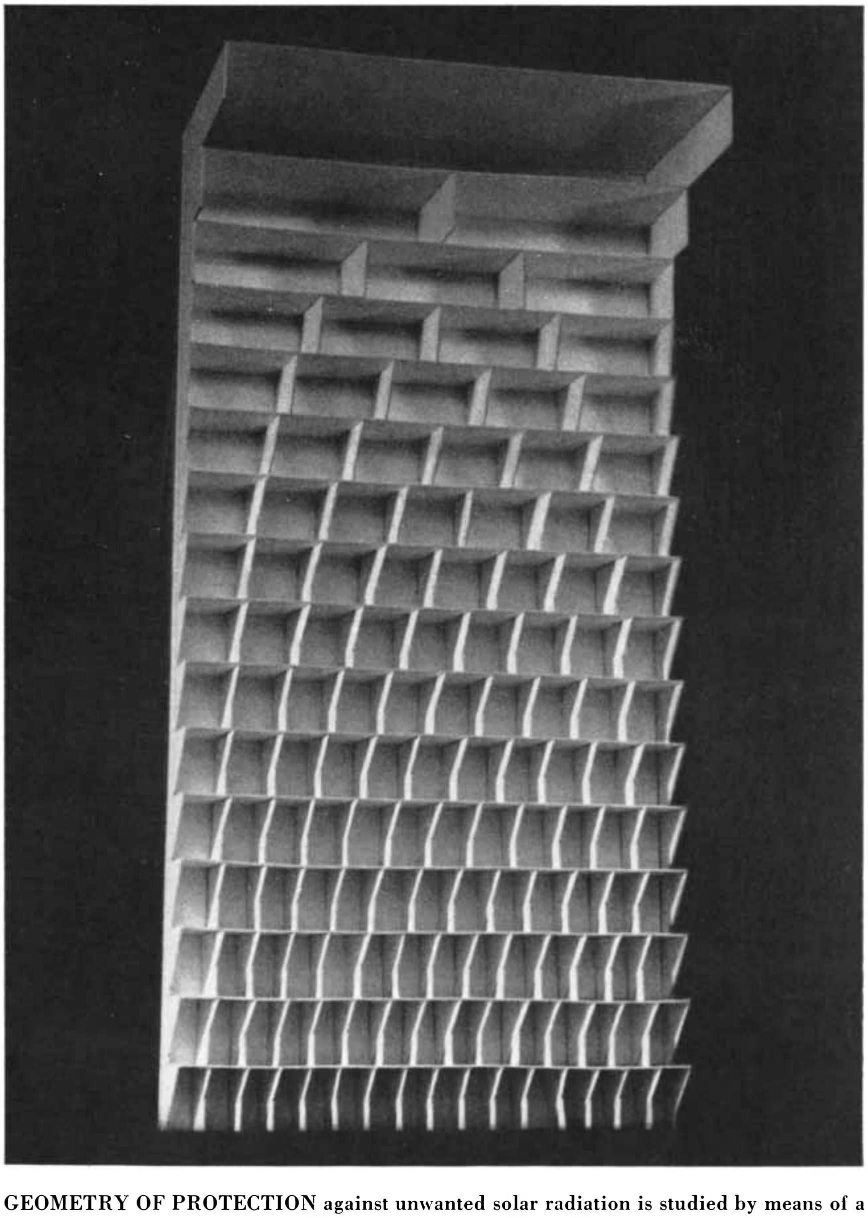
RADICAL SOLUTIONS to the problem of unwanted solar energy include construction of a revolving building (*left*) that would present the same windowless wall to the sun all day long, or a revolving sun screen (*right*) that would always intercept the sun's rays.

sunlight is undesirable. In regions of intense sunlight, such as the U.S. Southwest, or of feeble winter sunshine, such as the Canadian Arctic, effective use of the sunshine may be important not only for lighting but also for heating. Elsewhere, as in Lower California or the Persian Gulf region, cooling requirements demand that the building's interior be shielded from the sun. In any case, the orientation problem of course is complicated by the sun's movement across the sky and the seasonal variations in its angle. There are several possible means of coping with this movement. The building might be placed on a turntable that rotated it slowly in synchronization with the sun. Where the sunlight can be used for heating as well as lighting such a device might be economically feasible, particularly if an efficient and relatively frictionless turning apparatus were developed to minimize the power required to rotate the structure. Alternatively, the control of sunlight might be accomplished by a simpler mechanism: a solar screen that would run on a track and move around the building with the sun. It could be applied to large buildings as well as small and might serve as a windbreak in cold or stormy weather.

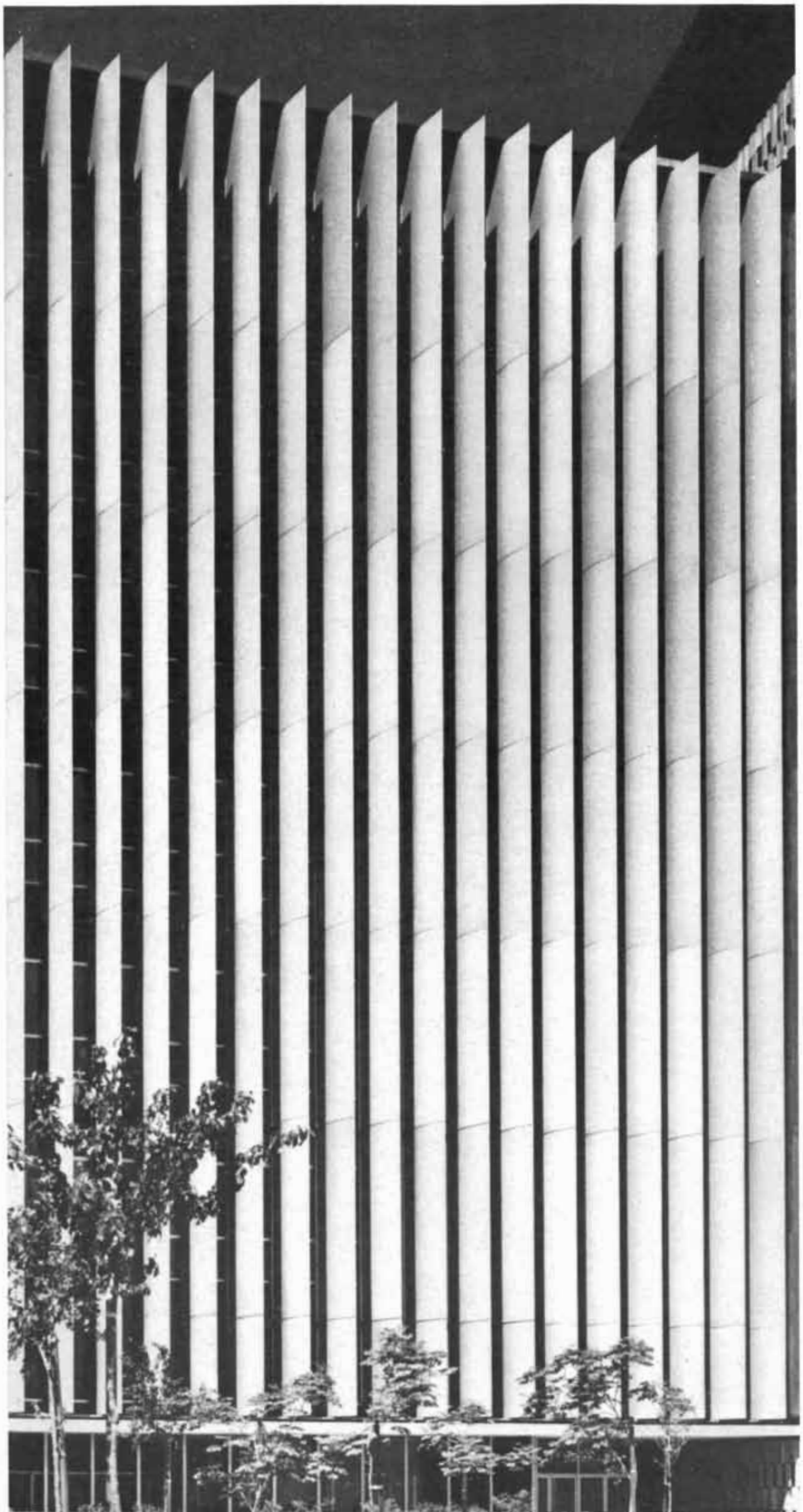
Both of these ideas, although still rather speculative, are actually extensions of a device that is already in fairly common use: namely, external sun shields consisting of large vanes that, like those of venetian blinds, can be changed in angle to keep out or let in sunlight as the sun shifts. With electronic controls these screens can rotate automatically in response to the sun's movement. They are particularly useful in warm, dry climates, where they are not subject to freezing or corrosion. Screens of this kind give far more satisfactory protection against the sun than the now common practice of building overhangs for windows, which often are more photogenic than useful because they do not allow sufficiently for variations in the angle of the sun.

Ralph Knowles of the University of Southern California has done some pioneering research on the surface responses of buildings to environmental forces—light, heat, gravity, air and sound. Using computerized techniques of analysis, he studied the surface response to light of structures in various shapes (cubic, tetrahedral, ellipsoidal and so on) and with various patterns of opaque walls. He concluded that rational parameters for the architectural control of sunlight effects and of other forces could be established. He is now studying the possibility of extending the same criteria to the modification of environmental forces not only for buildings but also for urban districts and even entire cities.

Knowles's approach is to use the structure itself as a means of manipulation and control of daylight. Since structural materials are necessarily opaque, the effectiveness of the system depends on the way the geometry of the wall itself intercepts direct light or admits indirect light. There are now, however, a wide variety of nonstructural surfacing materials of every degree of transparency that can be employed as filters. Even with ordinary plate glass one can obtain certain desired effects simply by adjusting the orientation or shape of the glass window. Curved glass that eliminates direct reflection of the bright outdoors can make a store window invisible for an observer looking in from the street; a glass wall angled from the vertical can likewise minimize disturbing reflections from indoor light sources and thus give a clear outward view, as in the famous Top of the Mark restaurant in San Francisco overlooking the city and the Golden Gate or the more mundane instance of airport control towers. Much more exciting, of course, are the effects now achievable with special glasses and other materials that filter, polarize, refract or focus light and thereby select the wavelengths of light to be admitted to the building or place the light where it is wanted.



GEOMETRY OF PROTECTION against unwanted solar radiation is studied by means of a model made at the Department of Architecture of Auburn University under the direction of Ralph Knowles. The design uses interlocking planes both to control the sunlight and to transfer building loads to the ground. J. H. R. Brady and D. L. Meador made the model.



CONTROL OF LIGHT AND HEAT is achieved at the Los Angeles Hall of Records by vertical louvers that resemble a venetian blind turned sideways. The angle at which the louvers are set is adjusted monthly to provide maximum shade throughout the year. Architects were Neutra and Alexander, Honnold and Rex, H. C. Light and James R. Friend.

The most familiar example—glass that is transparent to visible light but that blocks the infrared wavelengths—is now in wide use; in recent years it has been joined by new families of glasses and plastics that afford more subtle manipulations of sunlight.

One of the new glasses, coated with a thin film of metal on the inside face, acts as a one-way mirror, thus cloaking the interior of the building in privacy from outside observers in daytime while allowing the people inside to look out. (Actually on a bright day the exterior reflections on ordinary plate glass have much the same effect, making the interior almost as invisible to outsiders as if it were sheathed in polished granite.) The one-way mirror glass not only dispenses with the need for curtains or shades in daytime but also appears to be effective in blocking the entry of heat radiation.

A new type of glass now under development promises to introduce a novel mechanism for the management of sunlight. The glasses of this breed, called photochromic, are darkened by ultraviolet light, and oddly enough their reaction is reversible: as the ultraviolet intensity decreases, they recover their transparency proportionately. Hence the glass can maintain the intensity of the sunlight entering the building at a stable level. It should prove useful for classrooms, control towers, libraries and museums, where visual transparency is mandatory and a stable mix of natural and artificial light is desirable but difficult to maintain.

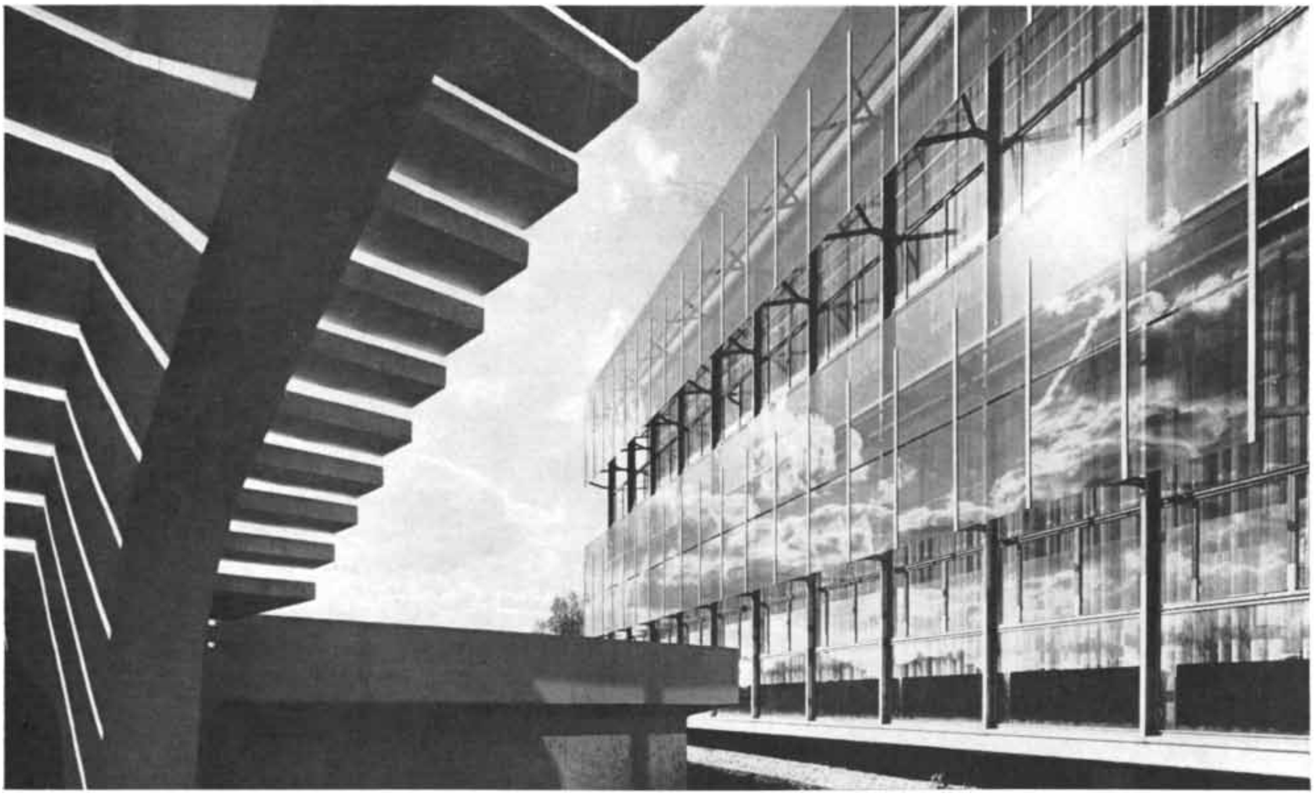
Another sophisticated innovation is embodied in a light-polarizing material formed by layers of plastics. It clarifies seeing and improves the efficiency of the use of light. Under ordinary illumination a surface is partly obscured by a "veil" of reflected light that tends to blur the colors and textures of the surface. Vertically plane-polarized light, which is absorbed by a surface and then reemitted, eliminates this veil and makes it possible to see the true qualities of the surface with greater ease and more accuracy. Polarized glass such as is used in sunglasses is not suitable, however, for purposes of illumination; it is effective only in certain directions, absorbs more than 50 percent of the light, is unpleasantly tinted and cannot be frosted to hide the light-bulb filament or soften the light. The new multilayer plastic polarizer avoids these shortcomings. The glare-reducing effect of this material on the illuminated surface varies, however, with the angle of vision from which it is viewed. Most desk work is done at angles between 0 and 40 degrees from the vertical, with the peak at 25 degrees, whereas the polarizer's most dramatic effects are from 40 degrees up, that is, in the field of middle vision. The plastic polarizer is not weatherproof and can only be used indoors, where it could serve well in ceiling fixtures and perhaps inside glass walls and skylights for daylight illumination of galleries and museums.

Another broadly applicable material for the manipulation of daylight is the so-called prismatic glass. Available in both sheet and block, it can deliver the incident daylight to any desired area of a room. It can be particularly useful for work that must be done under glareless light, such as matching colors, for illuminating paintings and for dramatic effects such as focusing a narrow beam of sunlight on an object—the "finger of God" effect that was cultivated by the baroque architects.

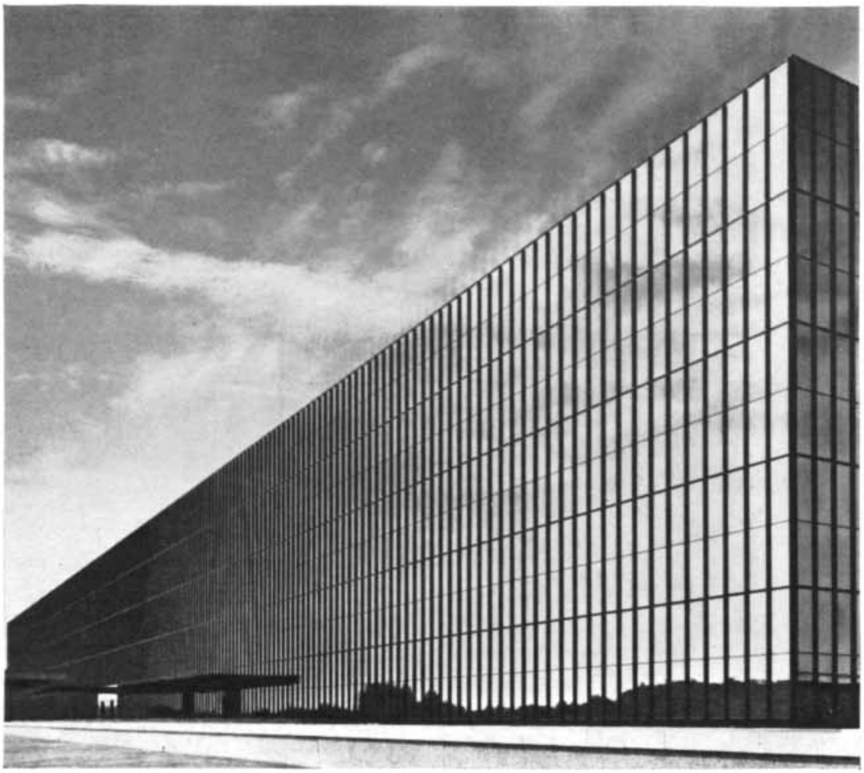
The sophisticated exploitation of sunlight is now more than matched by the ingenious exploitation of the possibilities of artificial illumination. Electricity, which in this century has supplanted all other sources of artificial lighting, has endowed us with an almost incredibly varied range of illumination devices. Lamps, fixtures, accessories, controls and methods of disseminating light are available in great variety, and their permutations and combinations run into the thousands. The list of ways that have been found to generate light by electricity is itself a long one.

The first electric-lighting device was the arc lamp, which jumps a bridge of luminous current across the gap between two electrodes. Much too hot and inflexible to be used in interior lighting, it is employed principally for motion-picture and television photography, for illumination of parking lots and playing fields and in large searchlights. The second-oldest electric lamp is the incandescent filament (now made of tungsten) enclosed in a sealed glass bulb. It is inefficient: only 10 percent of its energy output is in the form of light (the rest being lost as heat) and an additional proportion of the light will be absorbed by any colored bulb or filter that is used to modify its yellow-white color. The incandescent lamp is so flexible and convenient, however, and is available in such a wide range of sizes, shapes and capacities that it is still by far the most popular type for general lighting, and its efficiency has been improved nearly tenfold in recent decades.

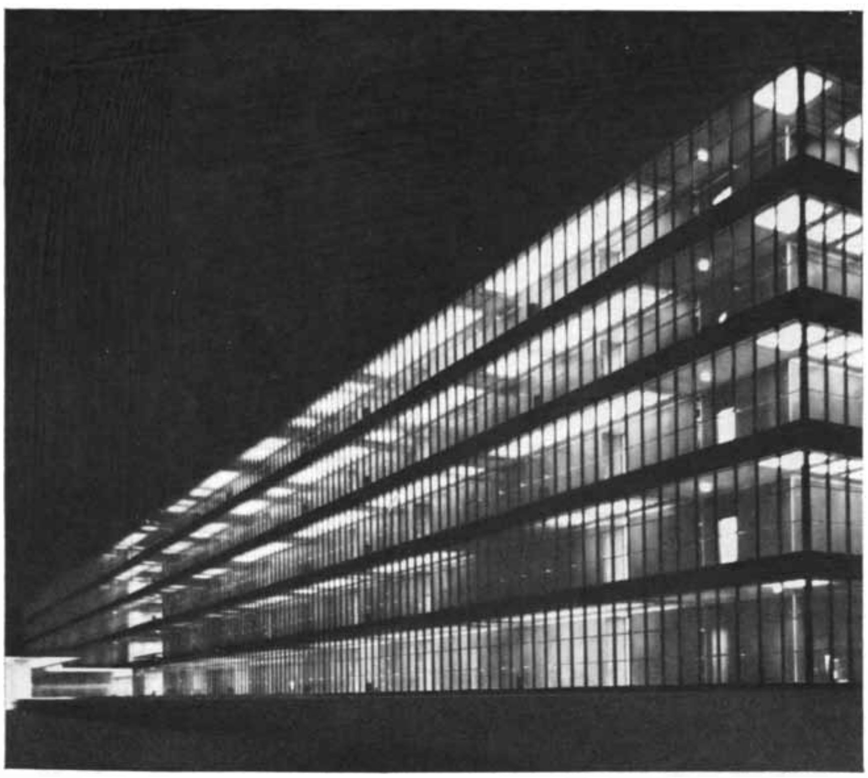
Artificial lighting is now largely dominated by the new and growing family of lamps based on the electrical excitation of luminous vapors, which already predominate in the fields of commercial, industrial and outdoor illumination. Sodium-vapor lamps, yielding an efficient output of 45 to 55 lumens of light per watt of power, have come into common use for the lighting of highways and bridges. Neon lamps in various colors, used mainly for signs, have become a ubiquitous—too ubiquitous—feature of the nighttime landscape. The most efficient of the vapor lamps are those employing mercury vapor; some produce more than 100 lumens per watt of power. Excited mercury atoms emit light at the blue-green end of the visible spectrum and into the near ultraviolet. Hence mercury-vapor lamps can be designed to serve as sunlamps, as light sources of high intensity or as fluorescent lamps, in which the ultraviolet emission from the mercury atoms is used to generate visible light from fluorescent material coated on the inside of a glass tube. The comparative coolness of a fluorescent lamp arises from the fact that mercury emits almost no energy at the red end of the spectrum and fluorescent emission itself possesses very little



SHADE WITHOUT SHADOW is obtained in the interior of the Van Leer Building in Amstelveen in the Netherlands by suspending horizontal panels of light- and heat-resistant glass at a distance from the southern wall of the building. Convection currents rise between the panels and the wall and help to dissipate the solar heat accumulation. The architects were Marcel Breuer and Associates.



OPAQUE IN DAYLIGHT, the glass walls of the Bell Telephone Laboratories building at Holmdel, N.J., are mirrors to an observer standing outside the building. The building's occupants, however, have a clear, shaded view of the exterior. A thin metallic film deposited on one surface of the glass acts as a mirror on the side that is most strongly illuminated.



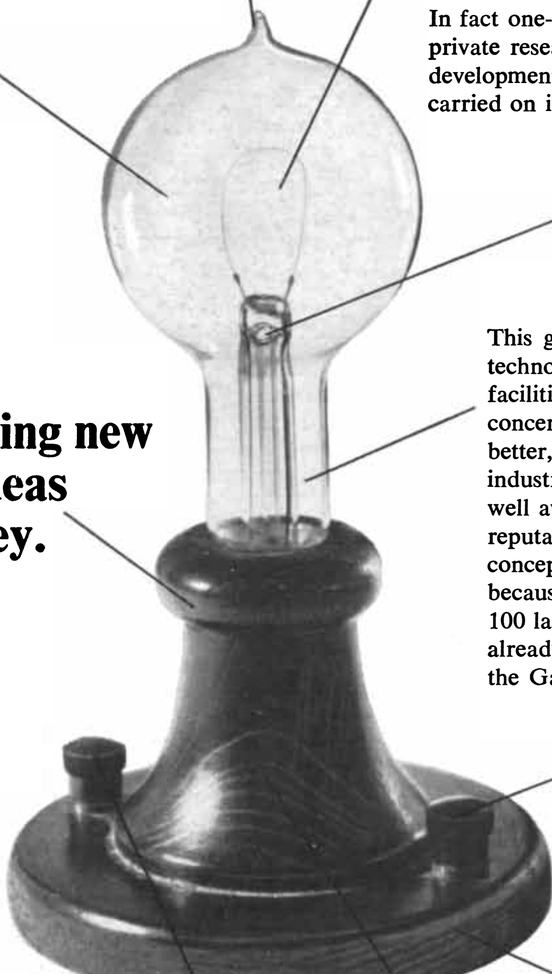
TRANSPARENT BY NIGHT, the Holmdel building emits a glow of light once the level of exterior illumination falls below that of the interior. The interior walls are now mirrors to the occupants. The glass rejects nearly 80 percent of the solar heat load. It is made by the Kinney Division of the New York Air Brake Co. Architects were Eero Saarinen and Associates.

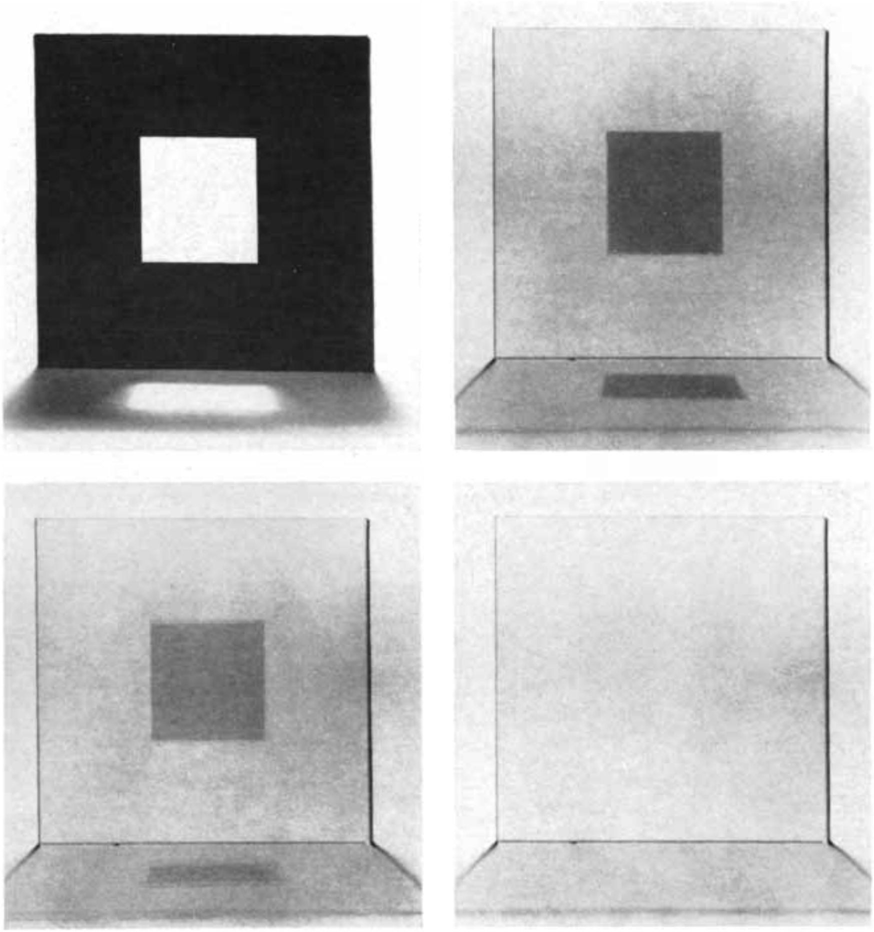
heat. A fluorescent tube is only about a fourth or a fifth as hot as the ordinary filament lamp. Moreover, it produces from 25 to 75 lumens per watt, depending on the color, and it makes available a wide range of color in lighting, including a close approximation of the daylight spectrum. The linear shape of a fluorescent tube does not necessarily limit it to linear applications. The tube itself can be bent into circular, square or spiral forms; it can be installed in parallel rows, in conjunction with appropriate reflectors and diffusers, and it can be made into a planar light source ("luminous ceiling").

Given the present variety of sources and of accessory means of disseminating artificial light, one has indeed a great range of flexibility for adapting its application to particular needs and situations. The problem of specifying and evaluating the requirements in given cases is of course highly complicated; every lighting problem involves a number of factors, subjective as well as objective. There are, however, a few helpful principles that seem well established.

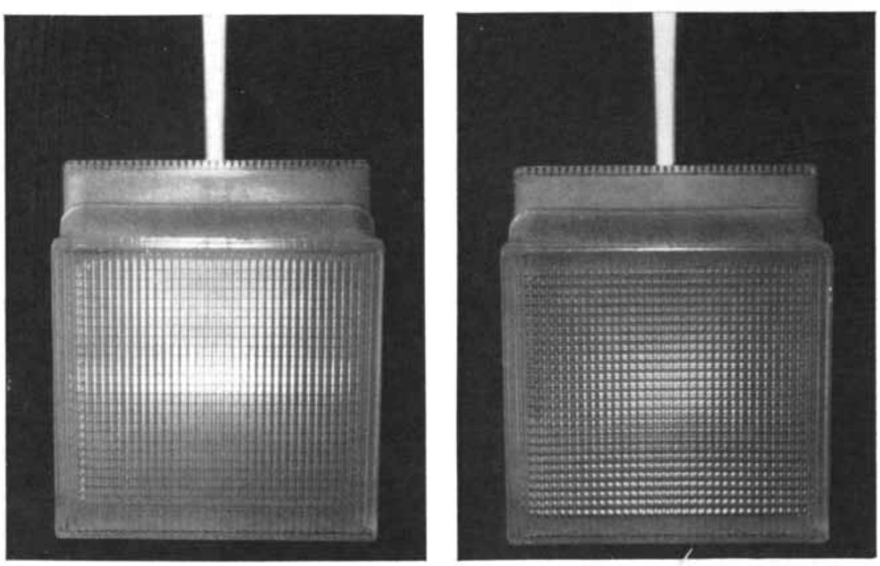
The first is that, as I have already mentioned, good seeing demands a high level of illumination. Within broad limits, the more light there is on the visual task, the easier vision becomes and the less stressful the task is on the organism as a whole. The second "law" of good lighting is that all areas of the room should be balanced in brightness, with no great contrasts between adjacent surfaces. The visual field surrounding the task should be at least a third as bright as the task itself and no part of it should be much brighter than the task. The third principle is that it is important to avoid glare, either from the light source or by reflection.

The optimal levels of illumination for specific visual tasks have not by any means been finally established; the recommended levels have steadily been raised over the past half-century and may well go higher still. Tasks that were once performed at only 10 to 15 foot-candles are now believed to call for 100 to 200 foot-candles. For certain fine seeing tasks, such as microsurgery and autopsy, illumination as high as 2,500 foot-candles is recommended. Incidentally, as illumination levels rise, the generated heat becomes more and more of a problem. In a space under 100 foot-candles of illumination the heat from the lamps may account for 37 percent of the load on the air-conditioning system in summer, and at the level of 400 foot-candles





SELF-DARKENING GLASS contains microscopic crystals of silver halide that react to near-ultraviolet wavelengths by absorbing as much as 75 percent of visible light. A masked pane of the glass is exposed to sunlight (*top left*). Its unmasked central rectangle darkens immediately (*top right*). Screened from further exposure to ultraviolet, the darkened area begins to fade; in five minutes it transmits about half as much light as the unexposed area (*bottom left*). In half an hour the darkened area has vanished (*bottom right*). Known as photochromic glass, the light-responsive material is made by the Corning Glass Works.



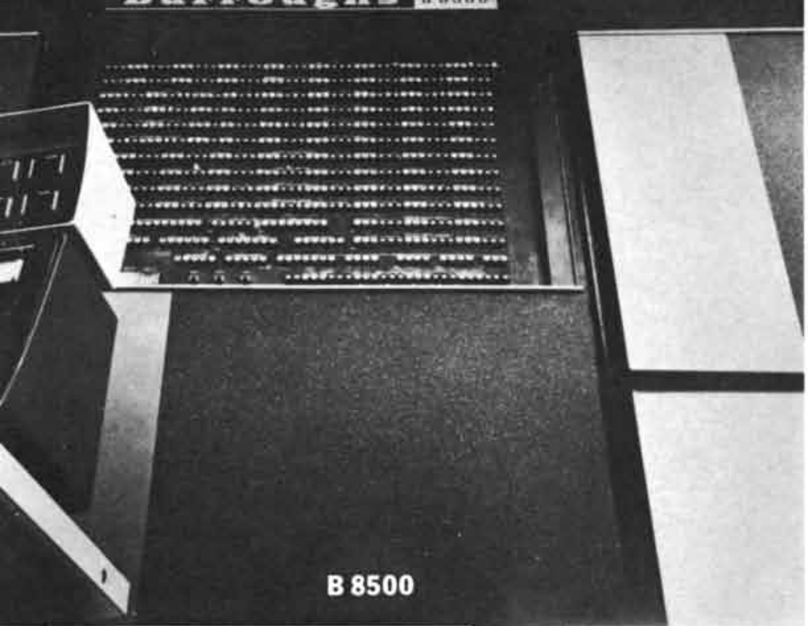
GLASS BRICK provides the architect with a translucent medium for bringing daylight indoors. At eye level or below, brick that acts as a general diffuser of daylight (*left*) is a practical wall material. Above eye level, prism-surfaced brick directs entering light up to ceilings to provide overall daylight (*right*). Bricks are made by the Pittsburgh Corning Corp.

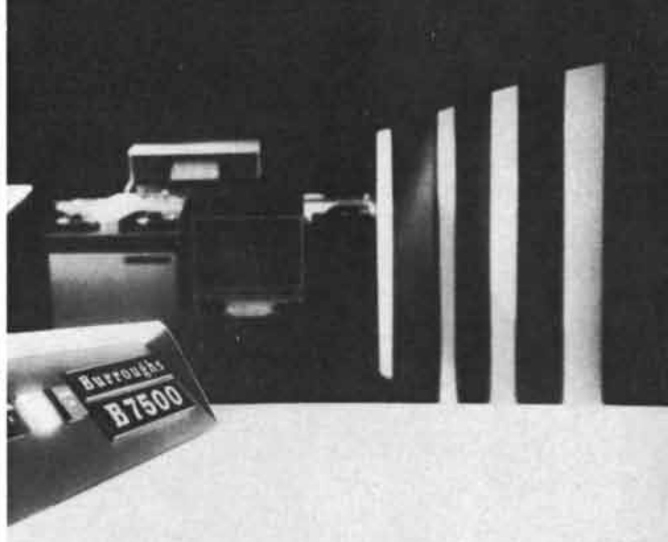
the contribution to the cooling load may rise to 70 percent. When waste heat reaches such proportions, it becomes a major factor in summer cooling. By the same token, it can be employed in winter heating, sometimes to the extent of becoming the entire source of heat. In these installations current practice is to siphon off this heat before it enters the conditioned space, either exhausting it in summer or feeding it back to the heating system in winter. Since such installations usually involve fluorescent tubing used in luminous ceilings, there is less waste heat and less of it is radiant. As much as 76 percent can be siphoned off directly into the return air system.

For many lighting problems, particularly on the macroscale, there are no readily determinable criteria, nor have they been given much systematic study. The illumination of retail stores and showrooms, for example, involves subtleties in dramatizing the qualities of the merchandise. (Obviously jewelry and automobiles need point sources for shine and glitter; furs and velvets show up best under floodlighting at acute angles.) Restaurants, bars and cafés have their own special lighting needs; so do art galleries and museums, theaters and churches, exposition buildings and pleasure gardens. Whether or not the purely intuitive approach in creating "effects" in these situations produces truly effective results is a moot question. The vogue of "mood" lighting in restaurants and cafés, where current taste seems to dictate that the illumination level be low and the color pink, has the unfortunate effect of making one's companions only dimly visible and laying an unappetizing patina on food and complexions.

Just as a blind architect would be a contradiction in terms, so too would be a completely lightless room (tombs and photographic darkrooms would be among the few exceptions). All designed spaces are conceived in visual terms. Many of the architect's decisions as to interior proportions, colors and textures actually deal with matters of surface response to light. They are all made with an eye to "how it all will look." Such a conceptual approach assumes that a stable luminous state is desirable, that the room will "read" the same way day and night, winter and summer.

In any windowless enclosure this is a simple matter, but in any room where glass plays an important role the situation is entirely altered. Such transparent membranes are conceived as (1) being a source of light and (2) affording visual access to an illuminated outdoors. With


B 8500

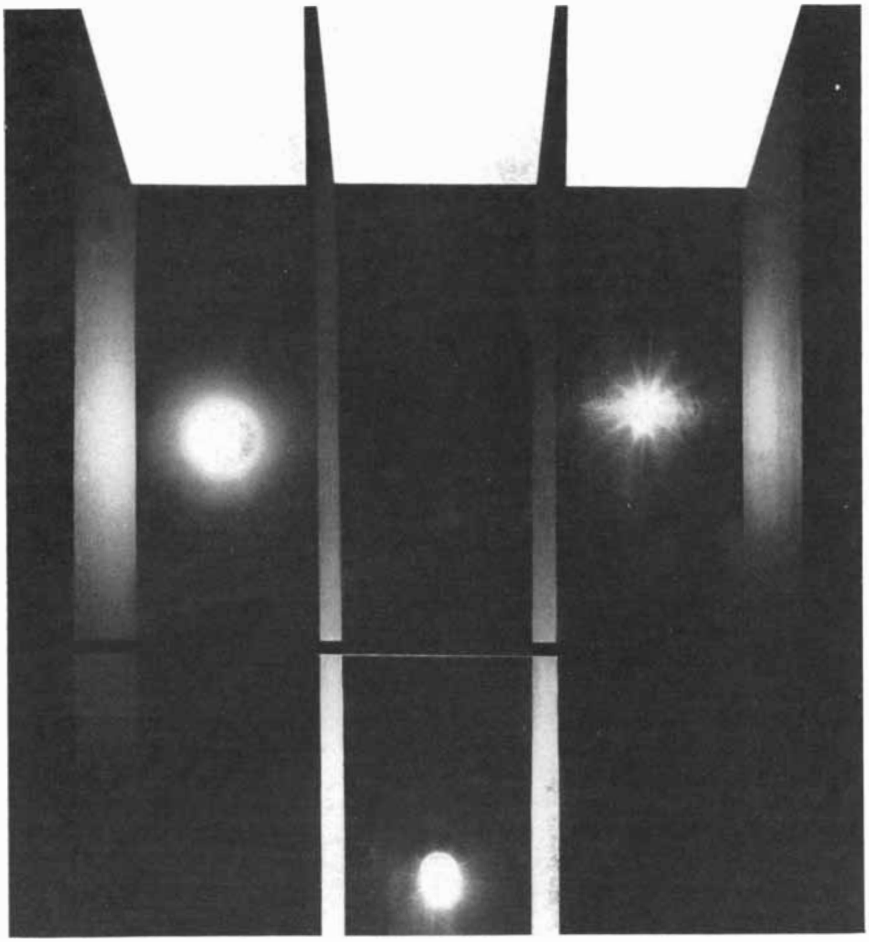


B 6500/7500 series

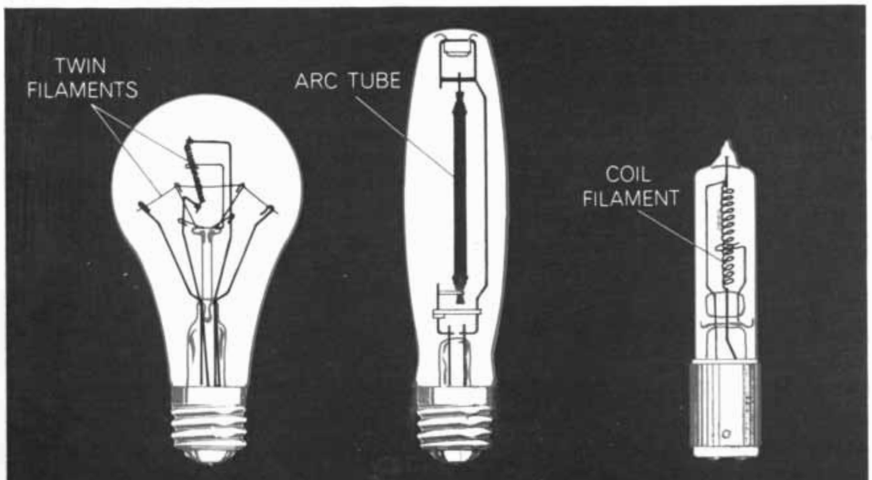

B 5500

B 500

B 2500/3500 series



IMPROVEMENTS in new kinds of lamps include an increase in light emission per watt input and longer life. Two new lamps are compared here with the familiar incandescent household lamp (*left*). All three are drawing approximately 250 watts; distance of each lamp from the equally illuminated targets indicates its light output. This is 16.5 lumens per watt for the incandescent lamp, more than 80 for the sodium-vapor lamp (*center*) and 17.5 for the tungsten halide lamp (*right*). The tungsten halide lamp has a 2,000-hour life expectancy.



ANATOMY OF ADVANCED LAMPS is compared with that of a two-filament, three-way incandescent lamp (*left*). In the high-intensity sodium-vapor lamp (*center*) the vapor is contained in a translucent ceramic tube sturdy enough to allow operation at a temperature and pressure that spread the sodium-emission wavelengths over most of the visible spectrum. The filament of the tungsten halide lamp (*right*) is sealed in a quartz tube containing iodine gas; evaporating tungsten reacts with the gas and is redeposited on the filament, thereby increasing its life. The lamps are the ones shown in the photograph at top of page.

nightfall, however, both of these conditions change. Surfaces that were a source of light become open sluices for its escape, and the lighted outdoors is replaced by a dimly mirrored image of the room. Traditional architecture had no real difficulty with this paradox. Although natural lighting was very important, the high cost of glass and of heating tended to keep windows small or few. And since the windows were always covered at night with curtains or blinds whose reflectance value approached that of the walls, they did not seriously affect the luminous response of the walls.

In modern architecture, with its wide use of glass walls and wide misconceptions of their optical behavior, the problem of nocturnal disequilibrium reaches serious dimensions. In such cases the interior can only be restored to its daytime shape by one of two measures: (1) by covering the glass with a reflective membrane (shade, shutter or blind) and (2) by raising the illumination level outside the glass to that of the room itself. Both measures are technically quite feasible, although for obvious reasons the first is likely to be the simplest and least costly.

The uninhibited excursions in lighting at recent international expositions have demonstrated the great variety and brilliance of lighting effects that are now available through the use of color, both luminous and pigmental. There is a large and growing literature on the alleged subjective reactions to color. We are told that red is exciting, purple is stately or mournful, yellow is joyful, green is calming, and so forth. There are even reports on experiments in the therapeutic use of color for treatment of the mentally ill. The University of California at Los Angeles psychologist Robert M. Gerard, working with normal adults, has found that as a general rule people do indeed show differential responses to different colors. Red light apparently brings about a rise in blood pressure, respiration rate and frequency of blinking; blue light, on the other hand, depresses activity. He concludes that the entire organism is affected by color, that different colors evoke different emotions and degrees of activity and that activity rises with increases in the wavelength and the intensity of the light.

Nighttime illumination of the outdoors by artificial light is another factor with a profound potential for affecting human life and activity. It is hard for us to imagine how great a transformation of living was introduced by this development. In preindustrial times nightfall

brought general movement and activity almost to a complete halt. For understandable reasons about the first application of gas and electrical illumination was for streetlights. The illumination of the urban environment at night doubled the daily period of mobility and activity for city dwellers. Moreover, it added a totally new aspect to the urban landscape.

Outdoor lighting has been carried further in the U.S. than anywhere else in the world; if not the best lighted, American cities are the *most* lighted on earth. Seen from the air on a clear night, with their structure vividly diagrammed by millions of lamps and illuminated signs, they are beautiful. Unfortunately at ground level the beauty and the clarity disappear. Grotesquely disparate in size and brightness, jostling one another in crowded profusion, garish and discordant in color, the lamps and signs are confusing to pedestrians, dangerously distracting to motorists and annoying to residents who must live in their nightly glare.

There are models showing how cities and their contents can be illuminated with highly aesthetic effects. The skillful lighting of the areas around Westminster Cathedral in London and the Louvre in Paris, of the Capitol in Washington and the Acropolis in Athens and of châteaus and gardens in France illustrates the possibilities in the urban use of illumination for spectacle. Most of these places are of course empty monuments. For inhabited areas of the city, designing systems of street and landscape lighting that will be functional but not disturbing to the residents is a more difficult and delicate matter. With skill and imagination, however, it should be possible to illuminate buildings, neighborhoods and the entire city in ways that will serve and satisfy everyone.

It is apparent that the nature of the luminous environment exerts profound physiological, psychological, social and economic effects on life in our urban culture. So far neither the effects nor the possible means of ameliorating them have been adequately analyzed. Obviously the establishment of a harmonious relation between man and his new environment of artificial illumination calls for cooperative studies by physical and biological scientists, engineers and architects.

NIGHT LIGHTING of New York's George Washington Bridge shows contrast between the illumination from mercury and sodium high-intensity lamps. When the photograph was made, lamp standards over outbound lanes (*left*) contained 400-watt mercury-vapor lamps and those over inbound lanes (*right*) 400-watt sodium-vapor lamps. The illumination of the inbound lanes is two to three times brighter than the illumination of the outbound lanes.

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The Processes of Vision

Light enables us to see, but optical images on the retina are only the starting point of the complex activities of visual perception and visual memory

by Ulric Neisser

It was Johannes Kepler who first compared the eye to a "camera" (a darkened chamber) with an image in focus on its rear surface. "Vision is brought about by pictures of the thing seen being formed on the white concave surface of the retina," he wrote in 1604. A generation later René Descartes tried to clinch this argument by direct observation. In a hole in a window shutter he set the eye of an ox, just in the position it would have had if the ox had been peering out. Looking at the back of the eye (which he had scraped to make it transparent), he could see a small inverted image of the scene outside the window.

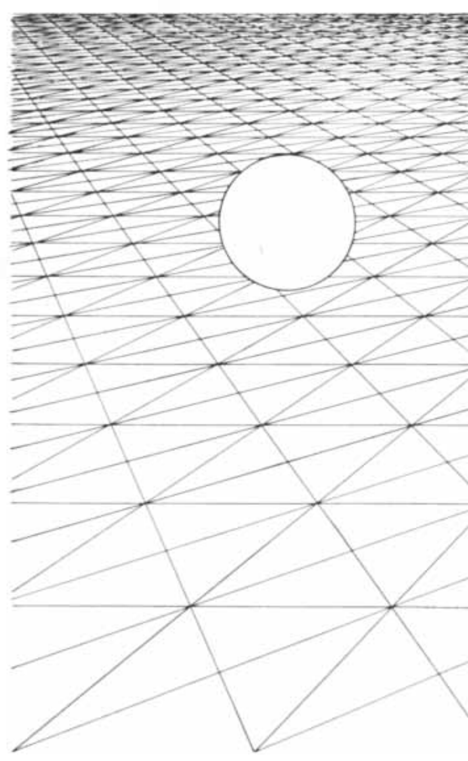
Since the 17th century the analogy between eye and camera has been elaborated in numerous textbooks. As an account of functional anatomy the analogy is not bad, but it carries some unfortunate implications for the study of vision. It suggests all too readily that the perceiver is in the position of Descartes and is in effect looking through the back of his own retina at the pictures that appear there. We use the same word—"image"—for both the optical pattern thrown on the retina by an object and the mental experience of seeing the object. It has been all too easy to treat this inner image as a copy of the outer one, to think of perceptual experiences as images formed by the nervous system acting as an optical instrument of extraordinarily ingenious design. Although this theory encounters insurmountable difficulties as soon as it is seriously considered, it has dominated philosophy and psychology for many years.

Not only perception but also memory has often been explained in terms of an image theory. Having looked at the retinal picture, the perceiver supposedly files it away somehow, as one might put a photograph in an album. Later, if he is lucky, he can take it out again in the form of a "memory image" and look at it a second time. The widespread notion that some people have a "photographic memory" reflects this analogy in a particularly literal way, but in a weaker form it is usually applied even to ordinary remembering. The analogy suggests that the mechanism of visual memory is a natural extension of the mechanisms of vision. Although there is some truth to this proposition, as we shall see below, it is not because both perception and memory are copying processes. Rather it is because *neither* perception *nor* memory is a copying process.

The fact is that one does not see the retinal image; one sees with the aid of the retinal image. The incoming pattern of light provides information that the nervous system is well adapted to pick up. This information is used by the perceiver to guide his movements, to anticipate events and to construct the internal representations of objects and of space called "conscious experience." These internal representations are not, however, at all like the corresponding optical images on the back of the eye. The retinal images of specific objects are at the mercy of every irrelevant change of position; their size, shape and location are hardly constant for a moment. Nevertheless, perception is usually accurate: real objects appear rigid and stable and appropriately located in three-dimensional space.

The first problem in the study of visual perception is therefore the discovery of the stimulus. What properties of the incoming optic array are informative for vision? In the entire distribution of light, over the retina and over a period of time, what determines the way things look? (Actually the light is distributed over two retinas, but the binocularity of vision has no relevance to the variables considered here. Although depth perception is more accurate with two eyes than with one, it is not fundamentally different. The world looks much the same with one eye closed as it does with both open; congenitally monocular people have more or less the same visual experiences as the rest of us.)

As a first step we can consider the patterns of reflected light that are formed when real objects and surfaces are illuminated in the ordinary way by



PERCEPTION OF SIZE relies heavily on cues provided by a textured surface. These five disks, if seen alone, would appear to lie

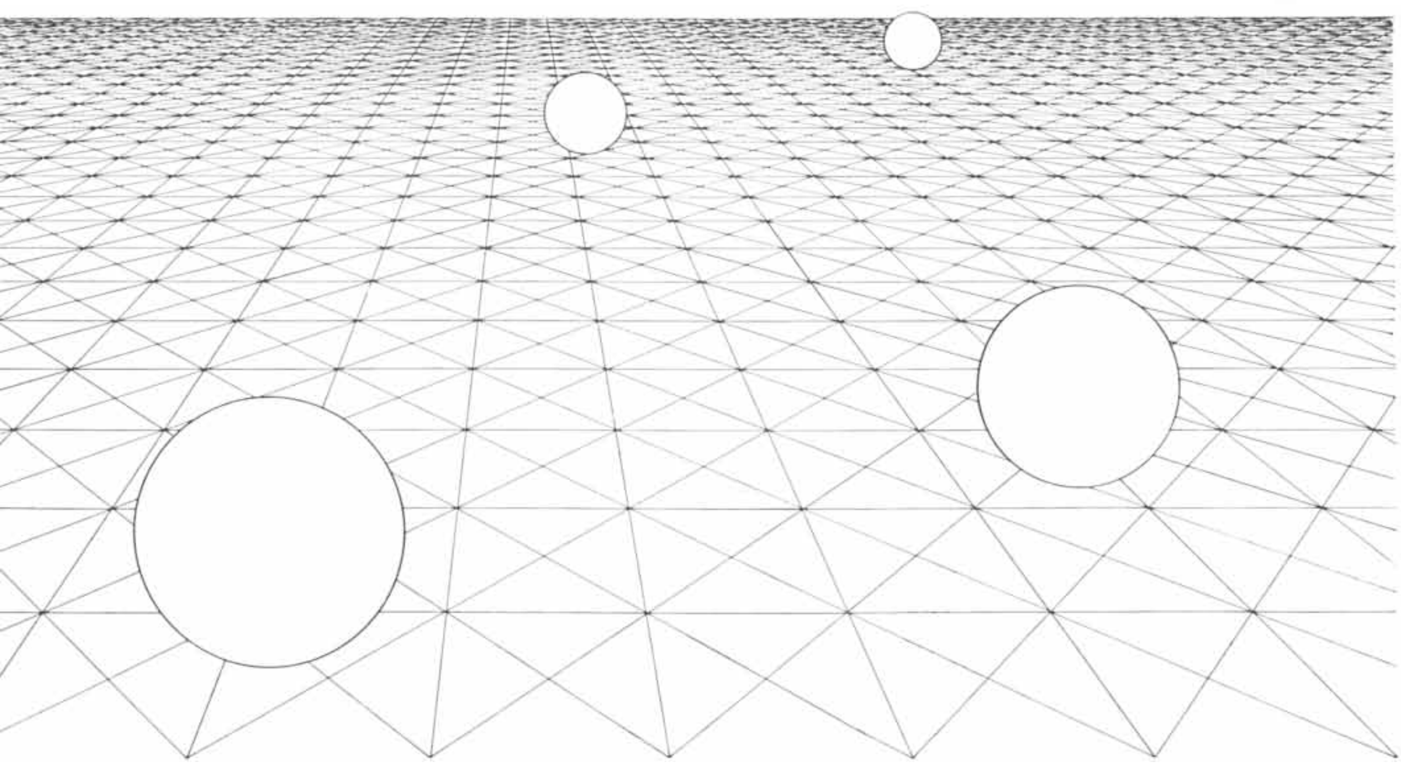
sunshine or lamplight. J. J. Gibson of Cornell University, who has contributed much to our understanding of perception, calls this inquiry "ecological optics." It is an optics in which point sources, homogeneous fields and the other basic elements of classical optics rarely appear. Instead the world we ordinarily look at consists mostly of *surfaces,* at various angles and in various relations to one another. This has significant consequences for the visual input.

One of these consequences (the only one we shall examine here) is to give the visual field a microstructure. Most surfaces have some kind of texture, such as the grain in wood, the individual stalks of grass in a field or the weave in a fabric. These textures structure the light reaching the eye in a way that carries vital information about the layout of environmental objects. In accordance with the principles of perspective the texture elements of more distant surfaces are represented closer to one another on the retina than the elements of surfaces nearby. Thus the microstructure of a surface that slants away from the observer is represented on the retina as a gradient of density—a gradient that carries information about the orientation of the surface.

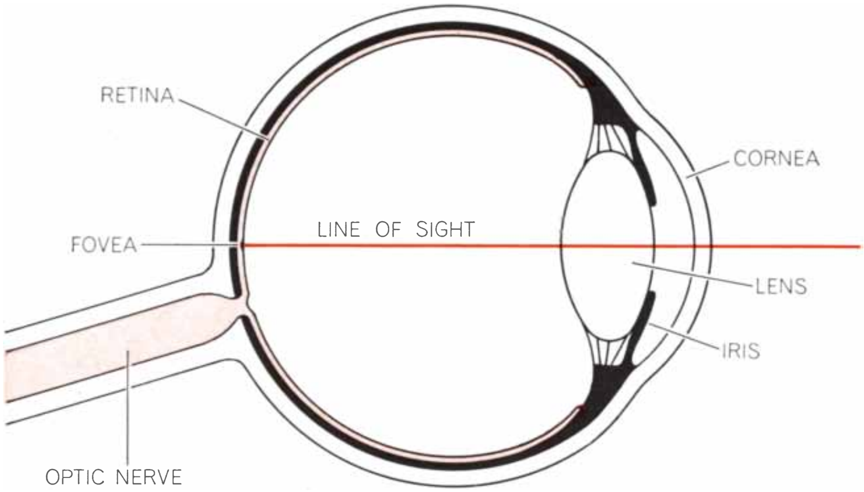
Consider now an ordinary scene in which discrete figures are superposed on textured surfaces. The gradient of increasing texture density on the retina, corresponding to increasing distance from the observer, gives a kind of "scale" for object sizes. In the ideal case when the texture units are identical, two figures of the same real size will always occlude the same number of texture units, regardless of how far away either one may be. That is, the relation between the retinal texture-size and the dimensions of the object's retinal image is invariant, in spite of changes of distance. This relation is a potentially valuable source of information about the real size of the object—more valuable than the retinal image of the object considered alone. That image, of course, changes in dimension whenever the distance between the object and the observer is altered.

Psychologists have long been interested in what is called "size constancy": the fact that the sizes of real objects are almost always perceived accurately in spite of the linear dependence of retinal-image size on distance. It must not be supposed that this phenomenon is fully explained by the scaling of size with respect to texture elements. There are a great many other sources of relevant information: binocular parallax, shifts of retinal position as the observer moves, relative position in the visual field, linear perspective and so on. It was once traditional to regard these sources of information as "cues" secondary to the size of the object's own retinal image. That is, they were thought to help the observer "correct" the size of the retinal image in the direction of accuracy. Perhaps this is not a bad description of Descartes's situation as he looked at the image on the back of the ox's eye: he may have tried to "correct" his perception of the size of the objects revealed to him on the ox's retina. Since one does not see one's own retina, however, nothing similar need be involved in normal perceiving. Instead the apparent size of an object is determined by information from the entire incoming light pattern, particularly by certain properties of the input that remain invariant with changes of the object's location.

The interrelation of textures, distances and relative retinal sizes is only one example of ecological optics. The example may be a misleadingly simple one, because it assumes a stationary eye, an eye fixed in space and stably oriented in a particular direction. This is by no means a characteristic of human vision. In normal use the eyes are rarely still for long. Apart from small tremors, their



in one plane and be of different sizes. Against this apparently receding surface, however, they seem to lie in five different planes. Since each disk masks the same amount of surface texture, there is a tendency to see them as being equal in size. This illustration, the one at the bottom of the next two pages and the one on page 208 are based on the work of J. J. Gibson of Cornell University.



SITE OF OPTICAL IMAGE is the retina, which contains the terminations of the optic nerve. In the tiny retinal depression known as the fovea the cone nerve endings are clustered. Their organization and dense packing make possible a high degree of visual acuity.

most common movement is the flick from one position to another called a "saccade." Saccades usually take less than a twentieth of a second, but they happen several times each second in reading and may be just as frequent when a picture or an actual scene is being inspected. This means that there is a new retinal image every few hundred milliseconds.

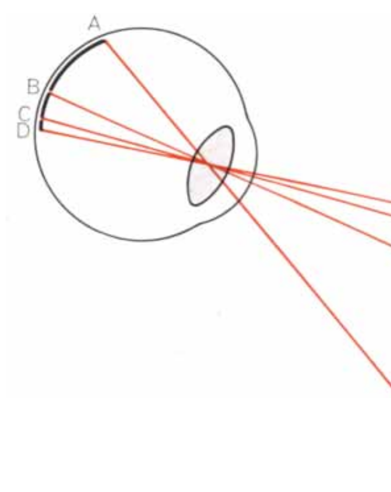
Such eye movements are necessary because the area of clear vision available to the stationary eye is severely limited. To see this for oneself it is only necessary to fixate on a point in some unfamiliar picture or on an unread printed page. Only a small region around the fixation point will be clear. Most of the page is seen peripherally, which means that it is hazily visible at best. Only in the fovea, the small central part of the retina, are the receptor cells packed close enough together (and appropriately organized) to make a high degree of visual acuity possible. This is the reason one must turn one's eyes (or head) to look directly at objects in which one is particularly interested. (Animals with nonfoveated eyes, such as the horse, do not find this necessary.) It is also the reason why the eye must make several fixations on each line in reading, and why it roves widely over pictures.

Although it is easy to understand the function of saccadic movements, it is difficult or impossible to reconcile them with an image theory of perception. As long as we think of the perceiver as a homunculus looking at his retinal image, we must expect his experience to be one of almost constant interruption and change. Clearly this is not the case; one sees the page or the scene as a whole without any apparent discontinuity in space or time. Most people are either unaware of their own eye movements or have erroneous notions about them. Far from being a copy of the retinal display, the visual world is somehow *constructed* on the basis of information taken in during many different fixations.

The same conclusion follows, perhaps even more compellingly, if we consider the motions of external objects rather than the motions of the eyes. If the analogy between eye and camera were valid, the thing one looked at would have to hold still like a photographer's model in order to be seen clearly. The opposite is true: far from obscuring the shapes and spatial relations of things, movement generally clarifies them. Consider the visual problem presented by a distant arrow-shaped weather vane. As long as the weather vane and the observer remain motionless, there is no way to tell whether it is a short arrow oriented at right angles to the line of sight or a longer arrow slanting toward (or away from) the observer. Let it begin to turn in the wind, however, and its true shape and orientation will become visible immediately. The reason lies in the systematic distortions of the retinal image produced by the object's rotation. Such distortions provide information that the nervous system can use. On the basis of a fluidly changing retinal pattern the perceiver comes to experience a rigid object. (An interesting aspect of this example is that the input information is ambiguous. The same retinal changes could be produced by either a clockwise or a counterclockwise rotation of the weather vane. As a result the perceiver may alternate, between two perceptual experiences, one of which is illusory.)

Some years ago Hans Wallach and D. N. O'Connell of Swarthmore College showed that such motion-produced changes in the input are indeed used as a source of information in perceiving; in fact this kind of information seems to be a more potent determiner of what we see than the traditionally emphasized cues for depth are. In their experiment the subject watched the shadow of a wire form cast on a translucent screen. He could not see the object itself. So long as the object remained stationary the subject saw only a two-dimensional shadow on a two-dimensional screen, as might be expected. The form was mounted in such a way, however, that it could be swiveled back and forth by a small electric motor. When the motor was turned on, the true three-dimensional shape of the form appeared at once, even though the only stimulation reaching the subject's eyes came from a distorting shadow on a flat screen. Here the kinetic depth effect, as it has been called, overrode binocular stereoscopic information that continued to indicate that all the movement was taking place in a flat plane.

In the kinetic depth effect the constructive nature of perception is particularly apparent. What one sees is somehow a composite based on information accumulated over a period of time. The same is true in reading or in any instance where eye movements are involved: information from past fixations is used together with information from the present fixation to determine what is seen. But if perception is a temporally extended act, some storage of information, some kind of memory, must be involved in it. How shall we conceive of this storage? How is it organized? How



CONTRACTION OF IMAGE takes place as the distance between the viewer and the

long does it last? What other functions might it serve?

With questions like these, we have moved beyond the problem of specifying the visual stimulus. In addition to identifying the sources of information for vision, we want to know how that information is processed. In the long run, perhaps, questions about processes should be answered in neurological terms. However, no such answers can be given at present. The neurophysiology of vision has recently made great strides, but it is still not ready to deal with the constructive processes that are central to perception. We shall have to be content with a relatively abstract account, one that does not specify the neural locus of the implicated mechanisms.

Although seeing requires storage of information, this memory cannot be thought of as a sequence of superposed retinal images. Superposition would give rise only to a sort of smear in which all detail is lost. Nor can we assume that the perceiver keeps careful track of his eye movements and thus is able to set each new retinal image in just the right place in relation to the older stored ones. Such an alignment would require a much finer monitoring of eye motion than is actually available. Moreover, the similar synthesis of information that is involved in the kinetic depth effect could not possibly be explained that way. It seems, therefore, that perceiving involves a memory that is not representational but schematic. During a series of fixations the perceiver synthesizes a model or schema of the scene before him, using information from each successive fixation to add detail or to extend the construction. This constructed whole is what guides his movements (including further eye movements in many cases) and it is what he describes when he is being introspective. In short, it is what he sees.

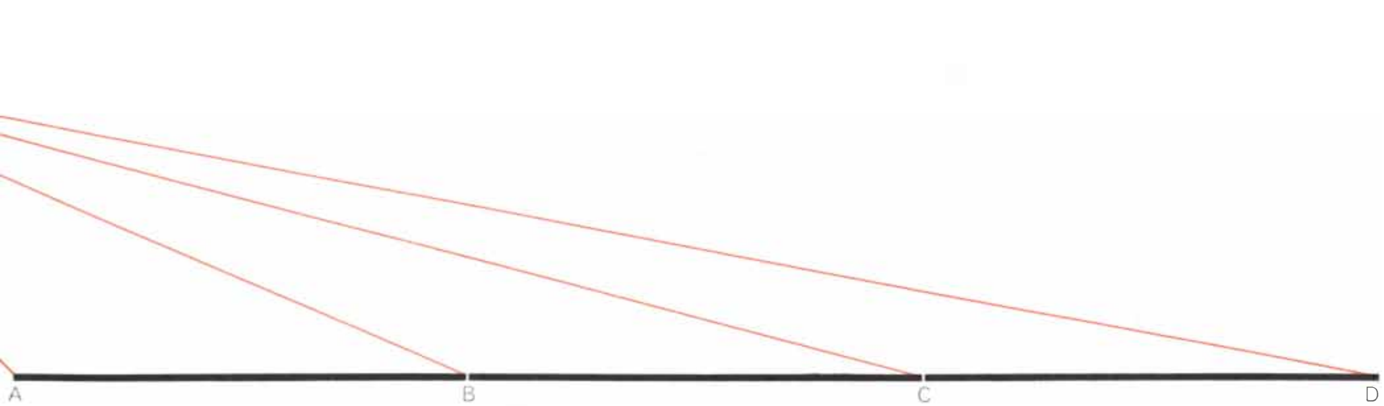
Interestingly enough, although the memory involved in visual synthesis cannot consist simply of stored retinal afterimages, recent experiments indicate that storage of this kind does exist under certain circumstances. After a momentary exposure (too short for eye movement) that is followed by a blank field the viewer preserves an iconic image of the input pattern for some fraction of a second. George Sperling of the Bell Telephone Laboratories has shown that a signal given during this postexposure period can serve to direct a viewer's attention to any arbitrary part of the field, just as if it were still present.

The displays used in Sperling's experiments consisted of several rows of letters—too many to be reported from a single glance. Nevertheless, subjects were able to report any *single row*, indicated by the postexposure signal, rather well. Such a signal must come quickly; letters to which the observer does not attend before the brief iconic memory has faded are lost. That is why the observer cannot report the entire display: the icon disappears before he can read it all.

Even under these unusual conditions, then, people display selectivity in their use of the information that reaches the eye. The selection is made from material presented in a single brief exposure, but only because the experimental arrangements precluded a second glance. Normally selection and construction take place over a series of glances; no iconic memory for individual "snapshots" can survive. Indeed, the presentation of a second stimulus figure shortly after the first in a brief-exposure experiment tends to destroy the iconic replica. The viewer may see a fusion of the two figures, only the second, or an apparent motion of the figures, depending on their temporal and spatial relations. He does not see them separately.

So far we have considered two kinds of short-term memory for visual information: the iconic replica of a brief and isolated stimulus, and the cumulative schema of the visible world that is constructed in the course of ordinary perception. Both of these processes (which may well be different manifestations of a single underlying mechanism) involve the storage of information over a period of time. Neither of them, however, is what the average man has in mind when he speaks of memory. Everyday experience testifies that visual information can be stored over long periods. Things seen yesterday can be recalled today; for that matter they may conceivably be recalled 20 years from now. Such recall may take many forms, but perhaps the most interesting is the phenomenon called visual imagery. In a certain sense one can see again what one has seen before. Are these mental images like optical ones? Are they revived copies of earlier stimulation? Indeed, does it make any sense at all to speak of "seeing" things that are not present? Can there be visual experience when there is no stimulation by light?

To deal with these problems effectively we must distinguish two issues: first, the degree to which the mechanisms involved in visual memory are like those involved in visual perception and, second, the degree to which the perceiver

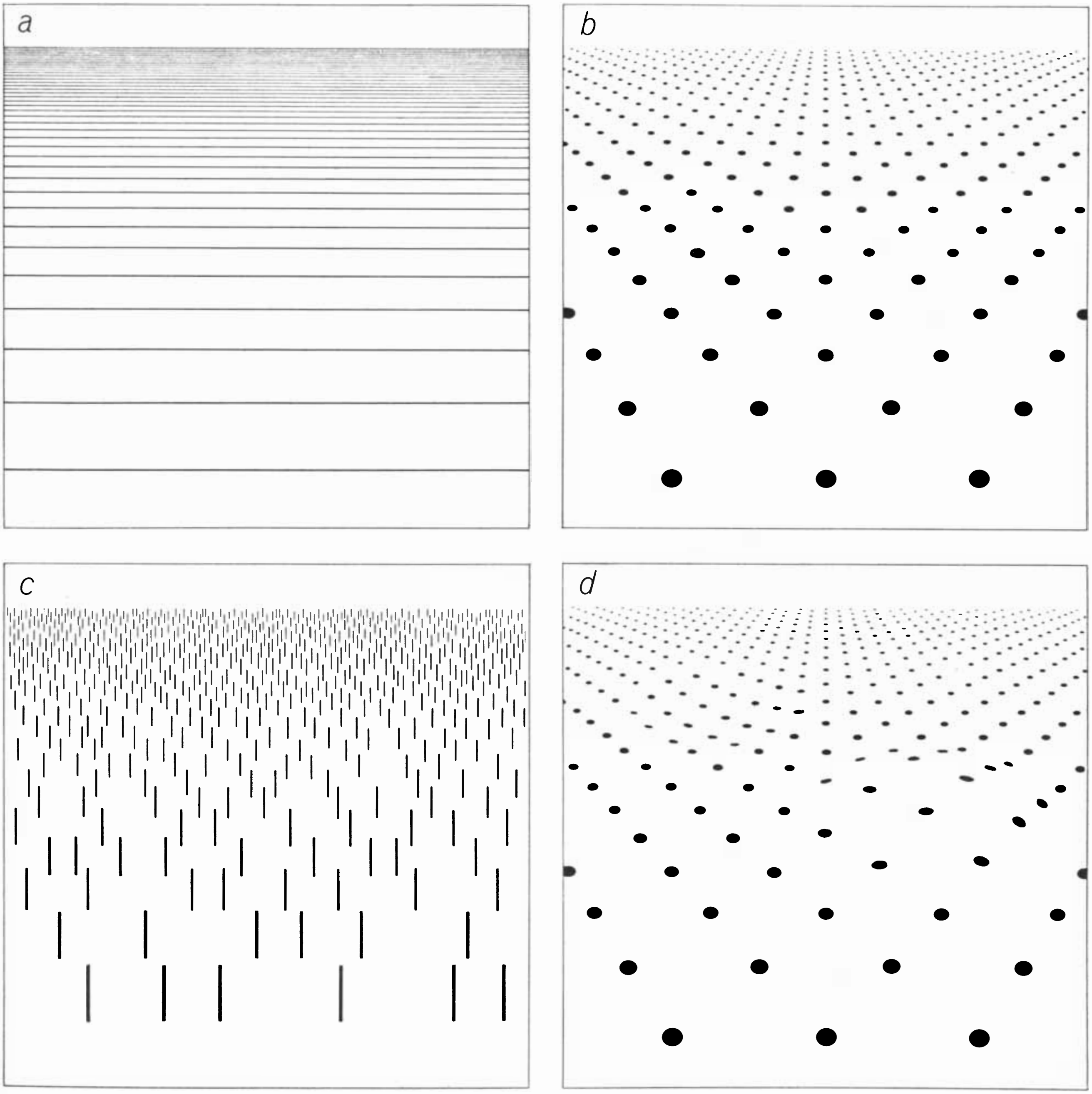


object in view increases. The texture elements of a distant surface are also projected closer together than similar elements nearby. Thus a textured surface slanting away from the viewer is represented optically as a density gradient (*see illustration on next page*).

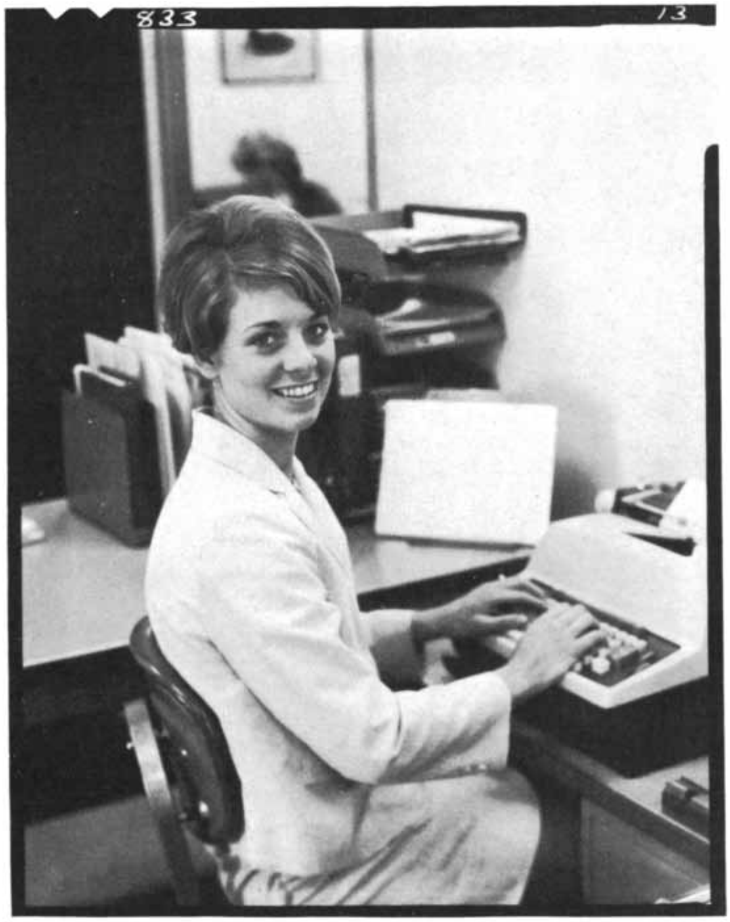
is willing to say his images look real, that is, like external things seen. Although the first issue is perhaps the more fundamental—and the most relevant here—the second has always attracted the most attention.

One reason for the perennial interest in the "realness" of images is the wide range of differences in imaging capacity from person to person and from time to time. When Francis Galton conducted the first empirical study of mental imagery (published in 1883), he found some of his associates skeptical of the very existence of imagery. They assumed that only poetic fancy allowed one to speak of "seeing" in connection with what one remembered; remembering consisted simply in a knowledge of facts. Other people, however, were quite ready to describe their mental imagery in terms normally applied to perception. Asked in the afternoon about their breakfast table, they said they could see it clearly, with colors bright (although perhaps a little dimmer than in the original experience) and objects suitably arranged.

These differences seem to matter less when one is asleep; many people who report little or no lifelike imagery while awake may have visual dreams and believe in the reality of what they see. On the other hand, some psychopathological states can endow images with such a compelling quality that they dominate the patient's experience. Students of per-



DENSITY GRADIENTS convey an impression of depth. Depending on the size, shape and spacing of its textural elements, the gradient may create the impression of a smooth flat surface (*a*, *b*), a rough flat surface (*c*) or a surface broken by an elevation and a depression (*d*). Like the gradients depicted, the textured surfaces of the visual world (by structuring the light that falls on the retina) convey information concerning the orientation of the surface. Textured surfaces also provide a scale for gauging the size of objects.



This picture was developed with heat. In a lighted room.

As a developer, heat has a lot to recommend it.

It's cheap.

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And it's fast. This picture was out of the finisher in one minute, fully developed.

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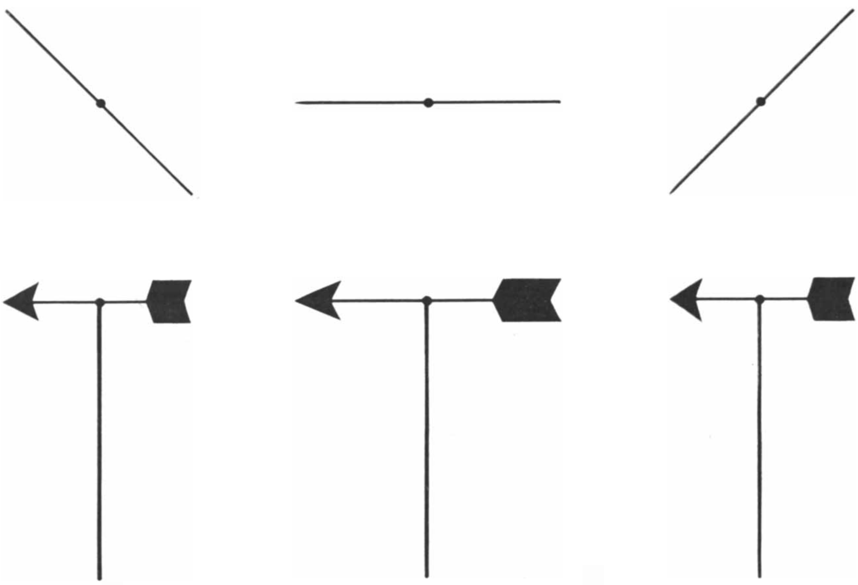
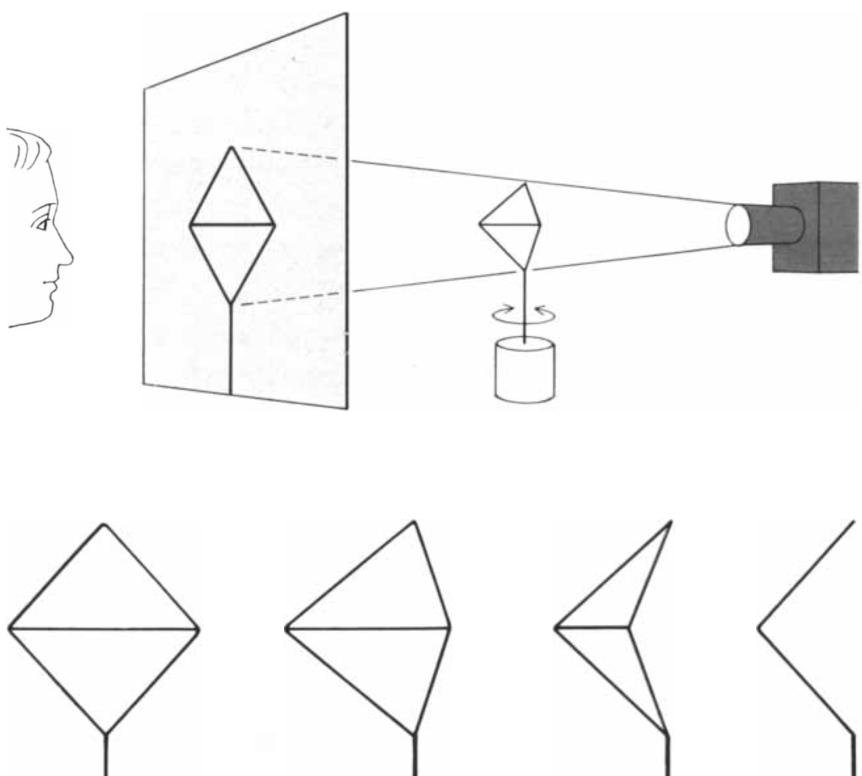


AMBIGUOUS VISUAL INPUT can arise from a stationary weather vane. The weather vane in three different orientations is shown as it would be seen from above (*top*) and in side view (*bottom*). If the vane begins to rotate, its real length will become apparent.



KINETIC DEPTH EFFECT shows how movement can endow perceived objects with three-dimensional shape. The shadow of a bent wire form (*shown at bottom in four different orientations*) looks as flat as the screen on which it is cast so long as the form remains stationary. When it is swiveled back and forth, the changing shadow is seen as a rigid rotating object with the appropriate three-dimensionality. The direction of rotation remains ambiguous, as in the case of the weather vane in the illustration at top of the page.

ception have often disregarded dreams and phantasms, considering them "hallucinatory" and thus irrelevant to normal seeing. However, this is a difficult position to defend either logically or empirically. Logically a sharp distinction between perception and hallucination would be easy enough if perceptions were copies of the retinal image; hallucinations would then be experiences that do *not* copy that image. But since perception does more than mirror the stimulus (and since hallucinations often incorporate stimulus information), this distinction is not clear-cut. Moreover, a number of recent findings seem to point up very specific relations between the processes of seeing and of imagining.

Perhaps the most unexpected of these findings has emerged from studies of sleep and dreams. The dreaming phase of sleep, which occurs several times each night, is regularly accompanied by bursts of rapid eye movements. In several studies William C. Dement and his collaborators have awakened experimental subjects immediately after a period of eye motion and asked them to report their just-preceding dream. Later the eye-movement records were compared with a transcript of the dream report to see if any relation between the two could be detected. Of course this was not possible in every case. (Indeed, we can be fairly sure that many of the eye movements of sleep have no visual significance; similar motions occur in the sleep of newborn babies, decorticated cats and congenitally blind adults.) Nevertheless, there was appreciably more correspondence between the two kinds of record than could be attributed to chance. The parallel between the eye movements of the dreamer and the content of the dream was sometimes striking. In one case five distinct upward deflections of the eyes were recorded just before the subject awoke and reported a dream of climbing five steps!

Another recent line of research has also implicated eye movements in the processes of visual memory. Ralph Norman Haber and his co-workers at Yale University reopened the study of eidetic imagery, which for a generation had remained untouched by psychological research. An eidetic image is an imaginative production that seems to be external to the viewer and to have a location in perceived space; it has a clarity comparable to that of genuinely perceived objects; it can be examined by the "*Eidetiker*," who may report details that he did not notice in the original presentation of the stimulus. Most *Eidetikers*

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ROAD TEST is a magazine that goes to extreme lengths to be objective. It does not accept any automotive advertising lest the accusing finger of bias should point. It uses a whole panel of specialists to test an automobile rather than relying on just one opinion.

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Its editors reason that one car taken from a total production of thousands is not necessarily representative of the breed. And, that the most demanding test cannot duplicate the experience of daily use over an extended period. So ROAD TEST hit on the idea of an Owners Survey. They asked their car-owning readers to complete an exhaustive questionnaire on the good and bad points of the cars they drive. The results are now in.

The most appreciated automobile.

Commenting on the first Owners Survey, ROAD TEST says this: "the weight of evidence is overwhelming. Reports have been received on no less than 63 different makes and models of cars, both domestic and imported. Even though Rover is not one of the top ten imports sold, more survey forms were completed on Rover than any import except Volkswagen. Of present Rover owners, 87.6% (the highest figure) state firmly that their next and only choice will again be Rover. On the scales of likes and dislikes the balance tilts so far in Rover's favor that there is material to fuel an adman's dreams for a lifetime. Also number one among non-owners but those considering imports is Rover."

They toot our horn.

That quote appears on page 18 of the May issue. From there on the magazine is totally devoted to analyzing, explaining, and extolling the virtues of the Rover 2000—including a history of how it got that way. We love and believe what they say and wish we could quote every word here.

For example, the article with the headline, "Rover Engineering—Why Can't Everybody Make a Car This Good?" Or the one titled, "From the Driver's Seat—Comfort and Convenience Beyond Expectations" or "The Mechanic Looks at Rover—Treated Right, It Should Last for Ever."

Alas, space if not modesty forbids. What we can do is something better—offer you your own copy of the magazine. Ask your Rover dealer, call the Rover zone office, or mail off the coupon. You choose.

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The best automobile advertisement ever written? Indeed! I'll be the judge of that.

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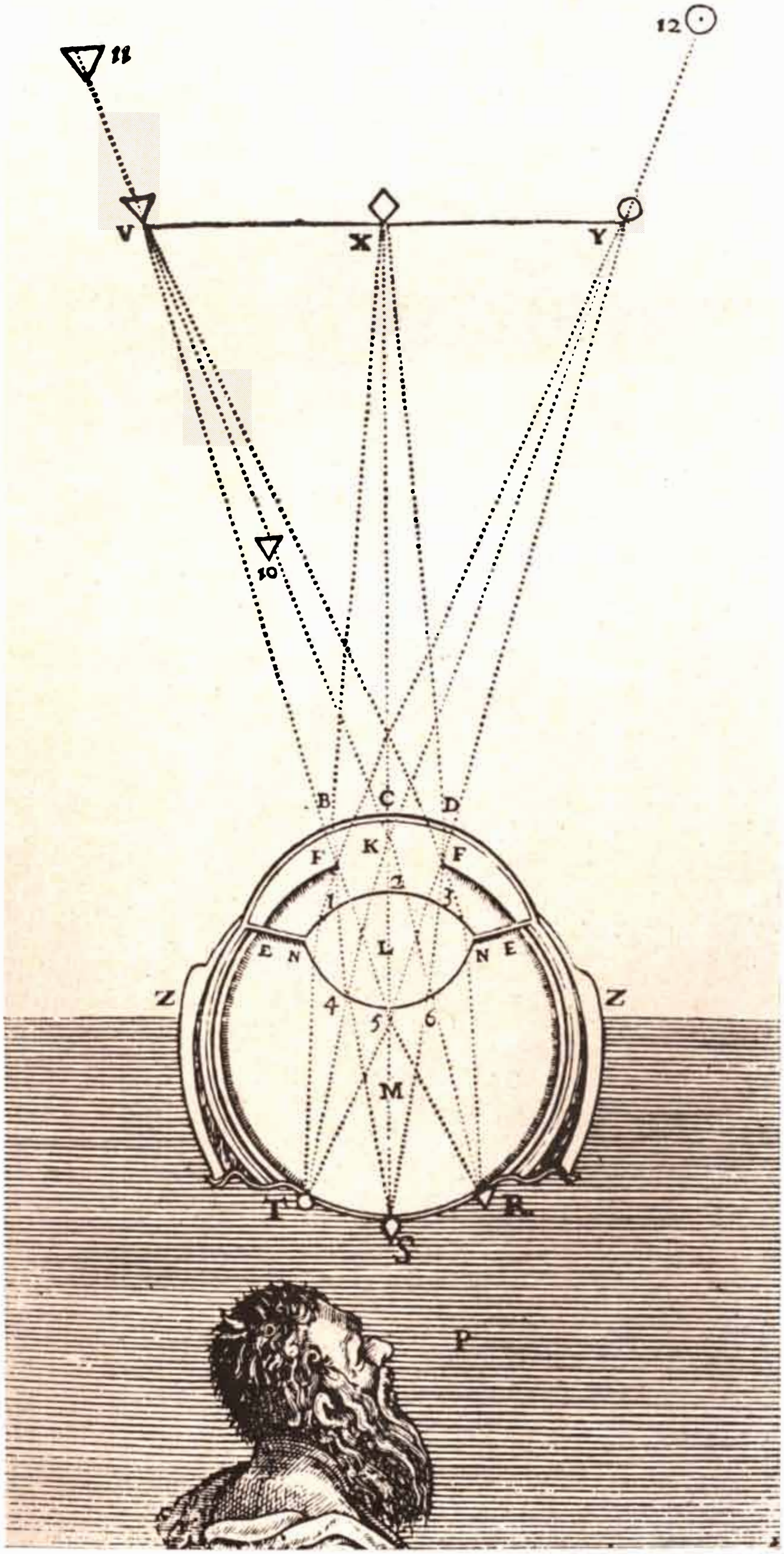


OPTICAL ANALYSIS BY DESCARTES included an experiment in which he removed the eye of an ox, scraped the back of the eye to make it transparent and observed on the retina the inverted image of a scene. The illustration is from Descartes's essay *La Dioptrique.*

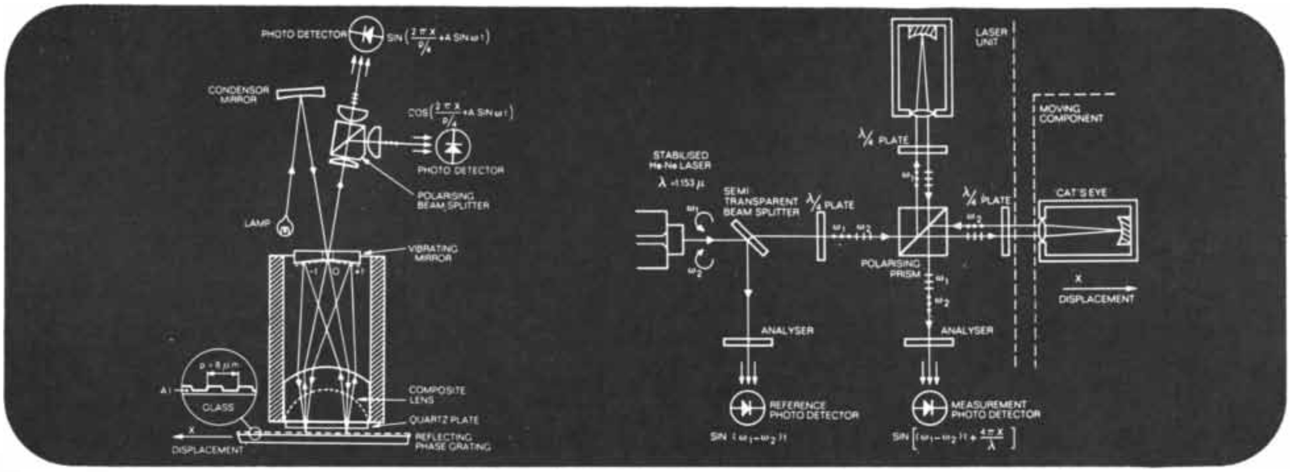
are children, but the developmental course of this rather rare ability is not well understood. What is most interesting about these images for the present argument is that the *Eidetiker* scans them with his eyes. Asked about a detail in one or another corner of the image, he moves his eyes to look at the appropriate part of the blank wall on which he has "projected" it. That is, he does just what anyone would do who was really looking at something.

Are these esoteric phenomena really relevant to the study of vision? It might be argued that they do not provide a safe basis for inference; dreaming is a very special physiological state and eidetic imagery is restricted to very special types of people. It is not difficult, however, to show that similar processes occur in persons who do not have vivid visual imagery at all. A simple demonstration suggested by Julian Hochberg of New York University helps to make this point: Try to remember how many windows there are in your own house or apartment.

If you have never considered this question before, it will be hard to find the answer without actively looking and counting. However, you will probably not need to look at the windows themselves. Most people, even those who say they have no visual imagery, can easily form and scan an *internal representation* of the walls, counting off the windows as they appear in them. This process evidently uses stored visual information. It seems to involve mechanisms much like those used for seeing and counting real windows.

We can draw three conclusions from this demonstration. First, seeing and imagining employ similar—perhaps the same—mechanisms. Second, images can be useful, even when they are not vivid or lifelike, even for people who do not have "good imagery." Third, mental images are constructs and not copies. This last point may have been obvious in any case—you might just as well have been asked to imagine a gryphon and to count its claws—but it bears further emphasis. All the windows could not have been optically imaged on the retina simultaneously, and they may not even have appeared there in rapid succession. The image (or series of images) developed in solving this problem is new; it is not a replica of any previous stimulus.

The first two of these points have received additional confirmation in a recent experiment by Lee R. Brooks of McMaster University, whose method puts imagery and visual perception in di-



Bringing light engineering into the workshop

Systems for extremely precise length measurement were well-known to optical laboratory workers before the introduction of lasers, or even of electronics. However, to-day's need for instantaneous displacement measurement in the machine shop, often to an accuracy better than one micron, calls for far more than simple adaptation of a laboratory method for workshop use. When Dr. de Lang and his group at the Philips Research Laboratories approached this problem, they knew that a suitable measuring device would have to be simple, easily mounted on machine tools, and above all insensitive to guidance errors, dust, and scratches. Although in essence Dr. de Lang and Dr. Ferguson based their work on known optical techniques (albeit from diverse fields) their combination of those techniques in a practical design gave results hardly surpassed by much more recent laser interferometers.

Optical gratings are frequently applied to displacement measurement. A small (though not extremely small) grating period of 8 microns was chosen, so that diffracted beams of orders +1 and −1 could be used instead of the more usual transmitted beam employed in moiré methods. This choice of diffraction orders differing by two automatically divides step length by a factor of two. The grating, which is connected mechanically to the moving machine component, is a phase grating of the reflection type, composed of rectangular cross-section grooves etched in a metal film on a glass substrate and afterwards completely sealed in glass. It combines high optical efficiency with convenience, since it only requires access to one side of the component or work piece.

The grating is imaged in its own plane by a spherical mirror and correction lens, giving another reduction of one-half in the step length. This method eliminates the need for strict parallel guidance, and also increases the depth of field. A quartz slab of suitable orientation and thickness, inserted in the optical system, gives an apparent relative image shift of one-sixteenth of a grating period for the two perpendicular polarisations in which the light can be split. Thus, the two photo detectors produce electric signals which vary with displacement as the sine and cosine respectively of one-quarter the grating period. By counting only the zero points in these sine wave outputs, the effective period is divided by a factor of four; precisely defined digital steps of 0.5 micron are therefore measured without any analogue interpolation. AC signals are obtained from the photo detectors, even with the system at rest, by vibrating the spherical mirror sinusoidally with a piezoelectric transducer. The electronics required to find zero points in the signal output and provide suitable counting and direction information are simple enough, even for the optics-orientated physicist!

Meanwhile, there was a need for accurate displacement measurement over longer distances than are practicable with a grating interferometer. Dr. de Lang was also engaged, together with Mr. G. Bouwhuis, on fundamental research into the polarisation properties of the gas laser. This work suggested the use of these properties as the basis of a new system which would be suitable for working over longer distances and have much greater flexibility in machine mounting. Such a system, dispensing with any form of grating, would give no scale linearity problems; the displacement sensor would be small and simple, needing no physical connection with the rest of the system save the light beam itself.

The de Lang/Bouwhuis laser interferometer has a digital resolution of 0.288 microns. The system comprises two units; a "cat's eye" arrangement of a mirror and a lens, which is mounted on the moving work-piece or machine component, and the laser unit itself, containing all the necessary optics and electronics.

The beam from a 15 cm isotropic He-Ne single-mode laser is split into two circularly polarised components of differing frequency by placing the laser in a 60 gauss axial magnetic field. The measurement system effectively translates mechanical displacement into a phase change in one of the two beam components which is linearly proportional to path length. This phase change is retained in a beat signal produced when the two beams interfere on a photodetector. The phase of this AC signal, referred to the output of the reference photo detector at the same frequency, can then be processed easily by digital electronics. The laser operating frequency is stabilised to one part in 10^9 by comparing the relative intensity of the two beam components and arranging control of effective laser length by a piezoelectric element, supplemented by thermal expansion.

Interferometers of both these types are already at work within Philips, controlling precision machine tools, making masks for integrated circuit production and the like. Of course, the laser interferometer can also be used, appropriately enough, to control production of the grating employed in the earlier model!

Further information on these systems may be had from Mr. G. Bouwhuis, Philips Research Laboratories, Eindhoven, the Netherlands.

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

rect competition. In one of his studies the subjects were shown a large block *F* and told to remember what it looked like. After the *F* was removed from view they were asked to describe the succession of corner points that would be encountered as one moved around it, responding "Yes" for each point that was either on the extreme top or the bottom of the *F*, and "No" for each point in between. This visual-memory task proved to be more difficult when the responses were made by *pointing* to a printed series of yeses and noes than when a spoken "Yes" or "No" was allowed. However, the difficulty was not intrinsic to the act of pointing; it resulted from the conflict between pointing and simultaneously visualizing the *F*. In another of Brooks's tasks the subjects had to respond "Yes" for each noun and "No" for each non-noun in a memorized sentence. In this case they tended to rely on verbal-auditory memory rather than visual memory. As a result spoken response was the more difficult of the two.

We would not have been surprised to find a conflict between visually guided pointing and corner-counting on an *F* the viewer was *looking at.* After all, he could not be expected to look in two places at once. Even if the *F* had appeared on the same sheet of paper with the yeses and noes, interference would have been easy to understand: the succession of glances required to examine the corners of the *F* would have conflicted with the visual organization needed to point at the right succession of responses. What Brooks has shown, rather surprisingly, is that this conflict exists even when the *F* is merely imagined. Visual images are apparently produced by the same integrative processes that make ordinary perception possible.

In short, the reaction of the nervous system to stimulation by light is far from passive. The eye and brain do not act as a camera or a recording instrument. Neither in perceiving nor in remembering is there any enduring copy of the optical input. In perceiving, complex patterns are extracted from that input and fed into the constructive processes of vision, so that the movements and the inner experience of the perceiver are usually in good correspondence with his environment. Visual memory differs from perception because it is based primarily on stored rather than on current information, but it involves the same kind of synthesis. Although the eyes have been called the windows of the soul, they are not so much peepholes as entry ports, supplying raw material for the constructive activity of the visual system.

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on scientific problems

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For example, such light sources as solid-state optical lasers (**l**ight **a**mplification by **s**timulated **e**mission of **r**adiation) and the more-powerful noble gas lasers are manufactured at RCA for military, industrial, scientific and commercial uses. The full range of RCA laser devices includes wavelengths from as short as $3x10^3$ Å to $11x10^3$ Å—spanning the electromagnetic spectrum from ultraviolet to near infrared, as shown in *Fig. 1.*

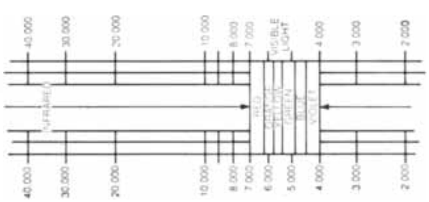


Fig. 1

Most such radiations far exceed the ability of the eye to detect, and this has given rise to the development by RCA of a wide variety of devices which is now available to designers and manufacturers of instrumentation for science, industry and for military and commercial applications. RCA Electronic Components offers electron tube image intensifiers which can produce a light intensification of as great as 10^5 or more. Such electron tubes, one of which is shown in *Fig. 2* in diagrammatic cross-section as well as photographically, are contributing to both military and medical developments and are bringing new dimensions to astronomy where they are helping scientists unravel the mysteries of the universe.

Because the emanation of "light" from many events is of short duration, another "family" of RCA-made devices has been developed to detect these "bursts." Known as "photomultipliers," these devices find application in instrumentation used in biological research, geological exploration, nuclear investigations, astronomy, and spectroscopy, for example.

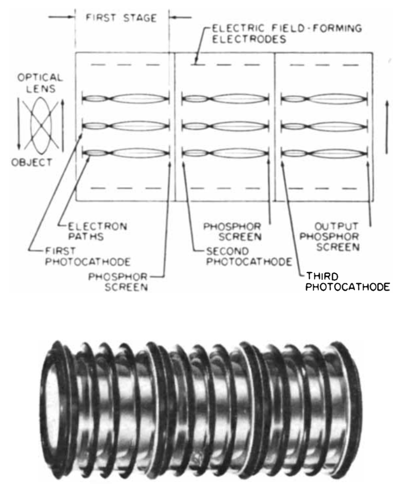


Fig. 2

RCA today is actively engaged in the manufacture of cathode-ray tubes for many "light" uses and display storage devices capable of "freezing" images for many minutes. Devices such as photocells and solar cells are employed in conjunction with "light"-operated equipment. Vidicons, image orthicons, and ISOCON camera tubes for entertainment and closed-circuit television cameras and tape pick-up units are included in the "family" of RCA light-sensitive devices. Currently under investigation are such new fields as photochromics — materials which change color in response to illumination at appropriate wavelengths—and the newly-announced applications of light-reflective nematic, smectic and cholesteric liquid crystal displays. *Fig. 3* shows some of the many RCA devices currently available for "light" applications.

To develop its wide range of light generation, intensification, storage and display devices, RCA calls upon a full array of specialists in numerous scientific disciplines within its divisions. Include those who specialize in glass, vacuum "technology," and electron optics, as well as mechanical engineers aiding in the development of the most-efficient structures for use in processing light. Then, too, there are the chemists required to develop phosphors, ways to refine them and to apply them to a range of devices. All of these people at RCA Electronic Components are immersed in the development of components for tomorrow's equipments—such as solid-state panels for display of images, that may result in the long-desired "picture frame" TV receiver for the home.

You will find—regardless of your light application—that RCA can be your best source for information and devices. For computer read-out; in medical electronics; in radar and in entertainment television—and in any application involving the generation, detection, and amplification of radiant energy, from ultraviolet to near infrared, and from a photon or two to light as bright as the sun, RCA Electronic Components is ready with the technology, the specific devices—and the economics of putting light to work.

For help with your specific problems, or for details about any of the current production types of light-processing or light-generating devices made by RCA, write RCA Electronic Components, Commercial Engineering, Section I95EC, Harrison, N. J. 07029.

Fig. 3

RCA

MATHEMATICAL GAMES

Counting systems and the relationship between numbers and the real world

by Martin Gardner

Ah why, ye gods! should two and two make four?

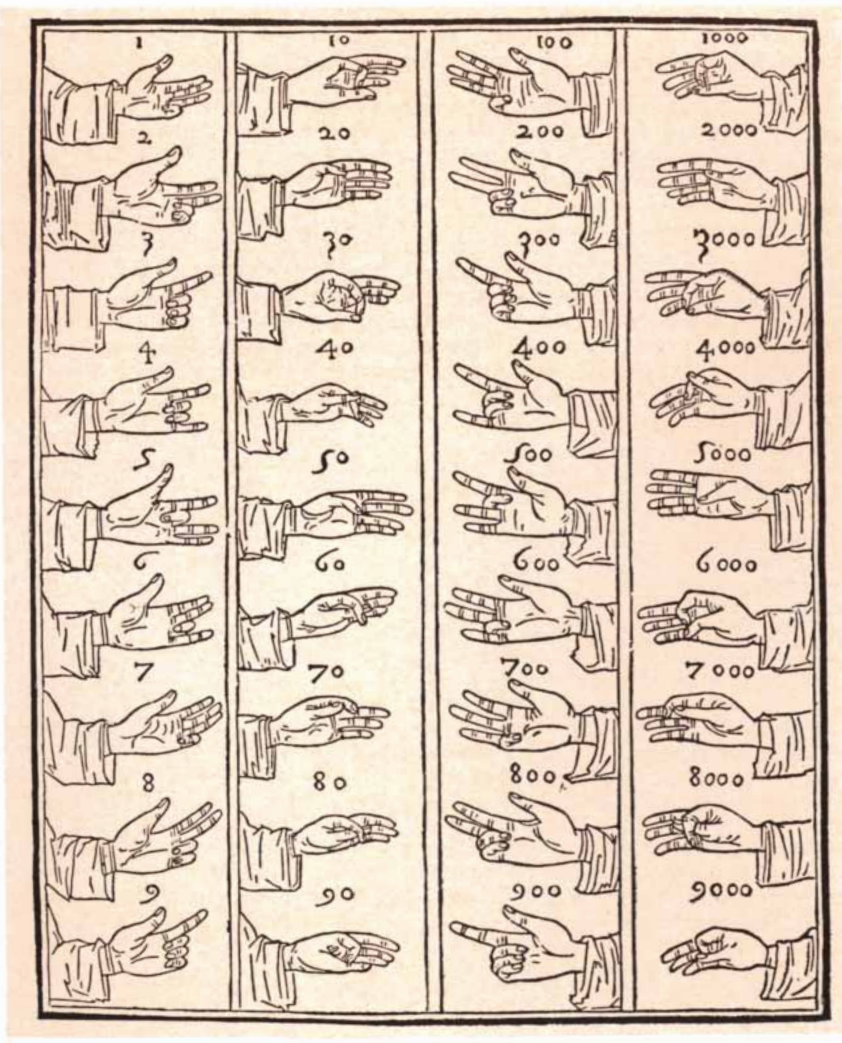
—ALEXANDER POPE, *The Dunciad, Book 2*

Anthropologists have yet to find a primitive society whose members are unable to count. For some time they assumed that if an aboriginal tribe had no words for numbers except "one," "two" and "many," its members could not count beyond two, and they were mystified by the uncanny ability of such people to look over a herd of sheep, for example, and say one was missing. Some anthropologists believed these tribesmen had a phenomenal memory, retaining in their heads a *Gestalt* of the entire herd, or perhaps knew each sheep personally and remembered its face. Later investigators discovered that the use of the same word for all numbers above two no more meant that a tribesman was unaware of the difference between five and six pebbles than the use of the same word for blue and green meant that he was unaware of the difference in color between green grass and blue sky. Tribes with limited number vocabularies had elaborate ways of counting on their fingers, toes and other parts of their anatomy in a specified order and entirely in their heads. Instead of remembering a word for 15 a man simply recalled that he had stopped his mental count on, say, his left big toe.

Most primitive counting systems were based on five, 10 or 20, and one of the few things on which cultural anthropologists are in total agreement (and in agreement with Aristotle) is that the reason for this is that the human animal has five fingers on one hand, 10 on both and 20 fingers and toes. There have been many exceptions. Certain aboriginal cultures in Africa, Australia and South America used a binary system. A few developed a ternary system; one tribe in Brazil is said to have counted on the three joints of each finger. The quaternary, or 4-base, system is even rarer, confined mostly to some South American tribes and the Yuki Indians of California, who counted on the spaces between their fingers.

The 5-base has been used much more widely than any other. In many languages the words for "five" and "hand" either are the same or are closely related to earlier words; *pentcha,* for example, is "hand" in Persian and *pantcha* is "five" in Sanskrit. The Tamanacos, a South American Indian tribe, used the same word for five that they used for "a whole hand." Their word for six meant "one on the other hand," seven was "two on the other hand," and so on for eight and nine. Ten was "both hands." For 11 through 14 they stretched out both hands and counted "one on the foot, two on the foot," and so forth, until they came to 15, which was "a whole foot." As one might guess, the system continued with 16 expressed as "one on the other foot," and so on through 19. Twenty was the Tamanacos' word for "one Indian," 21 was "one on the hand of another Indian." "Two Indians" meant 40, "three Indians" 60. The ancient Java and Aztec weeks were five days long, and there is a theory that the Roman X for 10 was derived from two V's, one upside down, and that the V was a representation of a human hand.

Early number words were frequently identical with words for fingers, toes and other parts of the body. The present English use of "digit," from the Latin for "finger," for the ten numbers 0



Italian finger symbolism as illustrated by Luca Pacioli in 1494

through 9 testifies to an early finger origin of Anglo-Saxon counting. There are amusing exceptions. The Maori word for four is "dog," apparently because a dog has four legs. Among the Abipónes, a now vanished South American Indian tribe, the word for four meant "the toes of the rhea"—three in front and one in back.

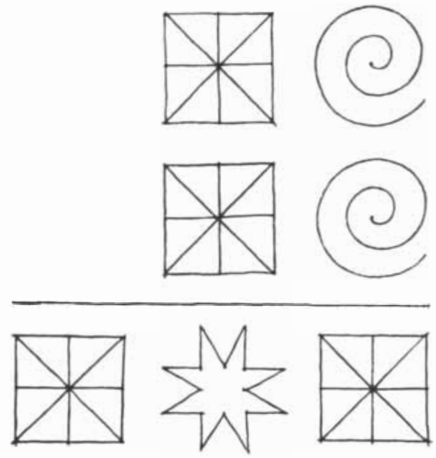
Primitive number systems with bases 6 through 9 are extremely rare. Apparently once people found a need to name numbers greater than five they usually jumped from one hand to the other and adopted a 10-base system. The ancient Chinese used a base of 10, as did the Egyptians, the Greeks and the Romans. One of the curiosities of ancient mathematics was the sexagesimal (base-60) system that the Babylonians took over from the Sumerians and with which they achieved a remarkably advanced mathematics. (Our ways of measuring time and angles are relics of the Babylonian system.) Today 10 is almost universal as a number base throughout the world, even among primitive tribes. David Eugene Smith, in the first chapter of his *History of Mathematics*, first published in 1923, reports that a survey of 70 African tribes revealed that all of them used a 10-base system.

Above 5, very few number systems have been based on primes. W. W. Rouse Ball, in *A Short Account of the History of Mathematics* (fourth edition, 1908), cites only the 7-base system of the Bolas, a West African tribe, and the 11-base system of the early Maoris, although I cannot vouch for either assertion. Vigesimal, or 20-base, systems (fingers plus toes) were fairly common, the Mayan system being the outstanding instance. Because it used both zero and positional notation it was one of the most advanced of the ancient number systems, far superior, for example, to the clumsy Roman system (a statement that gives the jitters to cultural relativists since it suggests a value judgment that vaults cultural boundaries). The 20-base system survives today as words in such languages as French (*quatre-vingts* for 80), English ("Fourscore and seven years ago . . .") and particularly Danish, in which number names are based on a curious mixture of the decimal and vigesimal systems.

The obvious connection between 5 and 10, the most popular ancient bases, and the fingers of one and two hands has suggested to many science-fiction writers that the number systems of extraterrestrial humanoids are likewise based on the number of fingers they possess. (The creatures in Walt Disney's animated-cartoon culture presumably use a 4- or 8-base system, since they have only four fingers on each hand.) Harry L. Nelson of Livermore, Calif., sent the following puzzle: Suppose a space probe to Venus sends back a picture of an addition sum scratched on a wall [*see illustration at right*]. Assuming that the Venusians use a positional notation like ours and a number base corresponding to the fingers on one Venusian hand, how many fingers are on that hand? It is an easy problem, the solution to which I shall give next month.

Now that the decimal system is so universally established there seems to be no chance that the human race will convert to another number base, in spite of the fact that a duodecimal (base-12) system offers certain practical advantages, such as having four divisors for the base compared with only two for the decimal base. It has had enthusiastic advocates for centuries. And there are technical advantages, although mostly for number theorists, to a prime-number base, such as 7 or 11, as argued by the 18th-century French mathematician Joseph Louis Lagrange.

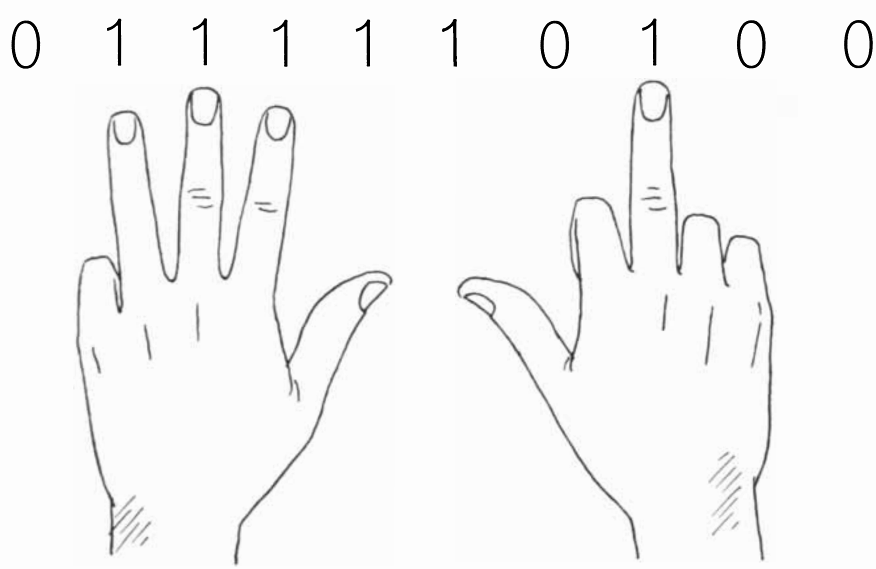
Powers of 2, particularly 8 and 16, have been defended as number bases by many mathematicians. "As there is no doubt that our ancestors originated the decimal system by counting on their fingers," wrote W. Woolsey Johnson in the *Bulletin of the New York Mathematical Society* (October, 1891, page 6), "we must, in view of the merits of the octonary system, feel profound regret that they should have perversely counted their thumbs, although nature has differentiated them from the fingers sufficiently, she might have thought, to save



A sum in "Venusian" notation

the race from this error." In my column for May, 1964 (on the ternary system), I mentioned the strange nomenclature devised by two mathematicians who preferred a 16-base. I hasten to add that modern computers have long been using a base-8 arithmetic; more recently a "hexadecimal" (base-16) arithmetic, using the 16 digits 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, A, B, C, D, E, F, has become an important part of the language of IBM's System/360 computers.

Just as primitive societies varied in their choice of a number base, so they varied in the style in which they counted. Since most people are right-handed, counting was usually started on the left hand, sometimes in an unvarying, ritualistic way and sometimes not. A person might begin the count at the thumb or little finger, either by tapping with a right finger, by bending down the left fingers or by starting with a closed fist and opening the fingers one at a time.



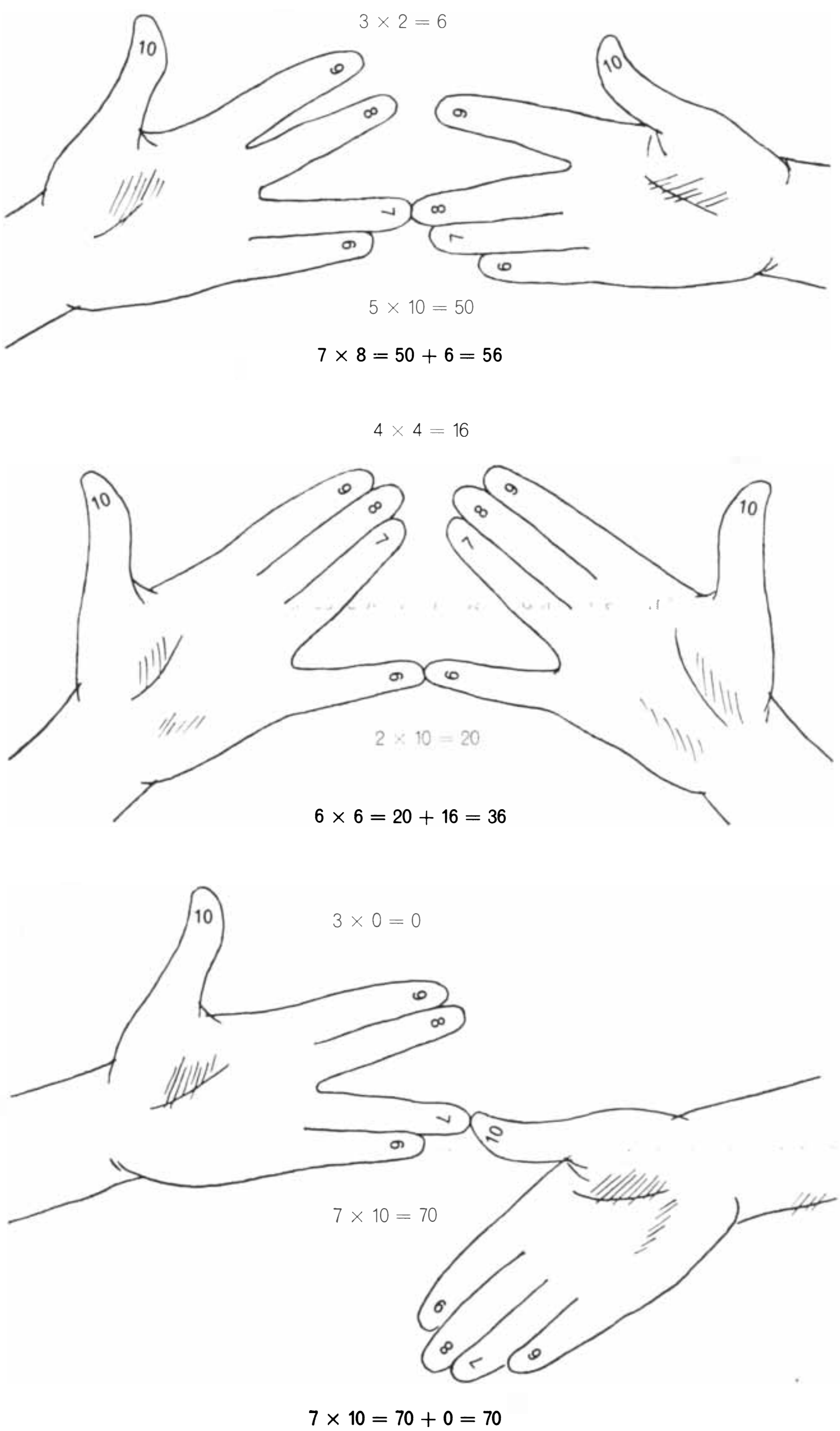
Binary 500 shown by the fingers

On the Andaman Islands in the Bay of Bengal people started with the little finger and tapped their nose with successive fingers. On an island in the Torres Strait between Australia and New Guinea people would count to five by tapping the fingers of their left hand, but instead of going on to the right hand they tapped their left wrist, left elbow, left shoulder, left nipple and sternum, then continued the count by reversing this order on the right side of their body. Mathematicians have made the point that when fingers and other parts of the body are successively tapped in counting, they are being used to express ordinal numbers (first, second, third and so on), whereas when fingers are raised all at once to signify, say, four frogs, they are expressing the cardinal number (one, two, three and so on) of a set.

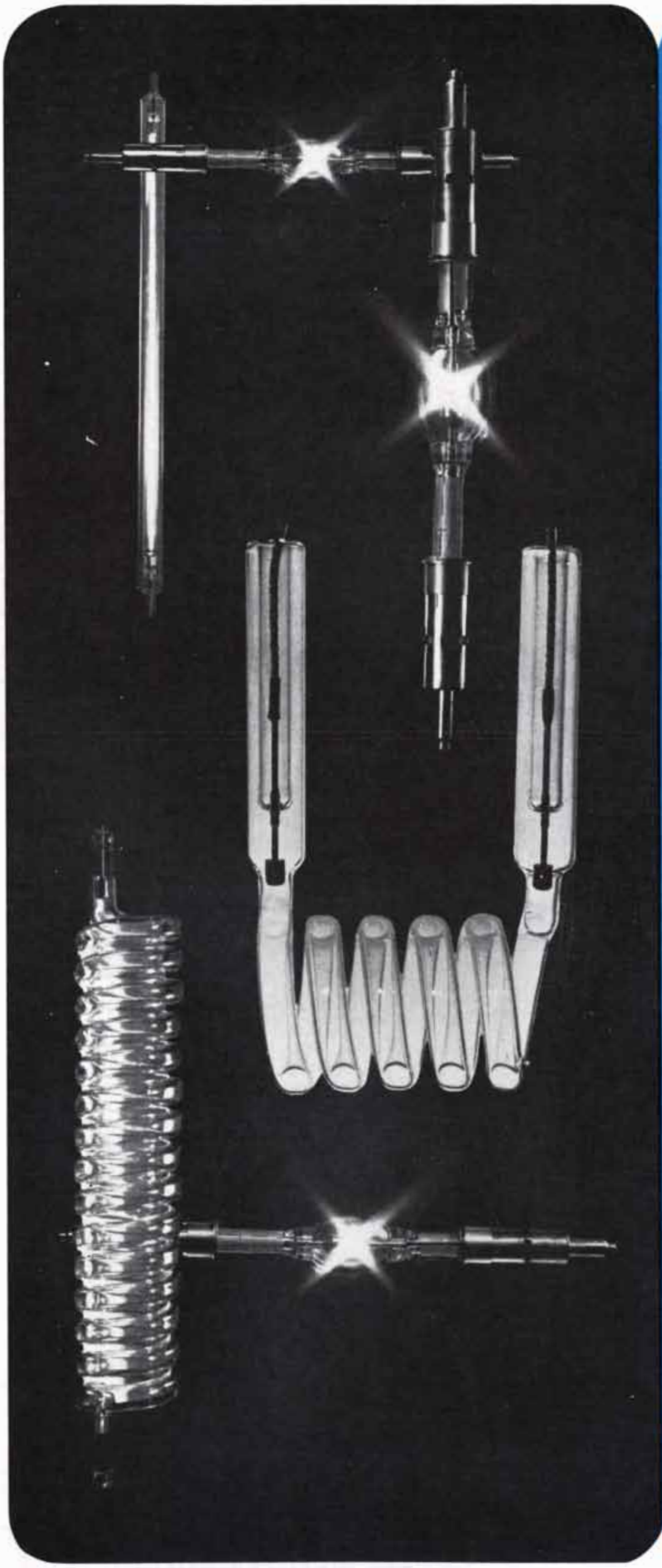
The ancient Greeks had an elaborate hand symbolism for counting from one to numbers in the thousands; it is mentioned by Herodotus but little is known about its finger positions. The ancient Chinese and other Oriental cultures had finger symbols of similar complexity that are still used for bargaining in bazaars, where the expressed number can be concealed from bystanders by a cloak. The Roman method of symbolizing numbers with the hands is mentioned by many Roman authors. In the eighth century the Venerable Bede devoted the first chapter of a Latin treatise on *The Reckoning of Times* (such as calculating the dates of Easter) to a Roman system of finger symbols that he extended to one million. (His symbol for one million is the clasping of both hands.)

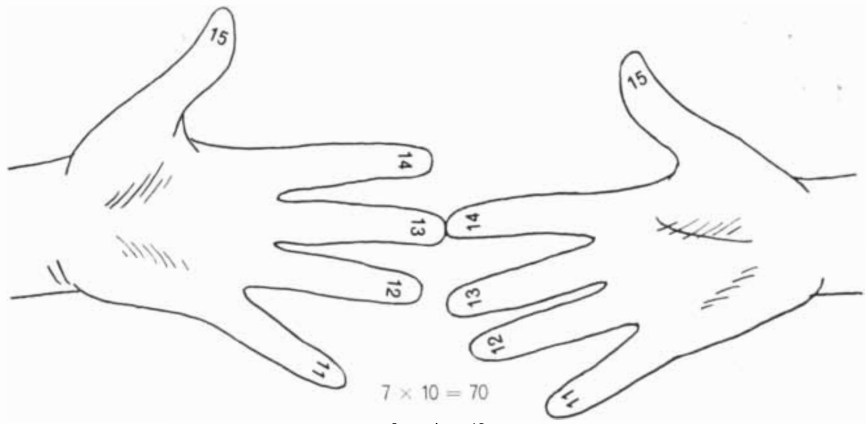
Most arithmetic manuals of the medieval and Renaissance periods included such methods. A typical system, shown in the illustration on page 218, is from the first important mathematical book to be printed, a 1494 Italian work by Luca Pacioli, a Franciscan friar (who later wrote a book on the golden ratio that was illustrated by his friend Leonardo da Vinci). The Roman poet Juvenal had such a system in mind when he wrote in his *Satires:* "Happy is he indeed who... finally numbers his years upon his right hand"; that is, happy is he who lives to be 100, the number at which the right hand was first used in the symbolism. Note that most of the left-hand symbols have right-hand duplicates and that even on the same hand certain symbols seem to be the same unless there are subtle differences not made clear in the crude drawings. St. Jerome wrote in the fourth century that 30 was associated with marriage, the circle formed by the thumb and first finger symbolizing the union of husband and wife; similarly, 60 was associated with widowhood, symbolized by the breaking of this circle.

All these old methods of finger symbolism have a 10-base, but there is no reason why fingers cannot be used just as easily for counting in systems with other bases. Indeed, the fingers are peculiarly adapted to the simplest of all systems, the binary, since a finger raised or lowered is comparable to a flip-flop circuit in modern computers that use binary counting. Frederik Pohl, in a magazine article on "How to Count on Your Fingers" reprinted in his *Digits and Dastards* (Ballantine, 1966), suggests starting with the fists closed, backs of hands up. An extended finger is one in the binary system, an unextended finger zero. Thus in order to count from one to 1111111111 (equivalent to 1,023 in



How fingers multiply pairs in the half-decade 6 through 10





3 × 4 = 12

13 × 14 = 70 + 12 + 100 = 182

Multiplying in the half-decade 11 through 15

the decimal system) one begins by extending the right little finger. To indicate the decimal two, which is 10 in the binary system, the little finger is retracted and the right ring finger raised. Extending both ring and little fingers yields 11, the decimal three. The bottom illustration on page 219 shows how the two hands represent 500 in the binary system. With a little practice one can learn to use the fingers for rapid binary counting and even, as Pohl explains, for doing binary addition and subtraction. Since the propositional calculus of symbolic logic is easily manipulated in the binary system (as explained in my *Logic Machines, Diagrams and Boolean Algebra,* reprinted this year as a Dover paperback), the hands can actually be used as a computer for solving simple problems in two-valued logic.

Any binary number consisting entirely of 1's is necessarily one less than a power of 2; the number 1,023, for example, indicated in binary digits by extending all 10 fingers, is $2^{10} - 1$. This suggested an interesting puzzle to Pohl. Suppose we wish to subtract a certain number n from 1,023 (or any lower number expressed in binary as a string of 1's). Can you think of an extremely simple way to perform such a subtraction quickly with the fingers? Next month I shall give Pohl's surprising answer.

Since few people in the Middle Ages and the Renaissance learned the multiplication table beyond 5 × 5 or had access to an abacus, a variety of simple methods were in use for obtaining the products of numbers from 6 through 10. One common method, called "an ancient rule" in a 1492 book, was to use the complements of the two numbers with respect to 10. (The complement of n would be $10 - n$.) To multiply 7 by 8, write down their complements, 3 and 2. Either complement, taken from the number with which it is *not* paired, gives 5, the number of 10's in the product of 7 and 8. The product of 3 and 2 is 6. Fifty added to 6 is 56, the final answer.

The fingers of both hands were often used as a computing device for this method. On each hand the fingers are assigned numbers from 6 through 10, starting with the little fingers. To multiply 7 and 8 touch the 7 finger of either hand to the 8 finger of the other, as shown at the top of the illustration on page 220. Note that the complement of 7 is represented by the three upper fingers (those above the touching fingers) of the left hand, and the complement of 8 by the two upper fingers of the right hand. The five lower fingers represent 5, the number of 10's in the answer. To 50 is added the product of the upper fingers, 2 × 3, or 6, to obtain 56. This simple method of using fingers to compute the product of any pair of numbers in the half-decade 6 through 10 was widely practiced during the Renaissance and is said to be used still by peasants in parts of Europe and Russia.

The method has considerable pedagogical value today in the elementary schools, not only because children are intrigued by it but also because it ties in neatly with the algebraic multiplication of binomials. Instead of using complements up to 10, we can best represent 7 and 8 as excesses over 5, writing them as the binomials (5 + 2) and (5 + 3), then performing the multiplication:

$$\begin{array}{r} 5 + 2 \\ 5 + 3 \\ \hline 25 + 10 \qquad \\ + 15 + 6 \\ \hline 25 + 25 + 6 = 56\,. \end{array}$$

The first two numbers on the lowest line

Basic Research at Honeywell
Research Center
Hopkins, Minnesota

The generation of digital information from solid state sensors

Computers demand digital information; but, up until the present time, sensors have had analog outputs. A new solid state transducer has now been developed which generates digital signals.

Computers, whether in the control loop of a chemical processing plant, a jet aircraft or a space flight monitoring system, feed on information originating at different sensors. These sensors detect changes in variables such as temperature, pressure and flow. Until now, the information generated by the sensors has been in the form of analog signals. In order to be used by the computer, these signals must be converted to digital form. Typically, the analog signal is transmitted to the computer, where it is converted. During transmission, it is subject to noise and to distance limitations.

A frequency or time signal, on the other hand, cannot be distorted by the intervening medium. Thus, a digital signal is inherently more accurate. When generated at the source, it eliminates the need for conversion and its associated gear. A complete system using a digital transducer would be smaller, lighter, cheaper and more reliable.

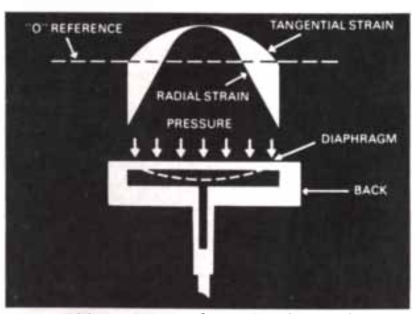
For several years, Honeywell scientists and engineers have been following different approaches in the development of a digital transducer.

One approach pairs the piezoresistance characteristics of semiconductors with a phase shift oscillator. It has proven very successful.

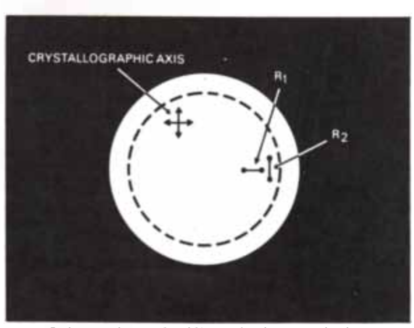
The Honeywell scientists and engineers use a silicon diaphragm which incorporates piezoresistive sensing elements. The resistance of a piezoresistive element changes considerably with strain, producing a large signal variation for a small pressure variation. If a resistor is properly positioned on a crystal, relative to its crystallographic orientation, and is subjected to a transverse strain, its resistance changes by an amount equal in magnitude, but opposite in sign, to the change resulting from the application of the same strain in a resistor in the longitudinal direction.

Referring to the diagrams, two resistance capacitance elements (RC elements) are oriented radially and tangentially on a silicon diaphragm. (Actually the elements are formed monolithically by integrated circuit techniques.) If, for example, the diaphragm is subjected to a pressure causing a tensile radial strain near the edge, the resistance of the radial RC element, R_1, will increase by an amount δR. This radial strain, acting transversely to the tangential RC element, R_2, will cause it to decrease in resistance by the same amount, δR. It is assumed for simplicity that the two resistances are equal at zero pressure.

Conventionally, the resistors would be used in a balanced bridge circuit to determine resistance change. Instead, Honeywell scientists have used them in a feedback loop of phase shift oscillators to control oscillator frequencies. When used this way, the RC elements can be related to oscillator frequency as $f = \frac{1.78}{RC}$ cycles per second.



Silicon Sensor Cross-Section and Profiles of Diaphragm Strains



Orientation of Diffused Piezoresistive Elements on Diaphragm

Upon application of pressure the resistance becomes $R + \delta R$ and $R - \delta R$ and the resulting frequencies are then:

$$f_1 = \frac{1.78}{(R + \delta R)C} \quad \text{and} \quad f_2 = \frac{1.78}{(R - \delta R)C}$$

When the two signals are combined, the resulting difference in frequency constitutes a digital signal directly proportional to the strain.

The oscillator circuit has been designed to optimize short-term (frequency jitter) and long-term stability. Thus, the frequency outputs remain repeatable relative to a set of calibration constants.

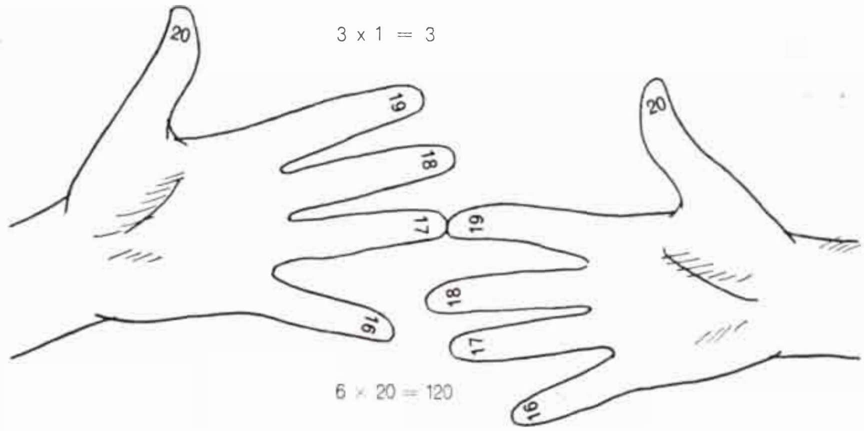
Results from tests conducted to date show that the digital pressure transducer can withstand: overload, extreme temperatures, humidity, vibration and acceleration. The unit is extremely sensitive to low pressures and for sizable loads needs only to be fabricated with a thicker diaphragm to minimize distortion.

Honeywell's first application is in an air data computer where the transducer is transmitting pressures reflecting altitude and air speed to an airborne computer. Many other uses are easily foreseen, particularly in the continuous process industries where real time computers are being inserted in the control loop.

Honeywell scientists are working with other characteristics of semiconductors so that additional variables such as temperatures and flow can be sensed and digital signals obtained.

If you are working in the field of solid state transducers and are interested in knowing more about Honeywell's work you are invited to correspond with Dr. Carl Nomura, Honeywell Solid State Electronics Center, 600 Second Street No., Hopkins, Minnesota 55343. If you are interested in further details about Honeywell's Air Data Computer, you are invited to write Mr. John Wagner, Honeywell Aeronautical Division, 2600 Ridgway Road, Minneapolis, Minnesota 55413.

Honeywell



17 × 19 = 120 + 3 + 200 = 323

Finger multiplication in the half-decade 16 through 20

correspond to the sum of the lower fingers multiplied by 10; the 6 corresponds to the product of the upper fingers.

The finger method of multiplying generalizes easily to half-decades higher than 10, although for all half-decades ending in 5 a slightly different procedure is used. Consider the next-higher half-decade, 11 through 15, and suppose we wish to multiply 14 and 13. The fingers are assigned numbers from 11 through 15, and the fingers representing the numbers to be multiplied are touched as shown in the illustration on page 222. The seven lower fingers are multiplied by 10 to obtain 70. Now, however, instead of adding the product of the upper fingers, we ignore the upper fingers and obtain the product of the two sets of lower fingers, 4 × 3, or 12. Adding this to 70 yields 82. The final step is to add the constant 100. This gives the final answer, 182.

There are many ways to explain why this works, but the simplest is to think in terms of binomial multiplication:

$$\begin{array}{r} 10 + 3 \\ 10 + 4 \\ \hline 100 + 30 \\ + 40 + 12 \\ \hline 100 + 70 + 12 = 182\,. \end{array}$$

The 100 on the left is the additive constant, 70 is the sum of the lower fingers multiplied by 10, and 12 is the product of the two sets of lower fingers.

For all half-decades ending in 0 we return to the first procedure. For 16 through 20 each lower finger has a value

DECADE	HALF-DECADES	VALUE OF LOWER FINGERS	ADDITIVE CONSTANT
1	1-5	0	0
	6-10	10	0
2	11-15	10	100
	16-20	20	200
3	21-25	20	400
	26-30	30	600
4	31-35	30	900
	36-40	40	1,200
5	41-45	40	1,600
	46-50	50	2,000

Chart showing finger values and constants for multiplying numbers up to 50

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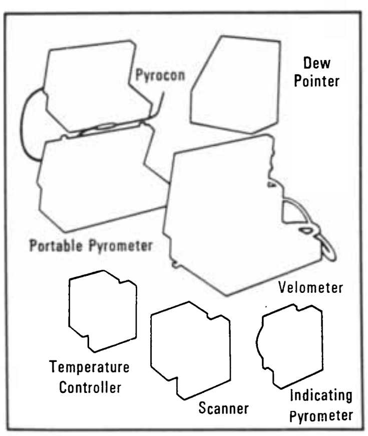

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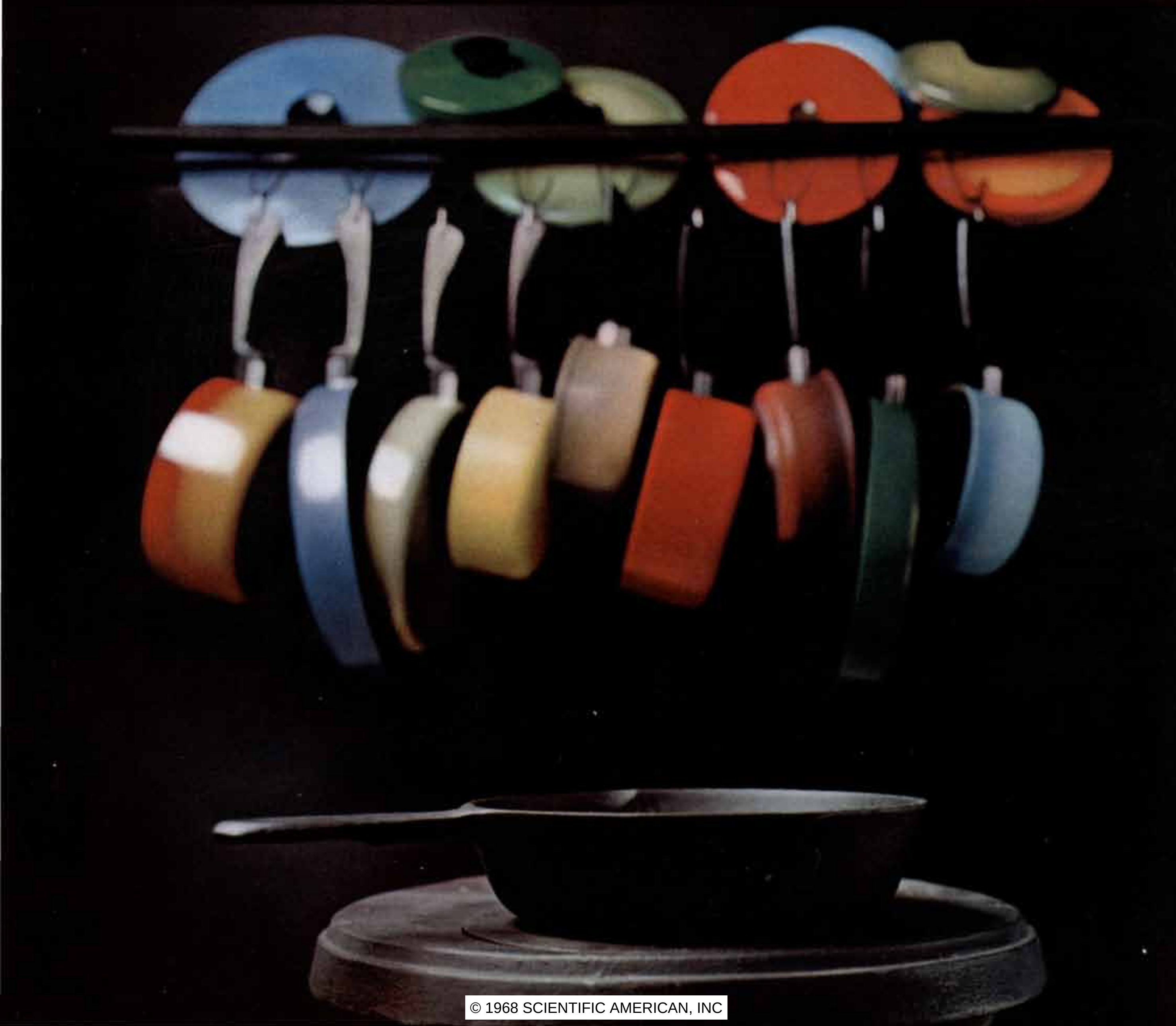


of 20 and the additive constant jumps to 200, as in the multiplication of 17 and 19 [*see top illustration on* *page 224*]. Multiplying the six lower fingers by 20 gives 120. The product of the two sets of upper fingers yields 3. To 123 we add the constant, 200, to get 323, the final answer. The binomial schemata is

$$\begin{array}{r} 10 + 7 \\ 10 + 9 \\ \hline 100 + 70 \\ + 90 + 63 \\ \hline 100 + 160 + 63 = 323\,. \end{array}$$

If we move the 100 in 160 to the left and the 60 in 63 to the middle, we have 200 + 120 + 3. This corresponds to the finger computation. The constant is 200, the sum of the lower fingers times 20 is 120 and the product of the upper sets of fingers is 3.

The chart on page 224, adapted from Ferd W. McElwain's article "Digital Computer—Nonelectronic" (in *Mathematics Teacher,* April, 1961, pages 224–228), gives the values assigned to the lower fingers for each half-decade as well as the additive constant. Remember, for each half-decade ending in 0 the first system is used, in which the upper fingers play a role. For half-decades ending in 5 the second system is used, in which the upper fingers are ignored. The value assigned to the lower fingers for half-decades ending in 5 is $10(d-1)$, where d is the number of the decade. For half-decades ending in 0 it is $10d$. The additive constant for half-decades ending in 5 is $100(d-1)^2$; for half-decades ending in 0 the constant is $100d(d-1)$.

The chart extends to all higher half-decades. There are many ways to write general formulas that cover the entire procedure. Nathan Altshiller Court, in *Mathematics in Fun and in Earnest* (Dial, 1958), gives the following:

$$(a+x)(a+y) = \\ 2a(x+y) + (a-x)(a-y),$$

which can also be written

$$(a+x)(a+y) = a(x+y) + xy + a^2\,,$$

where x and y are the final digits of the numbers to be multiplied and a can be 5, 10, 15, 20, 25, 30, . . . , the first numbers of each half-decade.

Can this finger-computing system be adapted to the multiplication of numbers from different half-decades, say 17 × 64? The answer is yes. The procedure is complicated, unfortunately, requiring the assignment of different values to fingers of each hand, so that I must refer the reader to McElwain's article cited above, in which a method is explained. Of course, one can always break the larger number into smaller parts for a series of finger multiplications that are then added to get the final result. Thus 9 × 13 can be obtained by adding (9 × 6) to (9 × 7).

There is a philosophical lesson in all of this. Pure mathematics, in one obvious sense, is a construction of the human mind, but there also is an astonishing fit between pure mathematics and the structure of the world. The fit is particularly close with respect to the behavior of physical objects, such as pebbles and fingers, that maintain their identities as units. Thus 2 + 2 = 4 is both a law of pure arithmetic, independent of the actual world, and a law of applied arithmetic. Every now and then a cultural anthropologist, overeager to drag science and mathematics into the folkways, argues that because different tribes have calculated with different number systems mathematical laws are entirely cultural, like traffic regulations and baseball rules. He forgets that different base systems for the natural numbers are no more than different ways of symbolizing and talking about the *same* numbers, and are subject to the same arithmetical laws regardless of whether the number manipulator is a Harvard mathematician or an aborigine adding on his fingers.

The plain fact is that there is no place on the earth or on any other planet where two fingers plus two fingers is anything but four fingers. The only exception I have come on is in George Orwell's *Nineteen Eighty-Four,* in that terrible torture scene in which Winston Smith is finally persuaded that two plus two is five:

O'Brien held up the fingers of his left hand, with the thumb concealed.

"There are five fingers there. Do you see five fingers?"

"Yes."

And he did see them, for a fleeting instant, before the scenery of his mind changed. He saw five fingers, and there was no deformity.

The same possibility had been raised by Dostoevski. "Mathematical certainty is, after all, something insufferable," says the narrator of *Notes from Underground.* "Twice two makes four seems to me simply a piece of insolence. Twice two makes four is a pert coxcomb who stands with arms akimbo barring your path and

MOVE	CARD	TO
1	K♥	T1
2	8♥	B4
3	7♥	B4
4	A♥	P1
5	2♥	P1
6	8♠	B3
7	2♠	T2
8	K♥	B2
9	Q♥	B2
10	6♥	B4
11	K♠	T1
12	7♠	B3
13	A♠	P2
14	2♠	P2
15	J♥	B2
16	10♥	B2
17	6♥	T2
18	7♥	B1
19	6♥	B1
20	8♥	T2
21	9♥	B2
22	3♥	P1
23	4♥	P1
24	5♥	P1
25	6♥	P1
26	7♥	P1
27	8♥	P1
28	9♥	P1
29	10♥	P1
30	J♥	P1
31	Q♥	P1
32	K♥	P1
33	7♠	T2
34	8♠	B1
35	9♠	B2
36	3♠	P2
37	10♠	B3
38	4♠	P2
39	J♠	B4
40	5♠	P2
41	Q♠	B5
42	6♠	P2
43	7♠	P2
44	8♠	P2
45	9♠	P2
46	10♠	P2
47	J♠	P2
48	Q♠	P2
49	K♠	P2

A 49-move solution for solitaire game

spitting. I admit that twice two makes four is an excellent thing, but if we are to give everything its due, twice two makes five is sometimes a very charming thing too."

Charming, perhaps, but applying to no logically possible world. It is a subjective, self-contradictory delusion, one that can be temporarily induced only by a "collective solipsism" (as Orwell called it) in which all truth, including scientific and mathematical truth, is defined without reference to the abstract laws of logic or to the mathematical patterns of the real world.

A 54-move solution to C. L. Baker's order-2 solitaire game, with the starting pattern shown in June, was published in July. Hundreds of readers sent shorter solutions. By July 10, 106 readers had sent 50-move solutions and 35 had sent 49-move versions. Forty-nine is probably the minimum. Although the 49-move solutions differed considerably, all had in common the placing of the 13 hearts on a *P* cell in 32 moves, with the remaining 17 moves being used to put the remaining spades on the other *P* cell.

The readers who sent 49-movers by July 10 were B. B. Abercrombie, Philip S. Abrams, Frank Anger, Gene C. Barton, Harold A. Beatty, P. H. Browning, William J. Butler, Jr., Donald B. Charnley, Roger D. Coleman, Charles W. Disbrow, Jr., Ralph Dumain, F. J. Dyson, Terry C. Gleason, John W. Gosling, A. W. Greig, Gordon G. Heath, Neale S. Hyatt, Peter Johansson (with Douglas Jacobs), Larry B. Klaasen, S. Kogan, R. C. Koleszar, William V. Lavin, Jr., Sanford Libman, Charles L. McClenon, John Mallinckrodt, Warren H. Ohlrich, John L. Sampson, Joan and Suzanne Schwartz, Walter C. Siff, Theodore and Judith Simon, Hereford A. Stuerke, A. Ungar, Samuel L. Ward, Charles B. Weinberg and Jack Whitney.

Dyson also sent a 54-move solution using only one *T* cell, and although he believes the pattern has no solution without a *T* cell, he is not yet sure. Ohlrich's 49-move solution, the first received, is given on the preceding page.

In August, problem 28 was incorrectly stated, and many readers pointed out that the ribbon's length is actually minimized when $AB = 0$. For a correct statement of the puzzle see problem 66 in the book cited in the answer. Many readers also saw that the answer to problem 31 involves a logical contradiction. My parenthetical "Thanks to Epimenides the Cretan" was a hint that this is a variant on the old liar paradox and was intended as a joke.

PROFESSIONAL ENVIRONMENT

The Fort Worth Division of General Dynamics strongly urges and encourages all personnel to take advantage of the excellent educational facilities in and near Fort Worth to further their professional development through participation in graduate and undergraduate degree programs at five area universities and colleges. Full tuition refund is provided by General Dynamics for successfully completed, job-related courses.

A graduate study program of exceptional merit is offered by University of Texas at Arlington, located within 15 minutes' drive of Fort Worth, with evening classes leading to the Master of Science degree in Electrical Engineering, Engineering Mechanics, and other fields.

Southern Methodist University and Texas Christian University, jointly, offer evening classes in Fort Worth leading to the Master of Science degree in five fields of engineering—electrical, mechanical, civil, and industrial engineering, and engineering mechanics. In addition, the Institute of Technology at Southern Methodist now offers "The Texas Twelve" —a new program of Cooperative Graduate Fellowships.

Short courses and seminars may be selectively attended at leading universities across the United States, and industry-education liaison programs with Caltech, MIT, and the University of Texas facilitate a continuing exchange of ideas and knowledge.

Assistance and P. E. registration are provided for all qualified engineers, and membership is encouraged in professional societies.

Informal in-plant courses relating to current projects are conducted during working hours, with periodic after-hours courses with voluntary enrollment provided in response to employee interest. Membership is also available to all professional and technical staff members in the General Dynamics Management Association of Fort Worth, which provides a broad spectrum of knowledge-heightening programs.

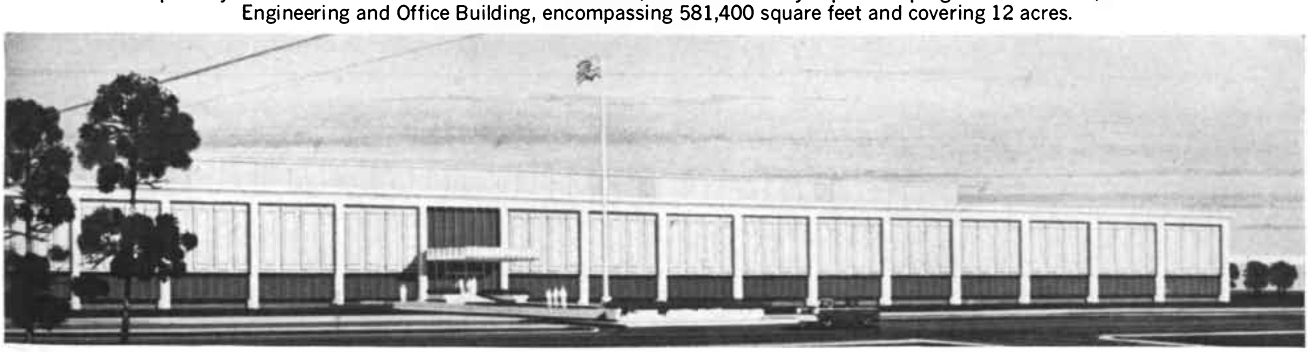
Engineering and scientific action is required to solve the intriguing problems posed by aerospace projects in research, development, design, test and evaluation now in progress at the Fort Worth Division of General Dynamics. If your creative background and education qualify you for advanced assignments, you'll find room to satisfy your potential. You'll enjoy action living, too, in smog-free Fort Worth, where residential areas are easily reached via uncrowded freeways . . . and where a broad range of cultural, recreational and upper level educational facilities is at hand.

A mild climate and low living costs make an added contribution to your career satisfaction. Call Collect—817-732-4811, Extension 3551; or send a résumé of your education and experience to Mr. J. B. Ellis, Industrial Relations Administrator-Engineering, General Dynamics, Fort Worth Division, P.O. Box 748C, Fort Worth, Texas 76101. An equal opportunity employer.

GENERAL DYNAMICS

Fort Worth Division

Of primary interest in the Fort Worth Division's current $37 million facility expansion program is the new $8 million Engineering and Office Building, encompassing 581,400 square feet and covering 12 acres.



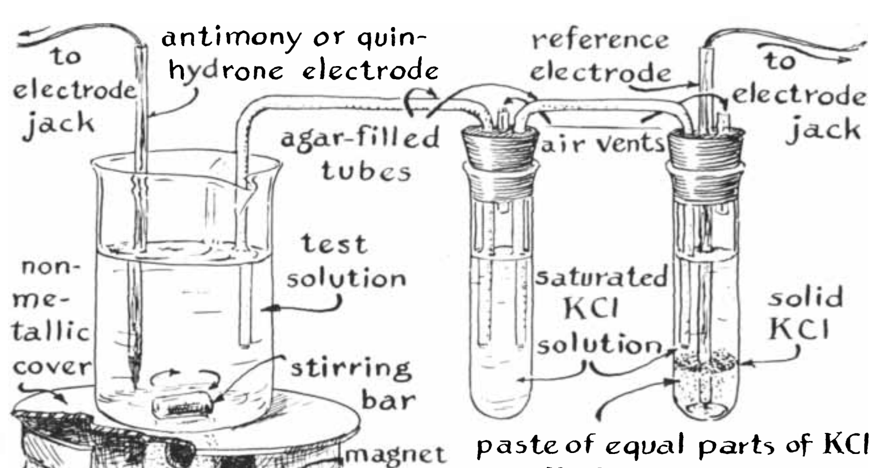
THE AMATEUR SCIENTIST

Making an apparatus that will measure the acidity or the alkalinity of solutions

Conducted by C. L. Stong

Almost everyone has occasion to alter by a specific amount the acid-base balance of water. Through the process of ionization a small, fixed fraction of the molecules in any given quantity of pure water break up into positively charged groups (hydronium ions) and an equal number of negatively charged groups (hydroxyl ions). Pure water is neutral, but if the proportion of hydronium ions is increased, it becomes acidic. A basic solution contains an excess of hydroxyl ions. For example, the proportion of hydronium ions in a beverage is increased if one adds juice from a lemon or a lime. The change imparts a tart or acid flavor to the drink. Conversely, cooks often reduce the proportion of hydronium ions in foods. For instance, the addition of baking soda to flour during the preparation of buttermilk pancakes increases the number of hydroxyl ions and so sweetens the dough.

Gardeners, particularly those who grow hydrangeas, use more precise techniques in adjusting the ionic balance of solutions. They first determine the relative proportion of hydronium to hydroxyl ions in the moisture of the soil by means of a simple chemical test. If the test indicates that there are more hydronium than hydroxyl ions, the soil is acid; if the reverse is true, the soil is basic or alkaline. Pink hydrangeas that are grown in acid soil are likely to turn blue, and blue varieties that are grown in alkaline soil usually turn pink. Accordingly the gardener adds to the flower bed a carefully measured quantity of either aluminum sulfate, which introduces additional hydronium ions and therefore an acid condition, or hydrated lime, which produces hydroxyl ions and therefore a basic condition, depending on whether blue or pink hydrangeas are wanted.



Sam Epstein's apparatus for measuring the pH of solutions

The pigments in flower petals and green leaves are sensitive to the ratio of hydronium to hydroxyl ions in water, as can be demonstrated by a simple experiment. Crush the petals from a red rose to a fine pulp with a mortar and pestle. Add to the pulp about five milliliters of tap water and continue grinding for a minute or so. Filter the fluid through a sheet of paper toweling into a clean glass container. Discard the pulp. Similarly, filter the juice of a lemon into a clean glass container and discard the pulp.

Place five milliliters of tap water in a clean glass container and make a saturated solution of baking soda by adding soda until no more will dissolve. In another container of clean, clear glass (preferably a small test tube) place 10 milliliters of tap water and to it add 10 drops of the filtered extract from the rose petals. The extract will impart a pink tint to the tap water.

Now add five drops of the concentrated soda solution to the pink water. Swirl the test tube for a few seconds to mix the fluids. The color of the mixture will soon turn light blue. Add 10 drops of filtered lemon juice to the mixture and swirl the tube as before. The pink tint will reappear.

The color can be cycled from pink to blue and back again many times by alternately increasing the concentration of hydronium ions with lemon juice and decreasing it with soda solution. Deeper colors can be developed by using stronger reagents. The addition of a single drop of concentrated lye solution (sodium hydroxide) will change the pink color to a rich brown. Two drops of hydrochloric acid will restore the pink hue.

A tap-water solution of pigment extracted from the petals of blue hydrangeas turns green when it is made acid and yellow when it is made basic. The pigment of most green leaves becomes clear in acid and yellow in basic solutions. Substances that react in this way are known to chemists as "indicators." They are frequently used to determine the approximate proportions of hydronium to hydroxyl ions in solutions. Sam Epstein, chief chemist of the Federated Metals Division plant of the American Smelting and Refining Company in Los Angeles, explains how to use indicators for measuring the acid-base balance of solutions, why they change color and how to make an instrument for determining the relative concentrations of hydronium to hydroxyl ions at which they change color. Epstein writes:

"Part of the explanation is found in the nature of water. The chemical formula for a molecule of this unique liquid can be written in either of two forms, H_2O or HOH. I prefer the H_2O formula because it suggests that the structure of a molecule of water is not symmetrical. The hydrogen atoms (H) are grouped on one side of the oxygen atom (O), not on precisely opposite sides.

"For this reason the molecule is also electrically asymmetrical. When water is placed between a pair of charged electrodes, the oxygen sides of its molecules turn toward the positive electrode and the hydrogen sides turn toward the negative electrode. The molecule is said to have an electric dipole moment.

"At room temperature the water molecules of a solution dart about randomly and knock into one another continuously. Occasionally an impact is so violent that a molecule splits into a pair of fragments. One fragment consists of the nucleus of a hydrogen atom (a proton). The other is a clump of particles consisting of the remaining hydrogen atom, the oxygen atom and the electron formerly associated with the dislodged proton. Both fragments now carry an electric charge. One fragment is H^+ (because the proton lost its electron) and the other one is OH^- (because the atoms of this fragment gained the unit charge carried by the acquired electron).

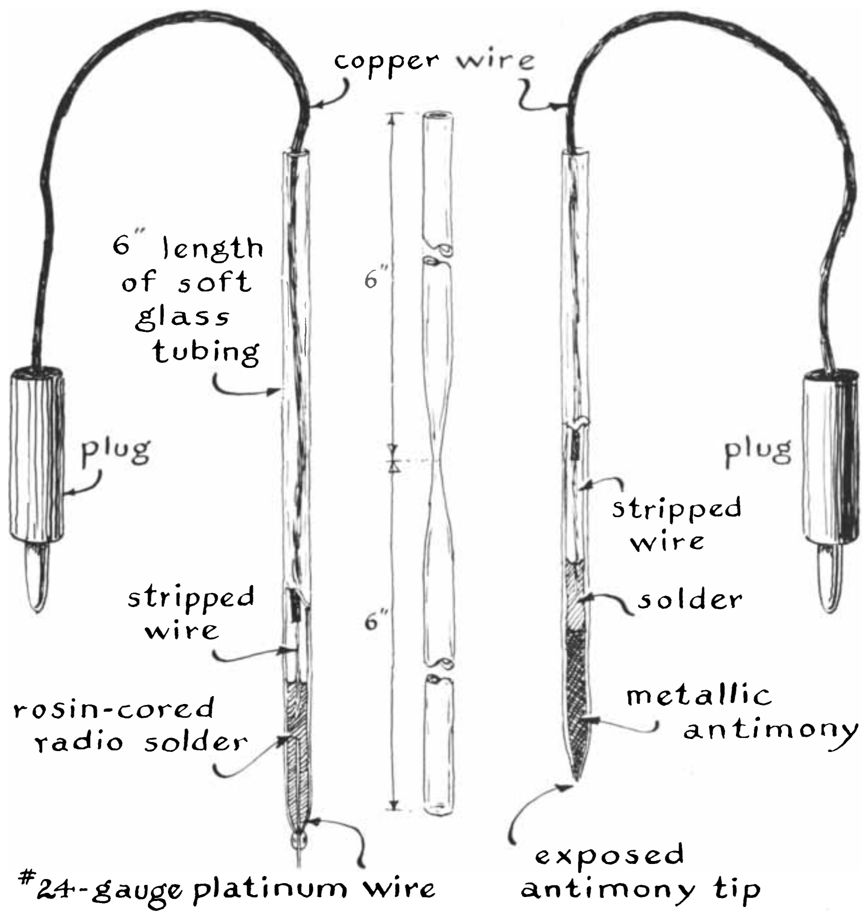
"The force of electric attraction between the oppositely charged fragments causes some pairs to reunite promptly. Occasionally, however, a proton is knocked a substantial distance by the impact and wanders briefly among neighboring molecules. The positive charge carried by the wandering H^+ ion soon responds to the negative side of a water molecule (H_2O) and unites with the molecule to form a new ion: H_3O^+. This particle is known as a hydronium ion.

"Water molecules, because of their electrical character, also tend to form clumps. The weakly positive side of one molecule attracts the weakly negative side of a neighbor. For this reason the H^+ ion may attach itself to a group, forming $H_5O_2^+$, $H_7O_3^+$, $H_9O_4^+$ and so on. All can be considered hydronium ions, but hereafter hydronium will refer to the H_3O^+ group.

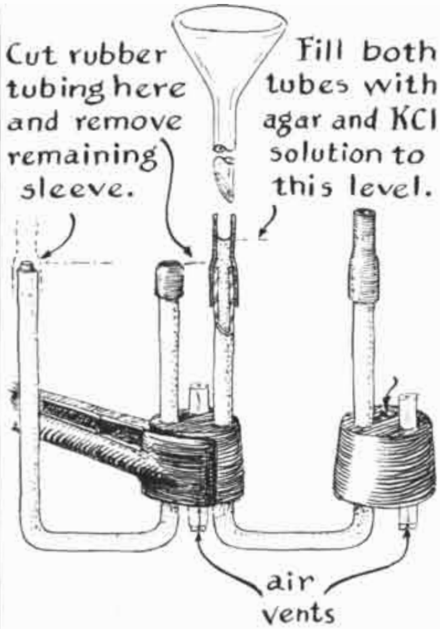
"The relatively massive remaining fragment, the OH^- or hydroxyl ion, tends to exist alone in solution because the polar forces of the molecules are too weak to bind it. In a liter of water at room temperature about 6×10^{16} molecules are ionized. As a result a liter of 'pure' water is actually a solution containing 6×10^{16} hydronium ions and the same number of hydroxyl ions. As large as this number is, it is only .0000002 percent of the number of molecules in a liter of water. This is a seemingly trivial percentage, yet it accounts for much of the chemical activity of water.

"Measuring the concentration of either ion in an aqueous solution automatically gives the concentration of the other one. Since a count of the electrified particles would result in an awkwardly large number, a convention has been adopted for expressing the hydronium-ion concentration of water solutions by means of an inverse logarithmic scale that ranges from 0 to 14 in units called *p*H. To make use of this scale the hydronium-ion concentration must first be known in terms of 'molarity.' One liter of a solution that is one 'molar' with respect to H_3O^+ contains one mole of H_3O^+, an amount whose weight in grams is equal to the sum of the atomic weights of the atoms in the chemical formula, that is, 19 grams of H_3O^+ ($3 \times 1 + 16 = 19$). The *p*H is defined as the logarithm of the reciprocal of hydronium-ion concentration. Pure water, or any neutral aqueous solution, contains 10^{-7} mole of H_3O^+ per liter, therefore its *p*H is 7 (logarithm of $1/10^{-7}$ = logarithm of $10^7 = 7$). A *p*H of less than 7 indicates that a solution contains an excess of hydronium ions and a correspondingly smaller amount of hydroxyl ions. Such solutions taste sour or acid and many of them are toxic. The *p*H of solutions that are deficient in hydronium ions and therefore contain an equivalent amount of excess hydroxyl ions is greater than 7. They taste bitter and feel soapy. Many basic solutions are also toxic.

"The *p*H of solutions can be measured



The platinum (left) *and antimony* (right) *electrodes for the* pH *meter*



Means of preparing the salt bridges

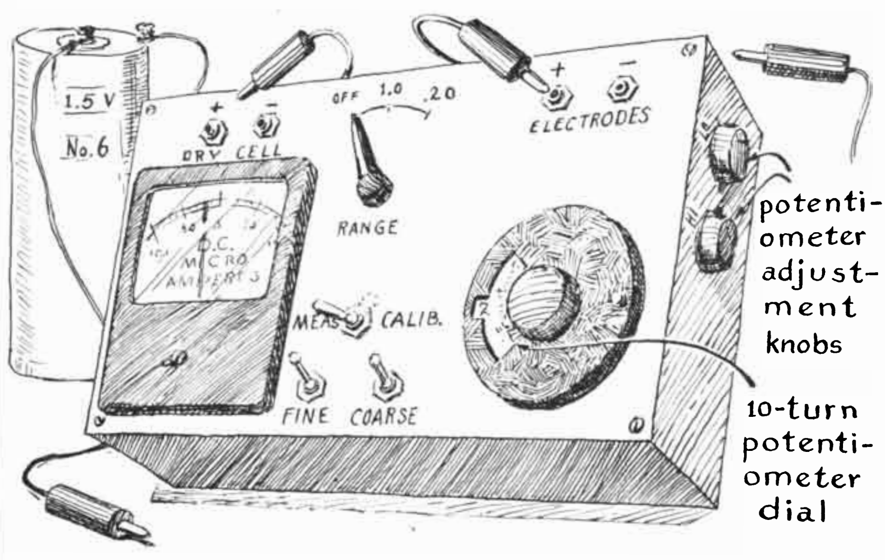
most easily and simply by the use of organic substances that resemble the pigments of flowers and act chemically like such pigments. They impart one color to a solution of given *p*H, change to a different hue at a higher *p*H and serve as indicators. Many of them are highly purified synthetic compounds that are designed to change color within a predetermined range of *p*H. Two common ones are phenolphthalein, which changes from colorless to red in the *p*H range between 8.5 and 10, and methyl orange, which undergoes a change from red to yellow in the *p*H range between 3 and 4.5.

"Indicators are also available in the form of impregnated strips of paper that are particularly convenient to use. One product, known as 'pHydrion' paper, is stained by a series of indicators that assume a characteristic color at each unit of *p*H from 1 to 11. After the paper strip has been dipped in the test solution the hue is estimated to the nearest *p*H unit by comparing the paper with a color chart supplied with each roll. This is an easy way to measure the *p*H of water in a swimming pool. Gardeners will find pHydrion paper equally convenient for measuring the *p*H of soil. To test soil mix a sample with a comparable amount of tap water, let most of the dirt settle and check the liquid with the paper.

"The *p*H range over which there are changes in the color of homemade indicators, such as those extracted from flower petals, leaves, red cabbage and the colored juices of berries, can be determined with an electrical *p*H meter that can be made at home. Building a meter and doing the experiments needed to calibrate it will provide an interesting introduction to the properties of acidic and basic solutions.

"The *p*H meter measures the voltage developed between two electrodes that are immersed in the solution being tested. In essence the electrodes and the solution constitute a voltaic cell that works much like an ordinary flashlight battery. The potential between the solution and one electrode, which is called the indicator electrode, varies with the concentration of hydronium ions in the solution. The potential between the solution and the other electrode, which is called the reference electrode, remains constant.

"The output of the cell is compared



Control panel of the pH *meter*

Computerography to the rescue

In an airplane over the plain states, a camera begins photographing the terrain below. It runs continuously, recording thousands of square miles of land under cultivation at several wavelengths of energy simultaneously. Hundreds of photographs will result, and expert analysts examining and comparing them will identify crops, determine their condition, evaluate water resources, count livestock, discover potential oil fields and minerals.

Three hundred photographs, times two flights a day, times 100 days a year, times 30 planes. Are there that many expert analysts?

As inevitably as we run short of analysts, we must be able to manipulate visual information — just as numbers were encoded to make possible the adding machine, and arithmetic was encoded to make possible the computer.

This is our business — interpreting visual information using optical, electronic and programmed devices. We have delivered systems that analyze seismograms and oil well logs, interpret oceanological data, extract positional information from theodolite photographs, examine biomedical samples, clean up soiled engineering drawings, read oscilloscope wave forms, and make charts and graphs from digital data.

We've hardly scratched the surface.

But we're pushing the inevitable, you might say. And your inquiry may add to the push.

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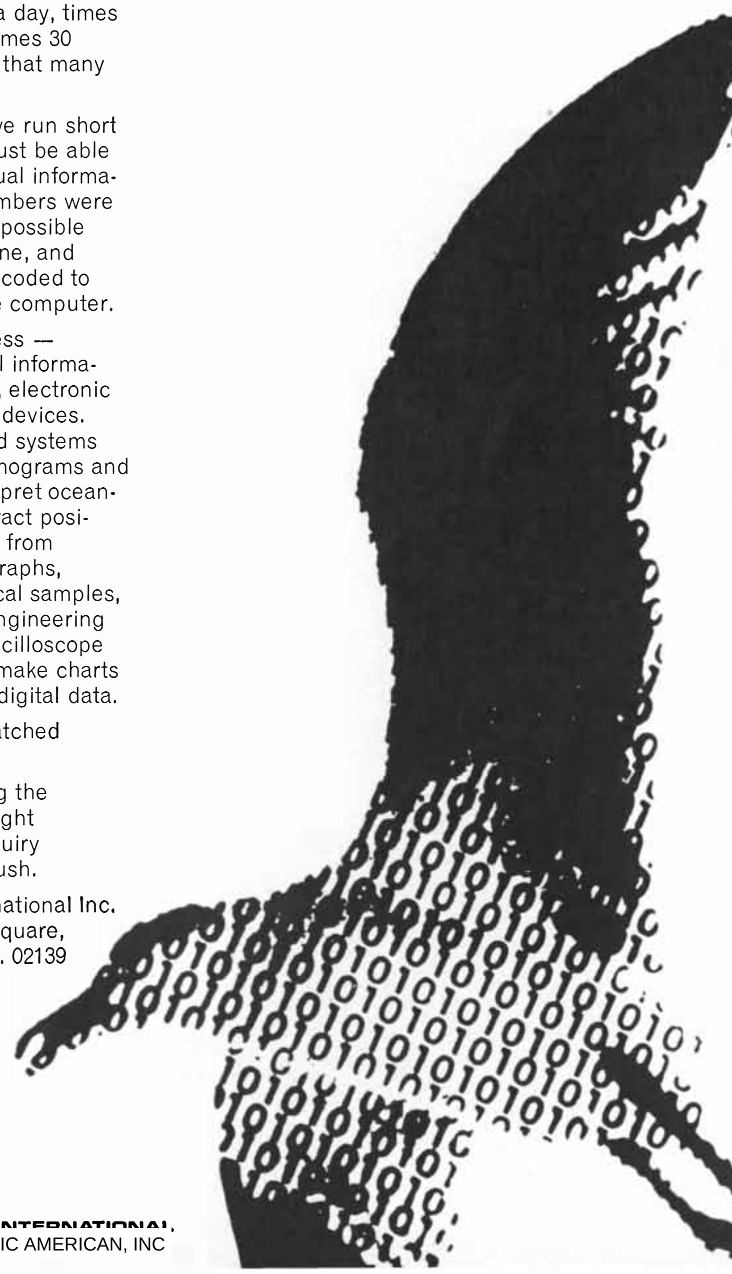

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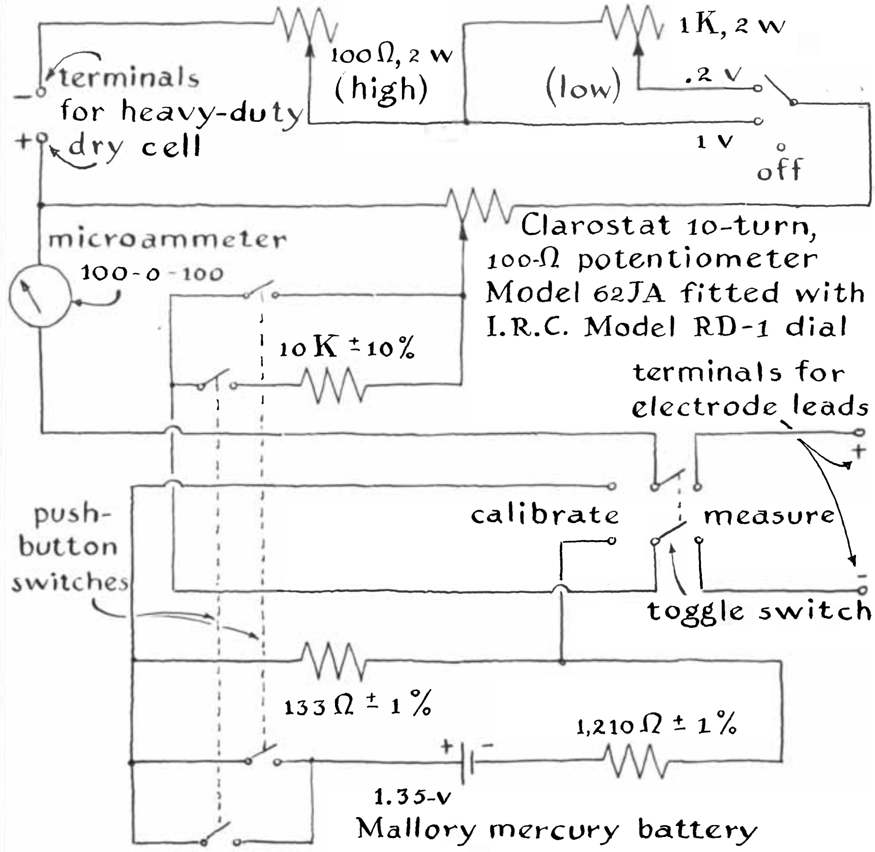


Circuitry of the meter

with a known voltage by means of a potentiometer. The *p*H of the test solution is determined by reference to a graph on which *p*H is plotted against voltage. The instrument can measure a hydronium-ion concentration accurately to a fraction of a *p*H unit.

"The apparatus can use indicator electrodes of two types, one of platinum wire and the other of antimony [*see illustration on page* 233]. When the platinum electrode is used, a small amount of quinhydrone is added to the solution being tested. For this reason the platinum-wire electrode is known as a quinhydrone electrode. The potential between the solution and the platinum-wire electrode varies directly with the hydronium-ion concentration, but the measurements are not reliable above *p*H 8. The antimony electrode works well in both acid and basic solutions, but it is more difficult to make.

"To make the electrodes, heat to redness a half-inch zone in the middle of a 12-inch length of 10-millimeter, soft glass tubing. The heat can be provided by a liquid-propane torch of the kind sold in hardware stores. Grasp the glass near the ends by both hands, pass the center of it through the flame a few times for gradual preheating and then rotate the glass directly in the flame until the midsection softens uniformly.

"Remove the glass from the fire, stretch the midsection, let the glass cool, nick the center of the constricted portion with the corner of a file and pull the ends apart. The tubing will break squarely where the glass was nicked. The finished pieces should have the form shown in the illustration.

"For the quinhydrone electrode slide a length of platinum wire into the tapered end of one tube so that half of the wire extends beyond the glass. Return the tip of the glass, with the wire, to the flame and apply heat until the glass melts uniformly around the wire. Rotate the assembly as required to prevent the glass from drooping. Remove the assembly from the flame and, while the glass is soft, push the exposed part of the wire sideways as necessary to align the wire with the axis of the tubing.

"Return the sealed end to the edge of the flame and, with the pointed end downward, feed enough rosin-core solder into the tube to immerse the inner end of the wire. Complete the electrode by pushing the cleaned end of a flexible, insulated copper wire into the molten solder. Remove the electrode from the

Did we ever introduce you to Hasselblad's version of the 35mm camera?

There's a peculiar tendency to picture the Hasselblad on a tripod in somebody's studio, and to immediately think of 35mm cameras in any outdoor "location" situation. But the fact is that the Hasselblad can go anywhere a 35mm goes and come back with better quality pictures.

The Hasselblad is every bit as portable and even more interchangeable than any 35mm camera (Hasselblad has 5 interchangeable film backs, 8 interchangeable lenses, an interchangeable focusing hood, and an interchangeable winding knob.) Hasselblad is a single lens reflex camera with an advantage over many 35mm single lens reflex cameras, because you can view your 3-dimensional image in two dimensions on a ground glass screen. Andof course, it's a $2\frac{1}{4}$ image instead of a pint sized 35mm image, which makes for sharper focusing, better framing, and vastly improved image quality when the negatives are enlarged to any degree.

The Hasselblad System even consists of four different Hasselblads. First, there is the standard 500C which accepts all 8 lenses, and multiple magazines.

The Super Wide C, equipped with a 38mm, 90° angle of view Zeiss Biogon f/4.5 lens allows you to take pictures previously considered impossible. The superb optics of the lens assures you perfect distortion-free horizontal and vertical delineation, with sharpness of image from corner to corner of the negative area, even at full aperture. (Depth of field at an aperture of f/22 is from 12 inches to infinity.)

The electrically driven Hasselblad 500EL automatically advances the film and cocks the shutter, allowing a rapid series of exposures to be made, either by use of the camera release or long release cords, timer, or remote radio control. The 500EL accepts all lenses and most accessories available for the 500C.

The electrically driven 70mm Hasselblad offers the same features as the 500EL, plus a 70mm film magazine which allows up to 70 exposures on casette loaded 70mm film. This frees the photographer from mechanical necessities when a large number of exposures is required.

The eight Hasselblad lenses, made by Carl Zeiss, all have built-in Synchro Compur shutter, with automatic stopping down at the moment of exposure and manual depth of field checks. Every lens has both M and X synchronization allowing the use of flash and strobe at all speeds up to 1/500th of a second. There is a 40, 50, 80, 120, 135, 150, 250, and 500mm lens.

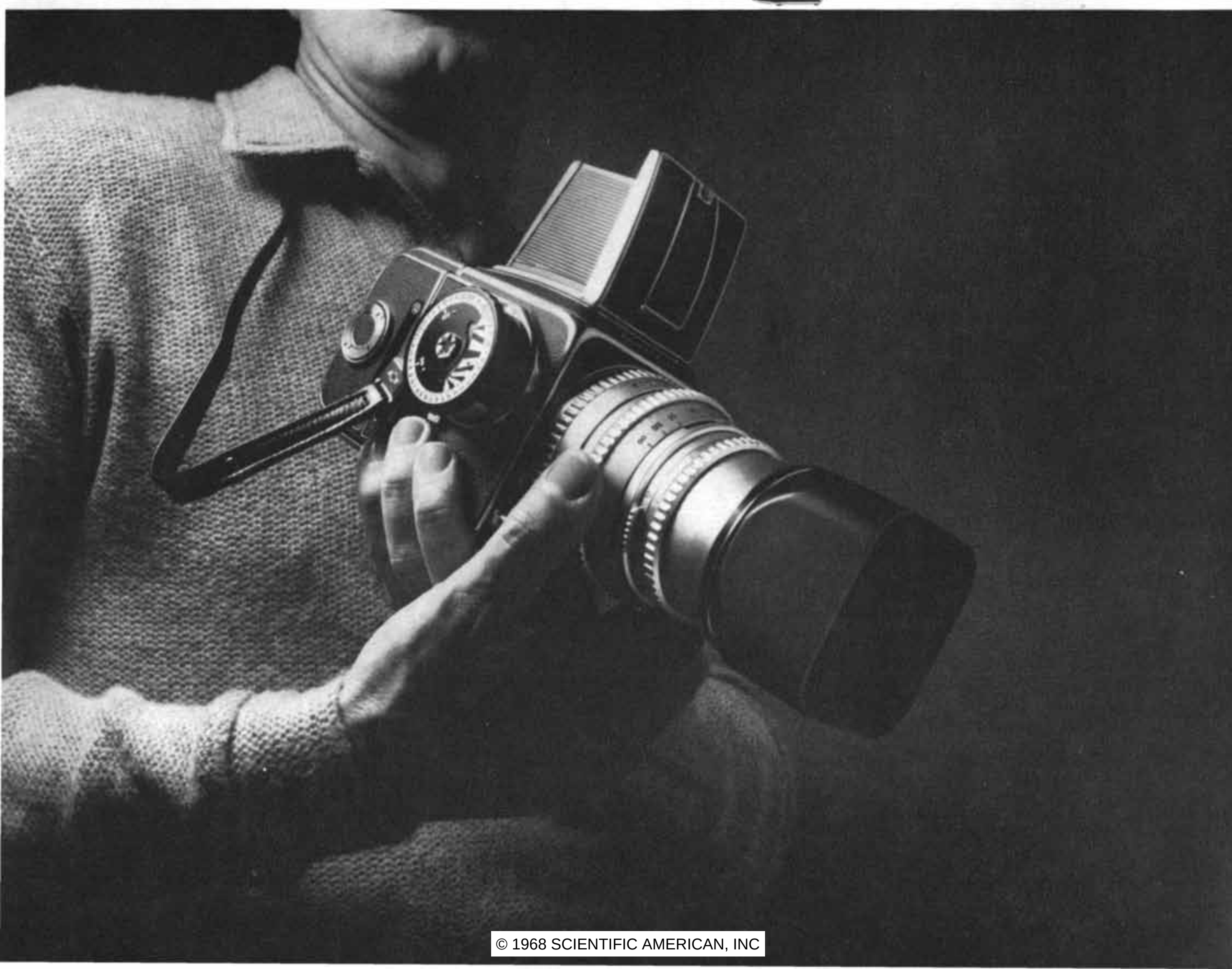
The five different interchangeable magazines allow you to make 12 or 16 exposures on 120 film, 24 exposures on 220 film, and 70 exposures on 70mm film. The magazines also permit the choice of 3 formats – $2\frac{1}{4}$ square, $2\frac{1}{4}$ X $1\frac{5}{8}$, $1\frac{5}{8}$ X $1\frac{5}{8}$, as well as allowing a change of film type (e.g. black and white to color or vice versa) in mid-roll.

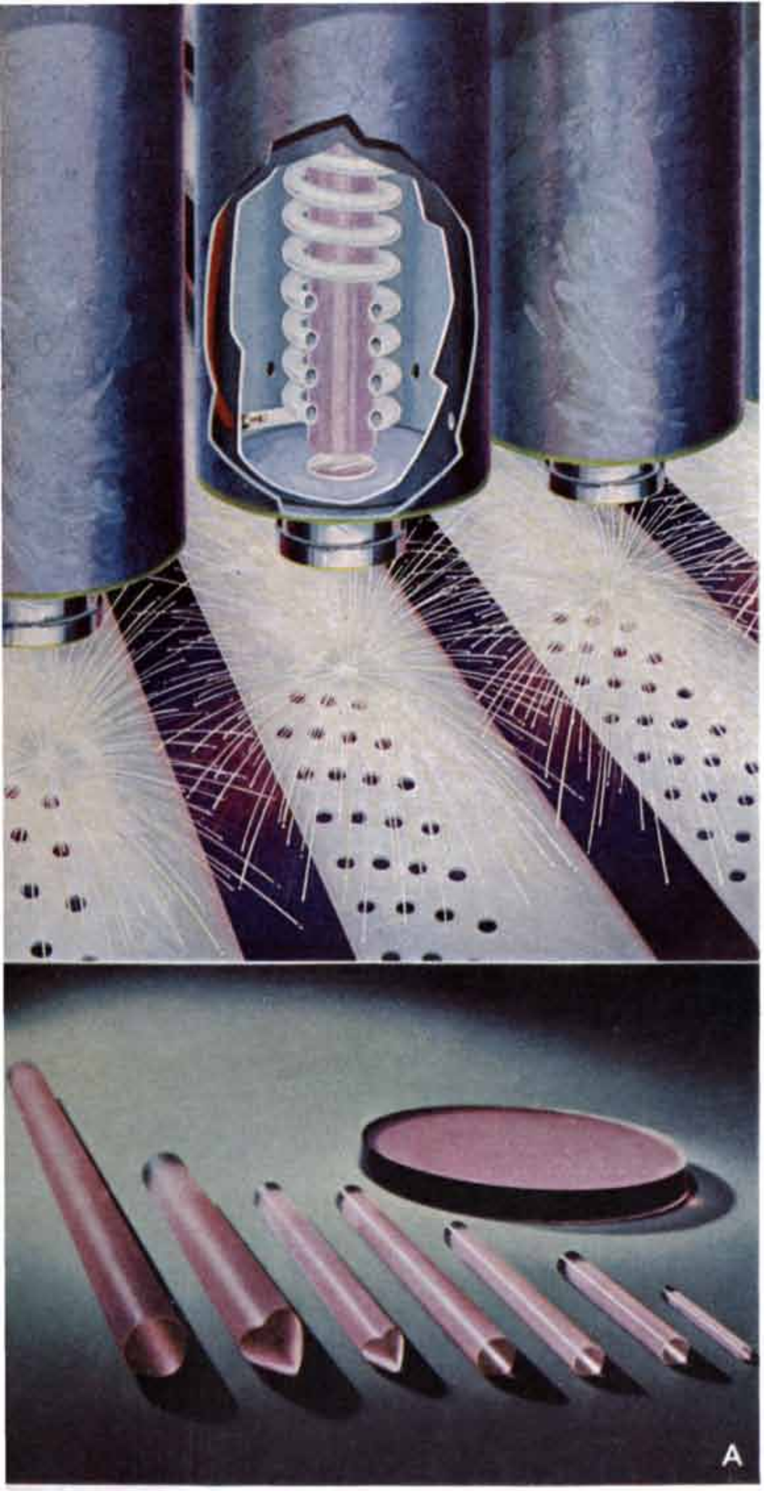
The Hasselblad System has a huge range of accessories that includes proxars, extension tubes and bellows extension for close-up work. Filters. Transparency copy holder. Cut film back. Eye level prism finders. Sun shades. Rapid winding crank. Quick focusing handles. Grips. Underwater housing. Ring light. Tripod quick coupling. Microscope attachments. And carrying cases.

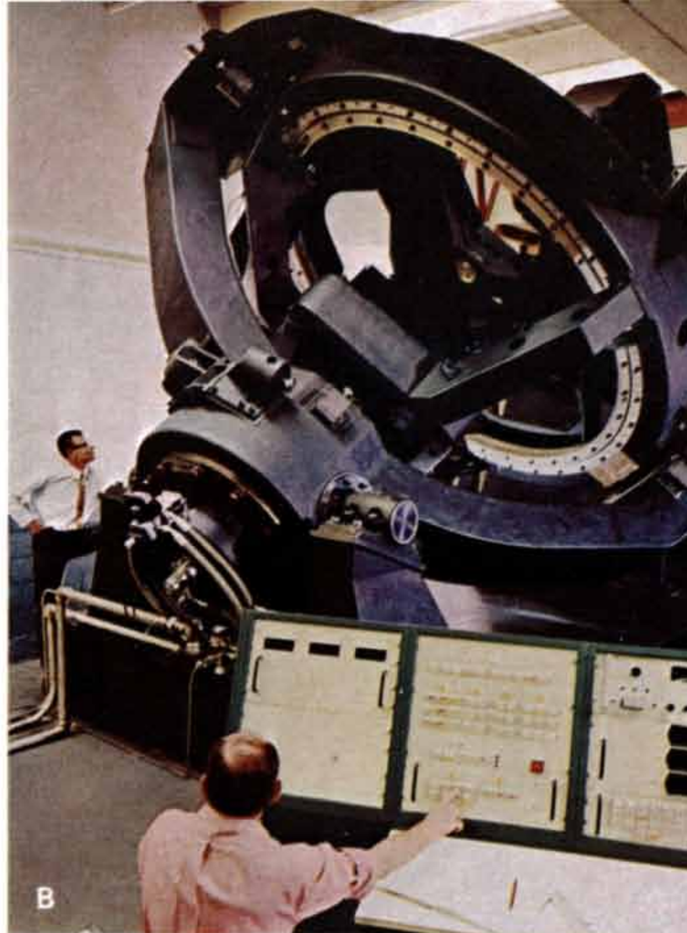
So the next time you're snapping away 36 35mm exposures and the best shot happens on the 37th exposure, think about the 70mm Hasselblad EL with 70 exposures. And the next time you lose a great color shot because there's black and white film in your camera, think of the Hasselblad interchangeable magazines. And next time you blow up a gorgeous 35mm transparency and the enlargement looks like multicolored cottage cheese, think about Hasselblad's $2\frac{1}{4}$ square format. And the next time you think about 35mm, think about Hasselblad.

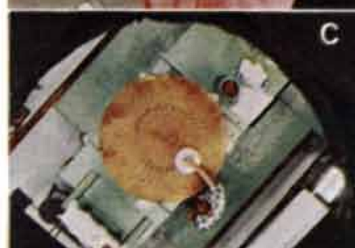
For more information, write to Paillard Incorporated, 1900 Lower Road, Linden, New Jersey 07036. We'll send you a free 40 page booklet on the Hasselblad.

The Hasselblad System









A new laser glass, Owens-Illinois ED-2, shows consistently higher efficiencies, better resistance to solarization, and better thermal conductivity.

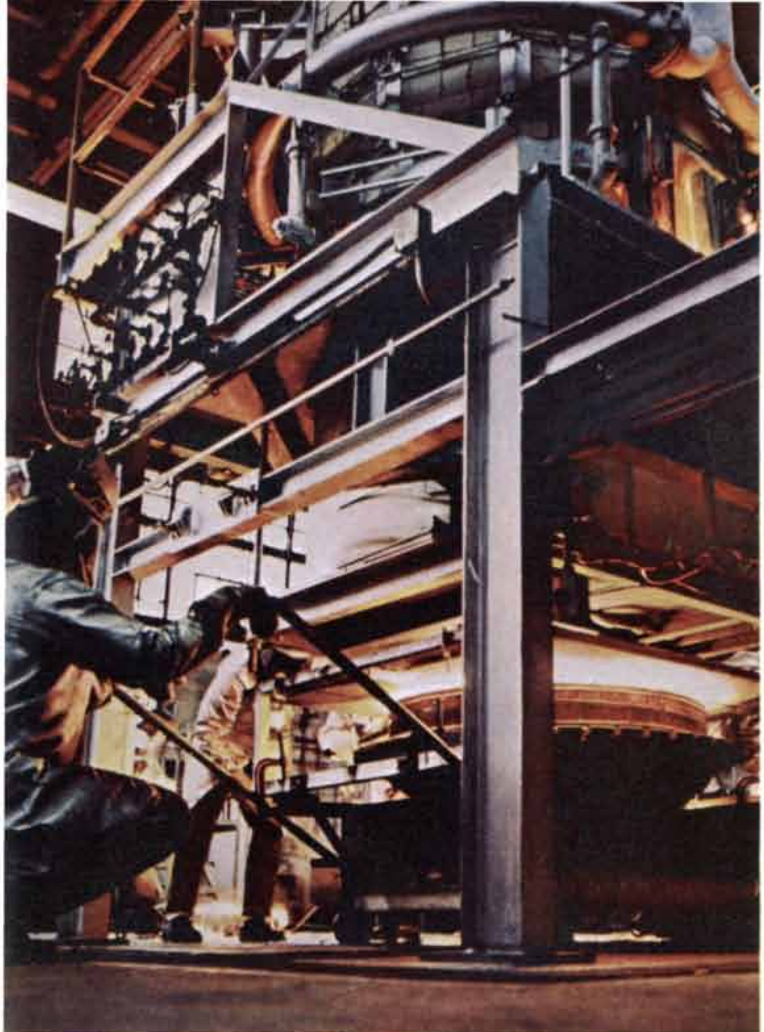
No knowledgeable scientist would claim an ultimate all-purpose success in a field so new and uncharted. But evaluative data since this January 1968 announcement is gratifying.

We are as anxious to invite trials to search out shortcomings as to extend our evidence of success in relation to your varying needs.

In the above photo (photo A), Owens-Illinois ED-2 laser glass of various configurations is displayed below a sketch of synchronized laser drills.

A current Fecker Systems project (photo B) is a computer-controlled 3-axis dynamic simulator, designed for pre-orbital evaluation of NASA's Apollo telescope mount control-moment gyros. Problem-oriented Fecker people work from concept to finished system, designing and assembling computers and electronic controls (photo D) as well as gimbal systems and optics.

A near-century of experience stands behind Fecker capabilities in telescope mirror production. Photo C shows a phase of the meticulous operation of figuring, grinding, and polishing a mirror blank to an accuracy within a millionth of an inch. Facilities are available to handle mirrors up to 150-inch category and constantly check progress without removal from the polishing machine. Computer facilities (photo E) give rapid reduction of test data as well as provide a high-speed optical design capability.



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new materials, new capabilities to harness the potency of light.

For the field of optics, Owens-Illinois offers three new inputs.

The uniqueness of our new glass-ceramic CER-VIT® material is that specific properties such as zero-expansion can be tailored into totally new combinations.

Owens-Illinois ED-2, a new laser glass in advanced evaluation, likewise encourages expectation of new levels of performance.

Broadened capabilities include our Fecker Systems Division whose custom engineering is identified in pioneer production of major telescope systems and in major space and defense projects.

Inter-disciplinary engineering which characterizes Fecker is now backed by research counterparts.

Both depth and scope are normal to Owens-Illinois research where we probe to basic beginnings for perfection and innovation in raw materials themselves — glass, paper, plastics and new-generation hybrids.

Owens-Illinois CER-VIT material, since it entered the market, has been chosen for more of the world's great telescope systems than any other mirror material. The unique combination of advantages available with CER-VIT material includes zero-expansion, homogeneous quality, freedom of design inherent in its castability, low strain, high strength, and faster finishing. Sketch F shows comparative dimensions of the 158" mirror destined for the U. S. observatory in Chile.

CER-VIT material's tailorability, for example to transmit infrared and microwave energy, or to alter its ionic, magnetic or electrical behavior suggests multiple new uses beyond the optics applications.

OWENS-ILLINOIS

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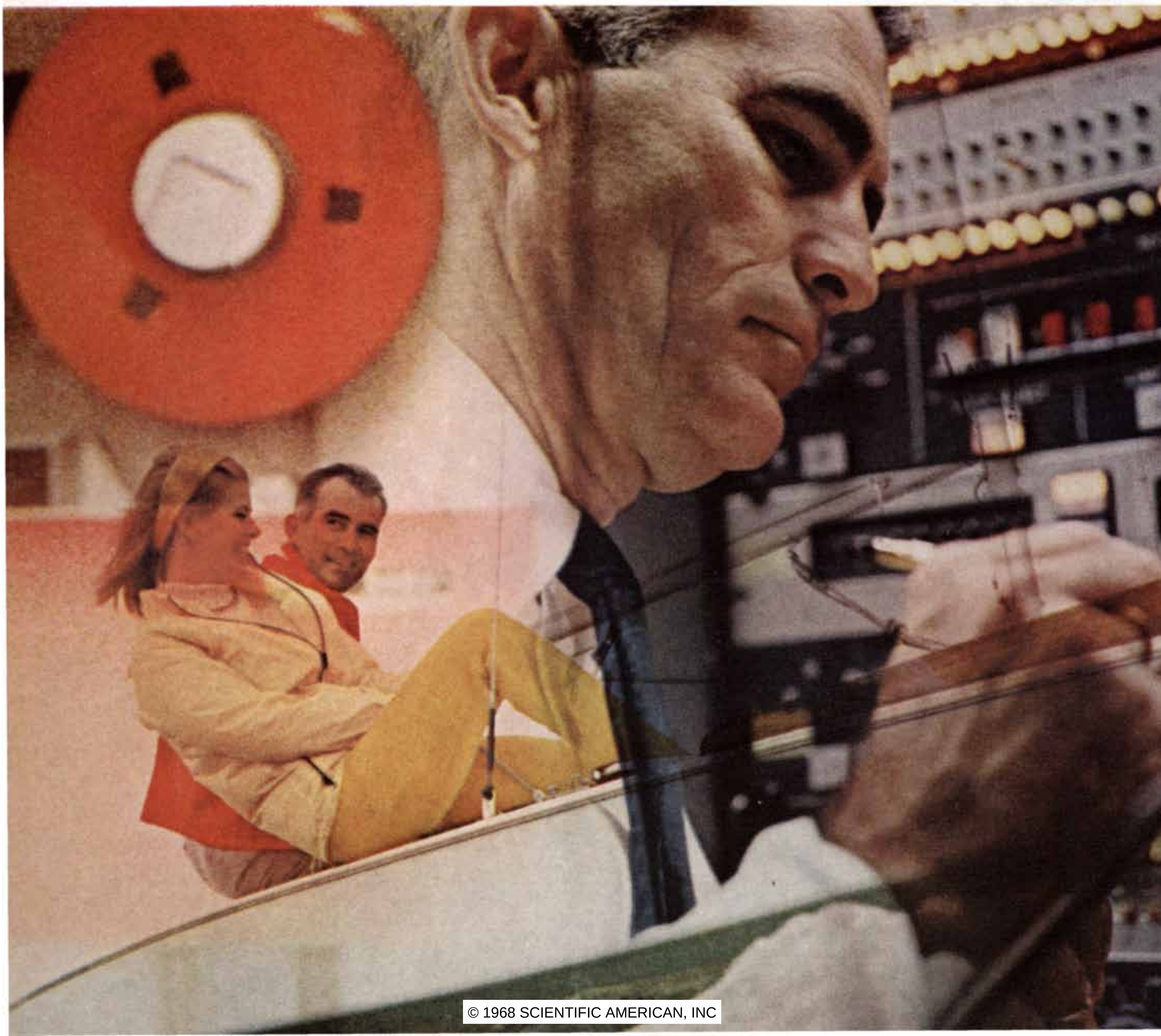
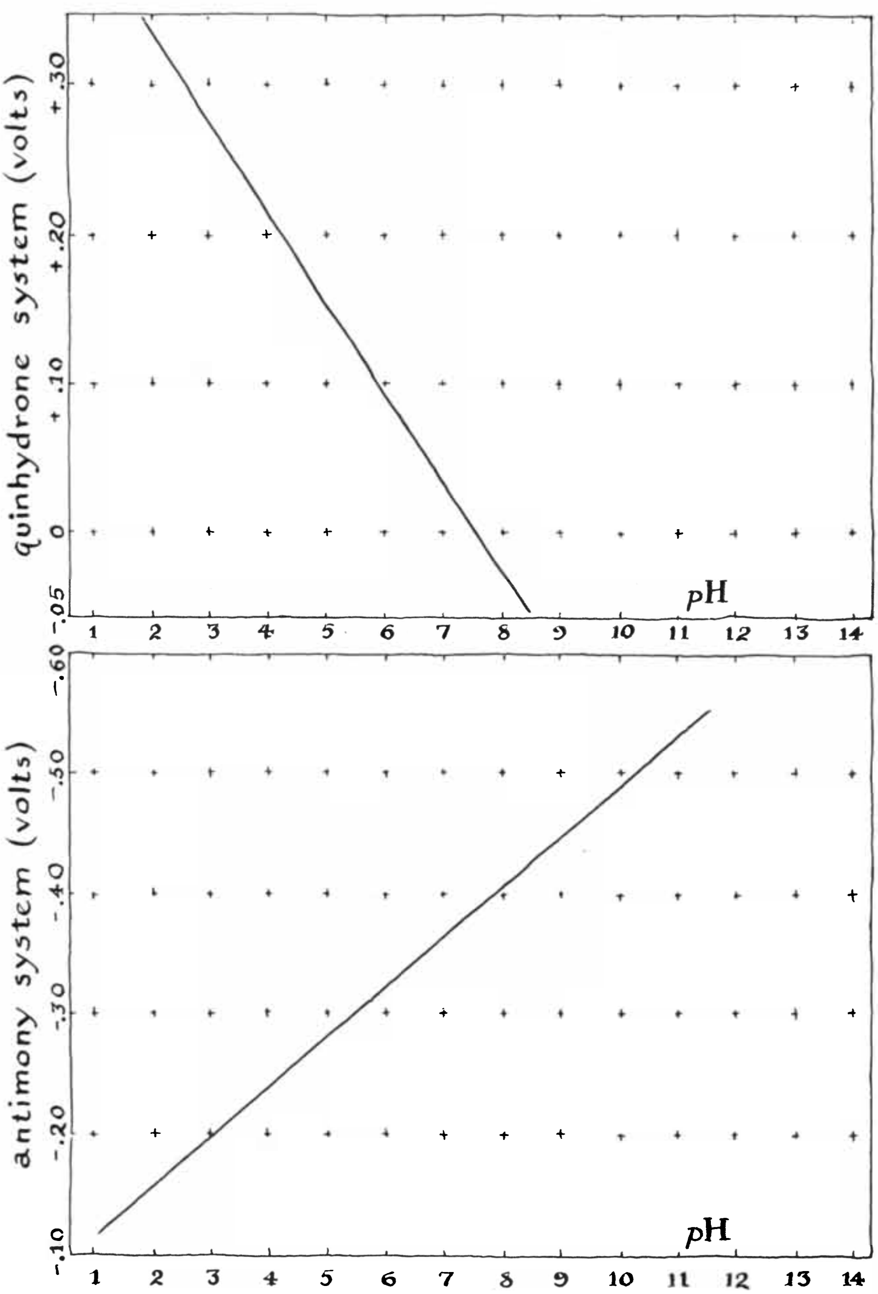


flame and let it cool in the upright position.

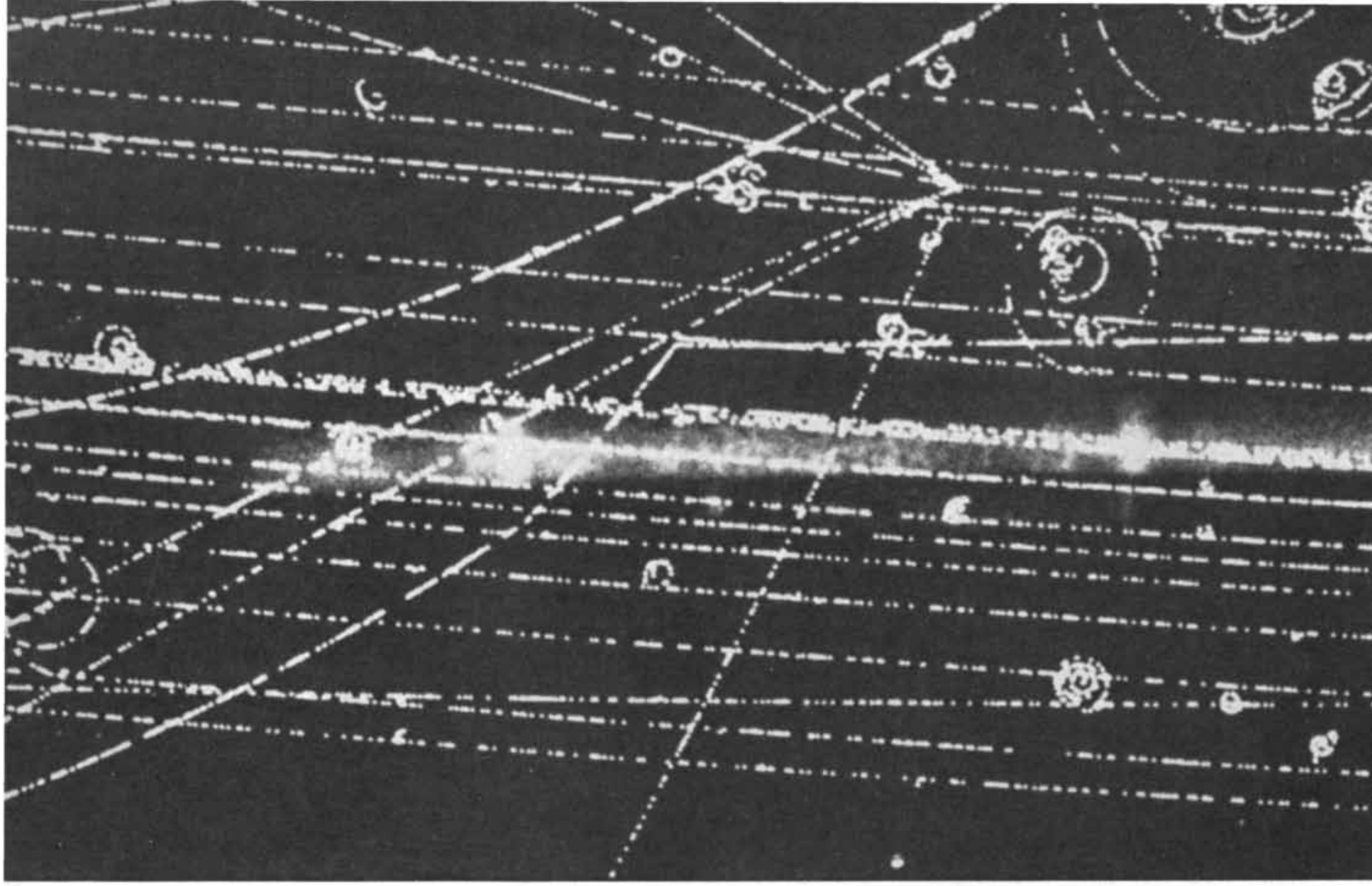
"To make the antimony electrode, melt the constricted tip of the second glass tube until it closes and fill the tube to a depth of about two inches with small lumps (not powder) of 99.8 percent pure antimony metal. Antimony of this grade can be bought in lots of 1/4 pound for about $2 from the Fisher Scientific Company, 711 Forbes Avenue, Pittsburgh, Pa. 15219. Heat the tube until the antimony melts. Shake the tube lightly as necessary to prevent bubbles of air from becoming trapped in the metal.

"Let the metal cool until it solidifies. Then add a layer of rosin-core solder and insert a copper lead wire into the solder. The solder should fuse to the antimony as well as to the copper. When the assembly cools, nick and break off the tip of the glass to expose a small cylinder of antimony, which will act as the electrode. Polish the exposed metal with crocus cloth.

"The reference electrode, which is also known as the saturated calomel electrode, must be connected to the test solution through two tubes of agar moistened with potassium chloride solution [*see illustration on page 232*]. The tubes are known as salt bridges. The complete electrode assembly consists of 40-milliliter centrifuge tubes or heavy-walled test tubes, U loops of quarter-inch



Typical graphs obtained with the meter



FIVE BOOKS IN PHYSICS FROM FREEMAN

Concepts of Classical Optics

JOHN STRONG, University of Massachusetts

1958, 692 pages, 414 illustrations, (57-6918), $10.00

Although it was written as a textbook for an intermediate course in optics, this volume, with its lively and original treatment of the subject, is useful also for reference purposes. Seventeen appendixes, consisting of essays written by authorities on topics of research interest, include several summaries of material that otherwise is not easily accessible.

"*Concepts of Classical Optics* combines the attributes of a one-author text and a collection of symposium papers by specialists in particular fields.... The style is less dry than the average text, and the explanations have a lucidity and succinctness not often found together. The book should serve its designed purpose well and certainly merits inclusion as a reference work in the advanced amateur telescope maker's library."— H. H. Selby, *Sky and Telescope*, December 1958

The New College Physics

A SPIRAL APPROACH

ALBERT V. BAEZ

1967, 739 pages, 743 illustrations, illustrated in 2 colors, (67-12180), $11.75

In this introduction to general physics for the layman, the author leads the reader gradually from the classical concepts of the science through the modern ones. The approach used is first to progress from one basic idea to another, giving specific examples of each, and then to return to these ideas at successively higher levels of difficulty

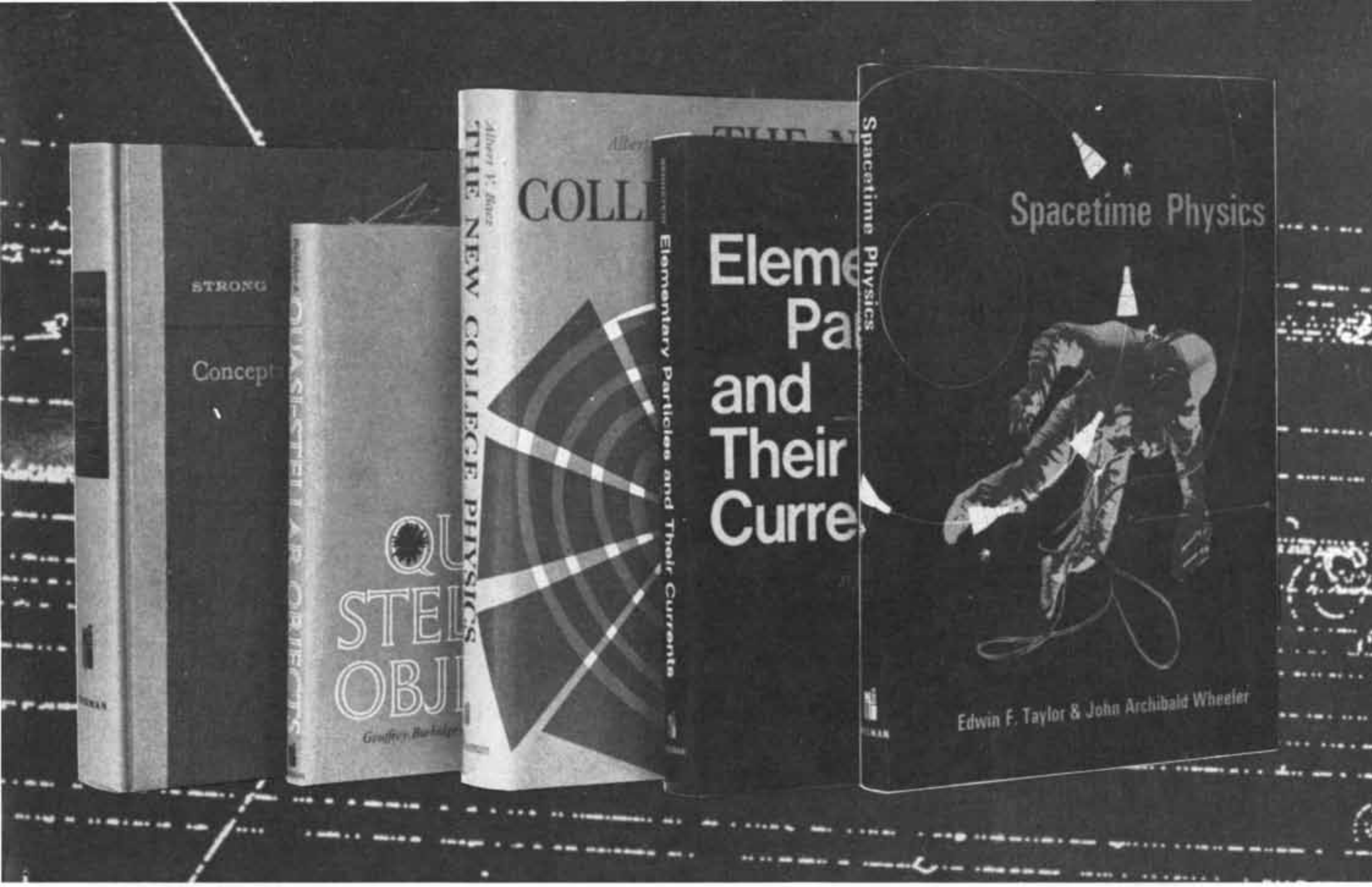
"A very creditable new approach.... The book is a valuable addition to the literature of general physics texts. It should be in the hands of all who teach general physics courses... and on the shelves of all college libraries." —*Science Books, A Quarterly Review,* September 1967

Quasi-Stellar Objects

GEOFFREY BURBIDGE and MARGARET BURBIDGE, University of California, San Diego

1967, 235 pages, 24 illustrations, 18 tables, (67-17457), $7.50

"Up-to-date (all relevant data up to early 1967), personal yet comprehensive, this small book is as good as its authorship suggests. Roughly half of it is a clear and crisp summary of the facts about quasars (150 are listed, with 100 red shifts), their identity, spectral lines, optical and radio continuum and variations, and distribution in depth and direction. The other half is an excellent summary and critique, partisan but fair, of the models proposed to make order out of the properties of these bewildering objects."— *Scientific American,* January 1968



Photograph from the Brookhaven National Laboratory.

Elementary Particles and Their Currents

JEREMY BERNSTEIN, Stevens Institute of Technology

1968, 322 pages, (68-21404), $12.00

This book emphasizes the important role played by currents in the physics of elementary particles. It treats the theory of elementary particles in a unified way under the general theme of currents—unlike many previous books which have placed heavy emphasis on the field equations for the strongly interacting fields. The author, a former Member of the Institute for Advanced Study and Brookhaven National Laboratory, has written more than thirty articles on the theory of elementary particles and weak interactions. He holds the Westinghouse-A. A. A. S. Science Writing Award (1964), and is a writer for *The New Yorker*.

"... [P]erhaps one of the most anxiously awaited books on a fast-changing field ... of great importance to all the research physicists dedicated to unravelling the mysteries of nature."— Ramesh Chand, Wayne State University

Spacetime Physics

EDWIN F. TAYLOR, Massachusetts Institute of Technology, and JOHN ARCHIBALD WHEELER, Princeton University

1966, 208 pages, 138 illustrations, 3 portraits, 15 tables, (65-13566), $5.50

The authors employ many pedagogical tools—including parables, diagrams, marginal notations and figures, and more than 100 provocative, original problems—to help the reader develop the special kind of intuition that is the basis of a true understanding of relativity.

"... In many ways ... an astounding book. ... The idea that there is nothing intrinsically difficult about relativity could be taken as the central theme of the book. ... Anyone who has the slightest interest in the special theory of relativity, be he undergraduate, graduate student, or professional physicist, will find this book well worth the modest price."— Frank C. Jones, *Transactions of the American Geophysical Union,* June 1967

From your bookseller, or from

W. H. Freeman and Company
660 Market Street, San Francisco, California 94104
Warner House, Folkestone, Kent, England

glass tubing and also the associated chemicals and hardware. The mercury, calomel paste, solid potassium chloride and saturated potassium chloride solution are prepared and placed in sequence in one of the centrifuge tubes. The relative proportions are not critical and can be judged from the illustration.

"Care must be taken, however, in preparing the agar-potassium chloride bridges, which protect the saturated calomel electrode from contamination by the test solutions. To prepare the bridges soak four grams of agar in a small beaker containing 100 milliliters of distilled water. Preferably the soaking should continue overnight.

"Place the small beaker in a larger one of boiling water and apply heat until the agar is fully dissolved. Add 30 grams of potassium chloride and, with the beaker still in the boiling water, stir the mixture until the potassium chloride has dissolved. If necessary, add just enough water to dissolve the salt completely.

"Invert the U tubes, fit the ends with short sleeves of rubber tubing, clamp the tubing and fill the assembly with the agar solution. The solution must completely fill the bridge tubes and the flexible sleeves. If it does not, air bubbles may be trapped when the tubes are inverted in the solutions.

"In spite of the best care the agar eventually becomes contaminated, producing erratic results. To replace it disassemble the apparatus, put the bridges in boiling water to melt the agar, rinse them thoroughly and refill them. The agar tube that dips into the test solution should be immersed in saturated potassium chloride solution when the calomel electrode is not in use.

"The voltage developed across the electrodes by reaction with the test solution must be measured by a potentiometer of the null balancing type, which is an instrument that draws no electric current during the interval when the unknown voltage is measured. In instruments of this type voltages of opposing polarity, one known and the other unknown, are simultaneously applied to a meter [*see illustration on page 236*]. The magnitude of the known voltage is adjusted until the meter reads zero. At this point it equals the unknown voltage. The instrument must be calibrated each time it is used.

"To make the calibration for measuring potentials up to one volt, plug in the leads from the dry cell and turn the range switch to the one-volt position. Rotate the dial of the precision potentiometer to the 135 position. Move the 'measure-calibrate' switch to the calibrate position. Set the knob of the high-current potentiometer to the center of its travel. Depress the 'coarse-read' button momentarily and note the meter deflection. Turn the knob of the high-current potentiometer slightly in either direction, depress the button again and note the response. If the pointer of the meter moves more violently in the same direction, readjust the high-current potentiometer in the other direction and depress the button again.

"The object is to adjust the high-current potentiometer to a position that causes a meter deflection of less than one scale division. The purpose of the coarse button is to protect the meter from possible damage by excessive current when the instrument is grossly unbalanced. Complete the calibration by alternately depressing the fine button and adjusting the high-current potentiometer until the meter deflection is negligible. When the instrument is so balanced, the potential of unknown voltage that is developed by the test solution is determined by dividing the number on the dial of the precision potentiometer by 1,000. For example, a dial reading of 250 indicates a potential of .250 volt (250/1,000 = .250).

"The instrument is similarly calibrated to measure the potential range from 0 to .2 volt (0 to 200 millivolts). To calibrate this range turn the range switch to the .2-volt position and the dial of the potentiometer to 675. Balance the instrument by alternately operating the coarse and the fine button and adjusting the low-current potentiometer until the meter shows negligible deflection. The dial readings when now multiplied by .0002 indicate the potential. For example, a dial reading of 250 indicates a potential of .05 volt (250 × .0002 = .05). The calibration is valid for only one range at a time. Calibration of the .2-volt range destroys the calibration of the one-volt range and vice versa.

"The electrode system must also be calibrated. Prepare with distilled water a solution of 1,000 milliliters that contains 28.4 grams of reagent-grade anhydrous disodium phosphate and another solution of the same volume that contains 21 grams of reagent-grade citric acid. Weigh the chemicals directly from freshly opened bottles and store the solutions in clean plastic containers.

"Put 39.2 milliliters of the citric acid solution and .8 milliliter of the phosphate solution, which is basic, in a clean beaker. The solutions can be transferred conveniently by using burettes, which are calibrated glass tubes that can dis-

The light brigade

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OTI Director and consultant.
Co-inventor of the laser.

Richard H. Pantell, Ph.D.
OTI consultant, Professor of Electrical Engineering, Stanford University.

Stuart Lee Adelman, Ph.D.
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charge solution one drop at a time, or by means of a calibrated pipette. The pH of the mixture is 2.2.

"Immerse the antimony electrode and the reference electrode in this mixture. Connect the antimony electrode to the negative terminal of the potentiometer and the reference electrode to the positive terminal. Mix the solution in an electrically operated agitator for a few minutes to saturate it with air. Measure the voltage developed by the test solution on the one-volt range. When making the test, set the measure-calibrate switch in the 'measure' position. If the potentiometer fails to balance, reverse the leads to the electrodes. Record the voltage and also the corresponding pH (2.2).

"Next, replace the antimony electrode by the platinum electrode and connect it to the positive terminal of the potentiometer. Connect the reference electrode to the negative terminal. Dissolve as much solid quinhydrone in 10 milliliters of rubbing alcohol as the alcohol will hold, thus making a saturated solution. This chemical can be obtained from the Fisher Scientific Company in lots of 1/4 pound for about $4. Add five drops to the 2.2-pH test solution. While stirring the mixture, measure and record the voltage.

"Repeat this procedure, alternately using the antimony and quinhydrone electrodes, to determine the voltage developed by solutions that contain the following volumes (in milliliters) of citric acid and sodium phosphate: 24.6 and 15.4, 14.7 and 25.3, 1.1 and 38.9. The pH of the three mixtures is respectively 4, 6 and 8.

"The polarity of the quinhydrone electrode reverses at a pH of approximately 7.6. For this reason the leads from the electrodes to the potentiometer must be reversed when the quinhydrone electrode is used for measuring solutions of concentration higher than 7.6 and the potentiometer must be operated on the .2-volt range. Indeed, accuracy is improved by using this range for measuring all potentials of less than .1 volt.

"Plot the recorded voltages and the corresponding pH in the form of two calibration graphs [*see illustration on page 241*]. Because of slight irregularities, including errors of observation, the plotted points may tend to scatter slightly on both sides of a straight line. Draw the graphs through the center of the scattered group of points so that equal numbers of points fall on each side of the line. Any point that is obviously out of line with the others should be remeasured.

"The range of pH through which an unknown indicator changes color can now be determined easily. For example, prepare an extract of pigment from rose petals or other flowers. Add a few drops of the extract to 35 milliliters of distilled water, enough to tint the water as viewed against a sheet of white paper. Insert the antimony and reference electrodes in the solution.

"Pour into a clean container a few milliliters of the citric acid solution used during the calibration; into another clean container pour a like amount of phosphate solution. Add the phosphate solution drop by drop to the test solution until the pigment just changes color. Stir the mixture continuously. Measure the pH. Add citric acid drop by drop until the color changes again. Measure the pH.

"These measurements establish the limits of the pH range through which the indicator is effective. The range of hues that indicate intermediate values of pH can be determined by beginning at either extreme and measuring the voltage of the system after the addition of each increment of acid or phosphate solution. The corresponding pH values are obtained from the antimony-electrode graph.

"Why do indicators change color when pH changes? Most indicators are weak acids—substances that can donate hydronium ions to solutions. The molecules of the acid display a characteristic color when the acid is placed in a solution whose pH is below a certain level, which will depend on the particular indicator involved. In solutions of higher pH the molecule ionizes, or splits. The ionized fragments have a different color. Thus it is possible to switch the color of an indicator back and forth a number of times by changing the pH of the solution.

"The potentiometer can be used to check the pH of aqueous solutions such as vinegar, baking soda, borax, Epsom salts, carbonated beverages, household ammonia and fruit juices. The instrument is also useful for measuring the pH of turbid or colored solutions that obscure the true color of an indicator.

"Warning: Many chemical compounds are toxic, particularly those containing mercury. If chemicals come in contact with the skin, wash the affected area promptly, preferably in running water. When making experiments, wash your hands frequently and keep them away from your mouth."

BOOKS

The remarkable story of the element helium

by Philip Morrison

HELIUM: CHILD OF THE SUN, by Clifford W. Seibel. University Press of Kansas ($4.95).

On August 19, 1868, looking at the sun as it rose over the green hills near the mouths of the River Kistna on the Bay of Bengal, Pierre J. C. Janssen became the first man to detect a sign of the element helium. Janssen, the tireless and venturesome founder of the observatory on Mont Blanc, had brought a large spectroscope to view the blood red prominences of the sun at a total eclipse the day before. All across India other savants from Europe were working (without benefit of photography); four spectroscopists besides Janssen had seen during the eclipse the bright lines—red, green, yellow and blue—that demonstrated the gaseous nature of the solar prominences.

In the brief glimpse an eclipse provides it was not easy to be sure that the single bright orange-yellow line, so close to the double line of sodium familiar in every yellow laboratory flame, was in fact at a different position. Janssen, however, had taken a long step beyond his rivals. He had realized from the brilliance of the glowing lines during the eclipse that with a high-dispersion spectroscope the continuous spectrum of sky light would be widely spread out and thus would be faint, whereas the narrow lines from the solar prominences would remain narrow and should be visible in contrast, without any need for the moon to fleetingly mask the sun's disk. He was ready the next day, and he found he could indeed map the prominences in full daylight. Moreover, he could compare the two Fraunhofer lines of sodium, seen as dark absorption shadows against the sun's disk, with the bright yellow line beyond the disk but adjoining it. The yellow line was patently displaced from the sodium ones by one part in 300, toward the blue. After a day or two he sent his account to the Académie des Sciences—a wonderful result of the still rather new spectroscope.

Within the same hour on October 21, 1868, when Janssen's letter from far-off Guntur was opened in Paris, the Académie opened first another letter on the same topic! J. Norman Lockyer, a brilliant and original man, a civil servant of the War Office in London and at that time still a gifted amateur of science, had for two years realized that a high-dispersion spectroscope ought to show prominences without benefit of an eclipse, if the prominences were in fact gaseous. He had persuaded the Royal Society to allow him a government grant of 40 pounds to help buy the new instrument, but they had not acted until 1867. The optician with whom he first placed the order died, and delivery was finally made only after Lockyer had heard sketchy news from India that there were indeed bright lines in the light from the edge of the sun. He received his spectroscope on October 16 and with it achieved the same startling result as Janssen's. The French were generous and struck a single gold medal for the two men who had found how to view the invisible flames of the sun. (Lockyer also got a grant of 60 pounds for 1869.)

At first the new yellow line was believed to be from hydrogen. The strongest of the other prominence lines were plain in the laboratory spectra of the battery-operated hydrogen discharge tubes of the day. The yellow line was perhaps a faint hydrogen line, brought out by the circumstance that near the edge of the sun one was viewing solar gas hundreds of thousands of miles thick. In a year or two, however, it became clear to solar spectroscopists that the small simultaneous Doppler shifts in width and position of all the hydrogen lines that revealed gas motions on the sun were not shared by the yellow line. Its source must be a new substance—some new atom or a molecule of an unusual compound. The fact that it remained visible high above the edge of the disk suggested that it was a light atom, nearly as light as or perhaps even lighter than hydrogen. (How poor this argument was can be gauged from the fact that a strong green line of the solar corona, for decades called coronium, was found about 1939 to emanate from iron 13 times ionized.) Lockyer christened the new element helium from *helios*, the sun, but neither he nor anyone else used the name much. After all, there were a dozen unknown bright lines in the spectra of the prominences and of the stars; there was of course no theory whatever of atomic spectral wavelengths.

That first event in the history of helium is strange enough. The second is perhaps even stranger. It took place in London in the cold winter of 1894–1895. The physicist Lord Rayleigh, working at his country home, had found that nitrogen separated from the air by removal of all the oxygen weighed a few parts per thousand more than pure nitrogen released from a nitrogenous compound such as ammonia. He accepted the offer of a London chemistry professor, William Ramsay, to analyze the nitrogen from air by the best methods available to the chemist. Ramsay found a gas fraction in the nitrogen sample that was even more inert than nitrogen—a residue that remained behind when nitrogen was carefully removed by high-temperature reactions. This gas the two investigators called argon, the inert one; they described it, its spectrum and its physical properties at an exciting evening meeting of the Royal Society in January, 1895. Henry Miers, Keeper of the Mineralogical Collection of the British Museum, could not attend the great session, but he wrote Ramsay a note in which he recalled that some years earlier an American geochemist had rather unexpectedly found a good deal of nitrogen in a uranium mineral. Could that unexamined nitrogen have also been part argon? Ramsay wrote to America for a sample, and meanwhile he bought a gram or two of a related form of uranium ore from a London dealer. One evening late in March he saw the discharge tube containing the purified gas he had extracted glow, not with the blue-gray of the argon spectrum but with bright yellow. He spoke of the gas as the hidden gas, krypton. (It was not what we now call krypton.) He could see at once that the color was not the yellow of sodium; no other gas looked like that. Next morning a confirming wire came from Sir William Crookes, the expert spectroscopist to whom Ramsay had earlier sent a sample for a check: "Your crypton is helium."

The stuff of the sun was here on the earth. It is curious that to this day the spectrum of the solar disk has revealed hardly a line of helium, although we know on other grounds that the sun is a quarter helium by weight. The electrons of helium are so tightly bound—hence the element's chemical inertia—that the modest temperatures of the solar disk cannot much excite the atom; moreover, the main lines helium can emit are deep in the ultraviolet. It is only high above the solar surface that some flow of energy still not well understood imparts an effective temperature tens and hundreds of times higher than that of the surface. There helium does show up strongly, with many even of its tightly bound energy levels excited by the high temperature.

This curious gas, second-simplest of the elements after hydrogen, was soon found to make up five parts per million of the air. Helium is present in all the exhalations of the earth—in the gases from volcanoes, hot springs and mineral waters—but never abundantly (usually only a part or two per thousand). The earth as a whole is poor in helium; how, after all, could the light and uncombining atoms of the stuff be held by the weak gravitational fields of our small planet? It leaves the atmosphere as steadily as it enters. Jupiter, Saturn, the sun and the stars are largely helium. The element is very rare on the earth but abundant in the cosmos.

Now the story of helium becomes an American story, a story of pragmatism and prairie, of Congress and corporation. The sophisticated metropolitan science of Europe fades into the distance, and we are in a rawer land. The intimate little book reviewed here celebrates this frontier tale. The author, Clifford W. Seibel, lived through it himself, beginning his work with helium in the days of Theodore Roosevelt and continuing it up to the present, years after his retirement as chief of the helium branch of the U.S. Department of the Interior.

Clifford Seibel came in about 1909 as a student to the University of Kansas, then "bleak and almost treeless; most of its thoroughfares . . . still unpaved." There was a young chemistry professor, himself a Kansas alumnus, Hamilton P. Cady. The chemistry department was new and ambitious, and for 10 years it had owned a liquid-air machine. This was no small piece of equipment; indeed, it gave access to the same technique that had made the young Ernest Rutherford willing to leave Cambridge for Montreal in those years. Cady had used the liquid-air machine brilliantly. In 1903 a "howling gasser" of a commercial well had been opened up by wildcatters hoping for oil, just a little north of the end of Main Street in the tiny town of Dexter, Kan. The gas roared out through an eight-inch pipe, and the jubilant citizens, with dreams of a future Pittsburgh in their heads, enjoyed the noise. There was an ugly rumor that the gas would not burn, but Dexter bravely scheduled a huge barbecue at which the mayor would ceremoniously ignite the gas with a burning bale of hay. The gas actually put out the fire; the rumor proved to be precise. The Kansas state geologist sent a sample of the disappointing fuel to the university in Lawrence, and one Kansas chemist found the gas was mostly nitrogen. It was Cady, using the liquid-air and adsorbent-charcoal purification technique, who found two years later, in 1905, that the Dexter gas was 1.84 percent helium. Many more Kansas and West Texas gases were sought out and found to contain helium in amounts up to several percent. Cady wrote in 1907: "Helium is no longer a rare element, but a very common element, existing in goodly quantity for the uses that are yet to be found for it."

Cady set young Seibel a thesis subject when Seibel became instructor of chemistry in 1913. It was to reanalyze the gas wells to see if the helium content had changed. It proved too hard to get the samples; instead Seibel analyzed one sample for all the rare gases. He read his paper to a meeting of chemists in Kansas City in 1917, a bit chagrined by its routine and inapplicable nature. He was by training a chemical engineer, and the U.S. had declared war a week earlier.

Now the red and gold thread of war enters the weave of the story. In Seibel's audience sat another man with a missing key, a British chemist and a student of Ramsay's. He was Richard B. Moore, then superintendent of the radium-production station of the Bureau of Mines at Golden, Colo. Moore had in his possession a letter Ramsay had written him two years earlier; he had hesi-

tated to make it public in a still neutral America. "I have been [looking] for helium for our Government. . . . The idea is to use helium for airships." Count Zeppelin's dirigibles had terrorized London with their bombs, dropped from heights above the aircraft service ceilings of 1914 and 1915. The great floating ships were, however, extremely vulnerable to ignition of the hydrogen with which they were filled. The Admiralty had intelligence that the zeppelins would soon be using a nonflammable lifting gas. Only helium was a possibility. Britain must be ready with its counterweapon; helium had to be found. Ramsay found none in Britain, but by 1917 a pilot plant had been created at the University of Toronto and a larger one was under construction to use a small supply of Canadian natural gas only a sixth as rich as the Dexter gas. Seibel had then in his laboratory nearly the entire U.S. supply of helium, about half a cubic foot. He had sold a few small samples at the rate of $2,500 per cubic foot. A zeppelinful—3,000 or 4,000 cubic feet—was hard to imagine, but fired by the energy of wartime the Bureau of Mines officials went to the Army Balloon Division and to the Army-Navy Airship Board with the proposal to take helium from the helium-rich gases of Kansas.

To this day more than 90 percent of all the known U.S. helium in natural gas is found in a region a couple of hundred miles in radius around Amarillo, Tex. One plant has also been opened in Saskatchewan in the past few years. There is an independent Russian supply, about which nothing is said in the literature. Apart from a rumored single well in South Africa, there are no other known helium sources large enough in volume and high enough in content to rival the gas fields just west of the old Chisholm Trail from Abilene to Dodge City. The rest of the world imports American helium or recovers it from the air at high prices. Middle East gases, for example, contain only a few hundredths of the helium content of West Texas gas.

The story of helium from 1917 on is a surprising precursor to the familiar tale of the Manhattan project. Seeking a new element under military guard and tight secrecy, building plant in haste on new principles, seething with conflict between the Government scientists and the corporate industrial engineers, breaking ridiculous governmental red tape before the exigencies of rapid innovation (the War Department contract did not explicitly cover "motor-propelled or horse-drawn passenger-carrying vehicles," and Seibel himself had to pay for the project's three cars until relieved by a special act of Congress)—the whole story appears in miniature. The project spent less than $1 million, employed some 10 scientists and made enough helium—code-named "argon" until confusion set in—to fill the first explosion-safe dirigible, the Navy's C-7 (shown in a fine period photograph a couple of months after the Armistice).

The years between the wars are the years of the establishment of the helium industry. It was centered on Amarillo; it was a self-sustaining Government near-monopoly (there was a somewhat unsavory and unsuccessful effort to enter it privately in the Hoover administration); it was technically efficient (it sold cheap He, 99.995 percent pure), and it wisely conserved the few rich fields of helium-bearing gas. Almost its only customer, however, was the dirigibles, and when they fell into the sea or were ripped in a line squall, helium fell too. The Nazi effort to make the dirigible economic, which worked so well and came to such terrible grief in the explosion of the *Hindenberg*, was hydrogen-based. In 1937 Congress allowed the commercial sale of helium for the first time, but Secretary Ickes prevented the sale to the Third Reich.

World War II brought the airship back; the Navy patrol blimps essential for troop convoys were helium-filled. The wartime production, with the usual story of forced growth, improvisation and devotion to success, leaped by a factor of 20 or more over the maximum capacity of the Amarillo plant. One Panhandle rancher with a gas field yielding about 1 percent helium "had no desire to part with a single acre" of his 30-square-mile ranch for a plant site. He was finally willing to exchange a few hundred acres for the gift of scrap lumber from construction.

The Government-owned helium fields amount to only 10 years' reserve at the present large consumption. It is no longer airships that take helium. Most of it is used in space vehicles, mainly for pressurizing liquid oxygen and liquid hydrogen, and a large second use is in the welding of aluminum and stainless steel under a shielding flow of the inert gas. The total use in 1966 was about 4,000 tons. Ahead lies a great growth in the use of liquid helium (the first commercial liquid-helium plants came into operation in the 1950's), someday perhaps for cooling superconducting power cables as well as the present superconducting magnets. The more wasteful uses may someday be abandoned, but undersea work, gas analysis and low-

temperature research are steadily increasing. Blimps and high-altitude balloons use as much as the big rigid ships ever did, but lifting is now only a few percent of all the demand. (Toy balloons take one part in 500, and they are well worth it!)

A new plan was put in operation by Congressional action in 1962. The natural gas of the region has long been piped afar to warm the cold Northern cities. So much gas is burned that even its few-parts-per-thousand average helium content is enough to double the helium content of the atmosphere of the Northeast on a cold winter day, as the helium flows unburned out of millions of burners. Under long-term contract the Government undertakes to buy crude helium (50 to 70 percent He, the rest mainly nitrogen) from four firms in the petroleum industry, which remove the helium from the natural gas en route from Panhandle fields to the cities. They pipe the crude helium down to Amarillo, where it is injected into the Government reserve field and so saved from wastage into the air. Storage is in the Bush Dome of the Cliffside field, a porous rock structure sealed off 3,500 feet below the surface; helium can be pumped in centrally and the stored gas withdrawn at the edge. Over a period of 22 years about 75 years' supply (at present rates of consumption) will be conserved. Some firms are also making and selling the 99.995-percent-pure helium as well. The program is to pay for itself. Now it receives money from the Treasury; as the sales increase the money will be repaid. The sale price is fixed at 3.5 cents per cubic foot. Both Government and private sales are currently growing. We export about 2 percent of the helium produced. Canada produces about the same amount.

Helium owes its uniqueness to its stability and to its lightness. It is tightly bound in both the atomic and the nuclear sense; in it the first electron shell and the first nucleon shell are filled. Yet it is a small and light structure, only four nucleons and two electrons. That is why it is a radioactive by-product, and why it is a quantum liquid. The helium on the earth, in the air and in natural gases is most certainly not the "child of the sun"; rather it is the slow product of the decay of uranium and thorium in the earth's crust over the span of geologic time. The gas wells contain helium because the rocks have lost it. The Texas wells are underlain by a layer of broken and heated granite, the Amarillo wash, whereas those, say, of the Middle East lie over an enormous layer of sedimentary rock, poorer in radioactivity, sealed and younger. This seems to be the explanation for the Panhandle near-monopoly on gas-well helium in high abundance, going up to a record 8 percent. Thus the helium we own and use, the helium Dr. Seibel and his colleagues turned from a sensational curiosity of the laboratory into an industrial product, is not truly the helium of the cosmos. The stars are rich in helium, made within the stars, or indeed within the ancient cosmic fireball itself; our earthy helium is a secondary derivation, a legacy passed on from the rare radioactive elements, which themselves were inherited by the solar nebula from an exploding star somewhere in the galaxy five billion years ago. Helium is new to man, and the substance itself is new, earth-born, although its kin on the sun are the oldest composite structures in the universe.

Short Reviews

ILLUSTRIOUS IMMIGRANTS: THE INTELLECTUAL MIGRATION FROM EUROPE 1930–41, by Laura Fermi. The University of Chicago Press ($7.95). An old-fashioned shibboleth of the schoolroom is the notion that the Renaissance could be dated to the fall of Constantinople in 1453 because the scholars were driven from Byzantium to seek refuge in Europe. One never heard just who those Hellenistic patriarchs were, or what they did for western Christendom. The suspicion arises that they mainly wrote histories so that later historians would give full credit to their period. About 1930 a threat to life and to scholarship sharper than the scimitar of Islam, the crooked cross of the Third Reich, was chiefly responsible for driving out of Europe a whole wave of intellectuals, luminaries in every field, who came mostly to the U.S. in the decade before war sealed the ports of the Continent with barbed wire.

This is the story of these men and women, written by one of them, in the graceful and generous style she has made her own. America had of course always been a land of immigrants, but the red scare and the racism of the 1920's had effectively closed the doors by 1927, on the infamous principle of quotas of national origin, ostensibly aimed at increasing the flow of northern Europeans. Under this law some loopholes could be found, and people sufficiently talented or rich or with friends could gain limited entry. "I have seen with my own eyes visas refused to an entire peasant family... because the youngest daughter, who ought to have

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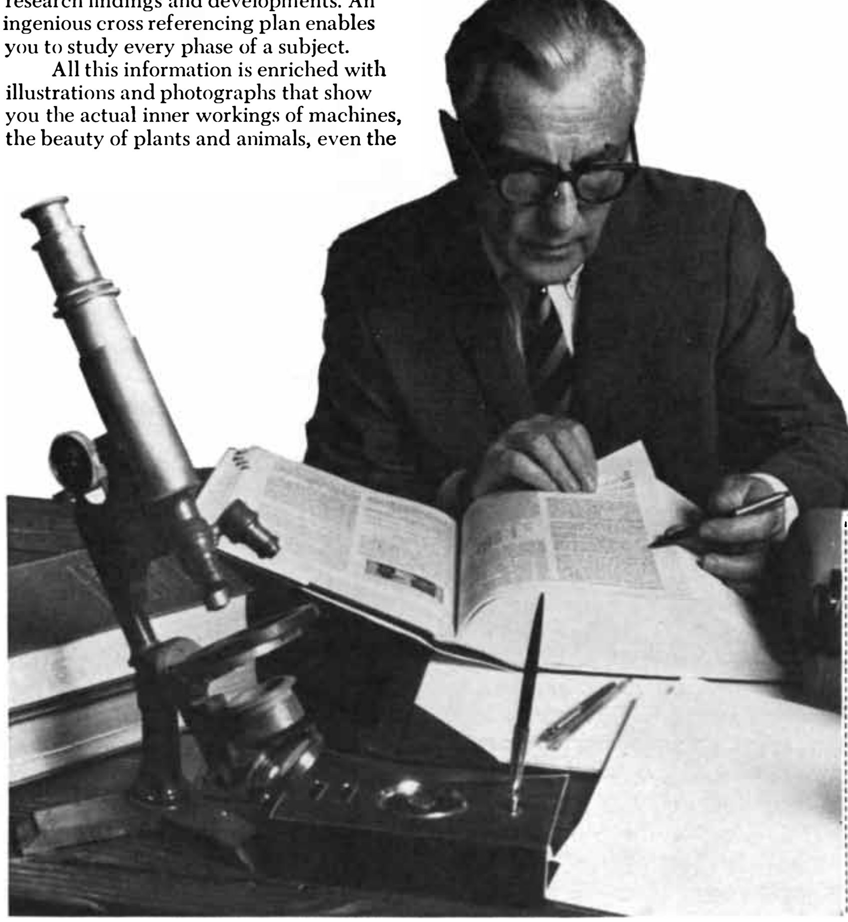

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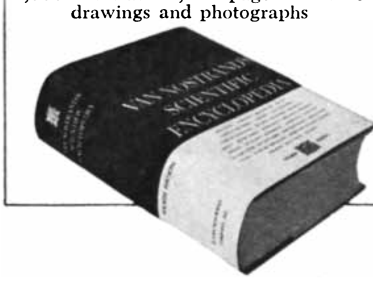

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been in fourth grade, [was] a second-grader.... In our own case... our seven-year-old daughter's unsuspected... eye defect" was surmounted because "a consular official whispered... that Fermi had received the Nobel Prize. American law had become a terrible snob." There were, however, Americans such as the Menningers of Topeka, Alvin Johnson of the New School for Social Research and Varian Fry who set themselves to succor refugees, particularly after the fall of France, when many made their second or third or fourth jump ahead of the secret police of more than one regime. The number of these refugees is hard to fix, because of course the definition is uncertain. Mrs. Fermi studies a sample of about 2,000 well-known people, and it would be reasonable to estimate that some 20,000 professionals came here as refugees, a capital flow in their education alone that must run to a couple of billions of 1968 dollars.

This work is not the study of an event but of people. What refugees they were! It is hard to form a picture of what American thought would have been if they had never come. For the critical there is Herbert Marcuse, from the famous Frankfurt school of sociology; for the theological, Paul Tillich. The mathematicians of course include Hermann Weyl and Kurt Gödel and Richard Courant, and that most brilliant proponent of the nuclear implosion, the computer and the theory of games, John von Neumann. The physicists are too well known to list, but one cannot omit Einstein, the symbol, or Szilard, whose mark as a refugee and a rescuer, as a political goad, as a chain-reaction inventor and as a biologist is all but proverbial. Then there are the Serkins and Landowska and poor Bartók. (The now popular composer died almost unrecognized in New York in 1945.) The French artists mostly returned to Paris, but in New York during the war one could meet Léger and Ernst, Duchamp and Mondrian and a dozen more in the French Canteen. Our great buildings are designed by Mies van der Rohe and Gropius, our hydrogen bomb by Ulam and Teller, our psychoanalysis is polarized among Alexander and Bettelheim and Erikson, our new scientific publishing firms were formed by energetic leaders from Leipzig and Amsterdam. Our great telescopes were manned by Baade and Minkowski. The list is long, and the anecdotes are by turns touching and charming, particularly to the generation of Americans who remember the years before the war.

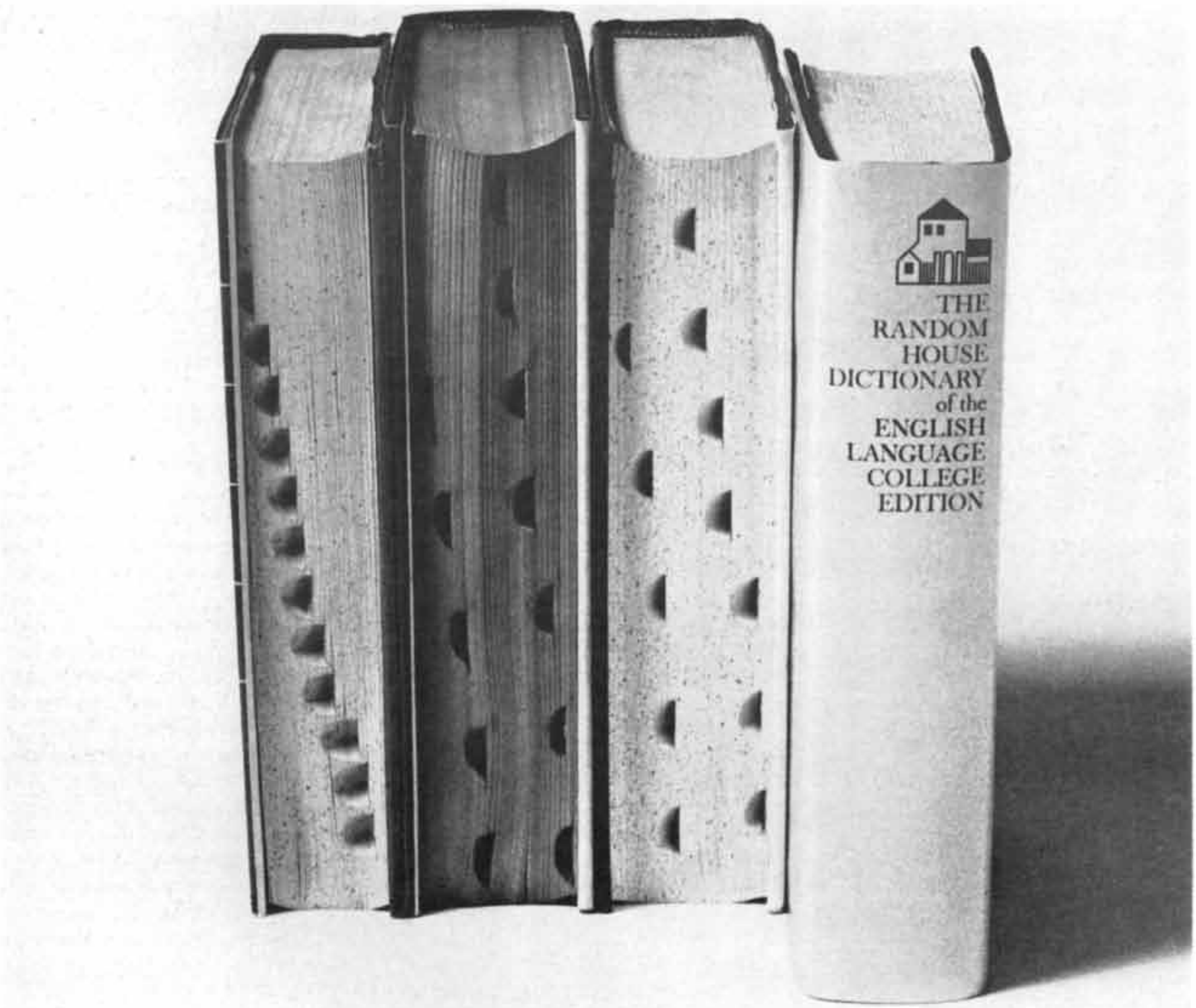
Two questions are faced interestingly. Why were there so many excellent scholars among the Hungarian refugees? It is an old query, for which one wry hypothesis suggests the dubious answer that Hungarians are the advance party of a long-planned invasion from Mars. Here we are told that old Hungary and Budapest, her capital, formed a middle class late, and that it was concentrated in that splendid city and was very strongly Jewish; there were five times as many Jews in Hungary as in Germany in relation to the population. Can another fruitful wave occur? No, the author thinks. It was a kind of vacuum that was filled in that decade; now the world is too small, too well linked and too busy. "The cross-fertilization of ideas... is achieved less by settlers from distant lands than by airplane travelers with return tickets in their pockets."

This is an optimistic book, a contribution to a singular chapter in the history of American science and learning.

"TORREY CANYON" POLLUTION AND MARINE LIFE: A REPORT BY THE PLYMOUTH LABORATORY OF THE MARINE BIOLOGICAL ASSOCIATION OF THE UNITED KINGDOM. Cambridge University Press ($9.50). "Kuwait crude oil is a dark brown liquid smelling like diesel fuel and having the consistency of heavy engine oil." One Saturday morning in March, 1967, the 970-foot *Torrey Canyon*, bearing about 117,000 tons of the oil, ran aground on the Seven Stones off Land's End at 17 knots and tore open six of her tanks. After six weeks she was a sunken wreck, emptied of her oil. This is the story of where the oil went and of what it did, illustrated with maps, graphs and good but discouraging color photographs.

Oil at sea is shaken with water like a salad dressing, first to form an emulsion resembling softened butter, sometimes the color of chocolate and sometimes more like yellow pea soup. Volatile fractions evaporate and the stuff floats more sluggishly. Stranded, it sticks tenaciously and darkens in a couple of days to a dead black. At sea it moves quite predictably with the wind, at a uniform 3.3 percent of wind velocity. This is close to the measured behavior of the sea surface itself. Air mapping of the big patches yielded these data. Fifty thousand tons leaked out in the first week, and the tanker broke open in a storm to release about 50,000 more on the eighth day; most of the rest burned when the tanker was bombed after 10 days.

About a quarter of all the oil came ashore in Cornwall, in Brittany and in



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the Channel Islands. The French navy sank a fifth of it at sea by loading it with powdered chalk when it had lost the volatile fractions; a special ship sucked up 1,000 tons of the oil; most of the rest probably evaporated. At sea the oil-water mix killed thousands of seabirds, but it had no other important effects. Drifting ashore, however, the material represented a disaster for long stretches of beach. The main economic task was to rescue the Cornish beach resorts by removing the dreadful layer—enough of it to stretch 30 feet wide and an inch deep for 125 miles. This was done by vigorously dispersing the layer with special nonfoaming (not household) detergents, which when sprayed onto the oil can turn it from its buttery state into a whitish milky layer by mixing in a much larger volume of water in droplets so small that with good luck the mix is stable. Then the stuff is washed out to the open sea by the tide and the waves, to disappear months later when the bacteria of the sea have oxidized the last tiny droplets.

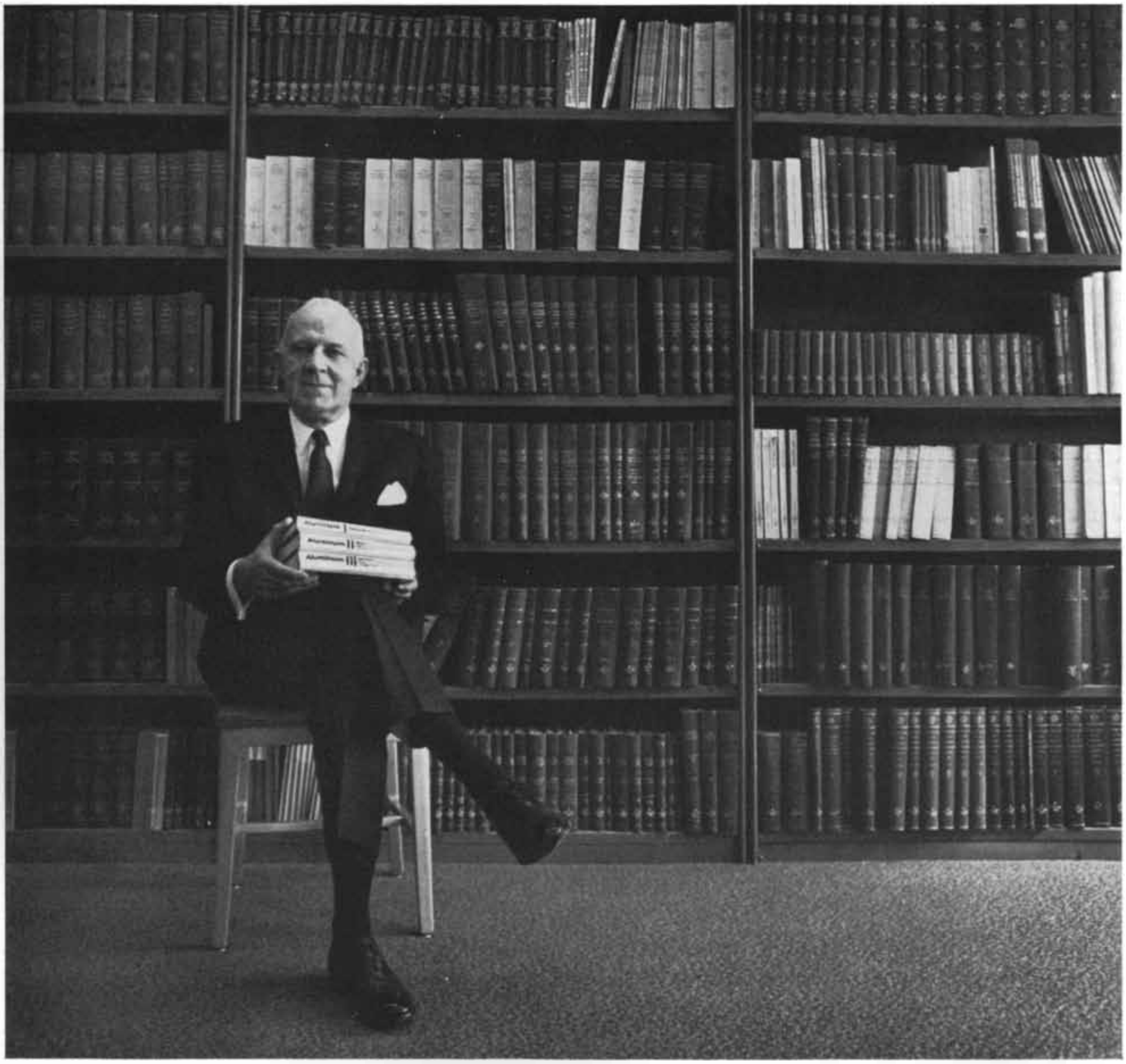
The Cornish beaches were cleaned, but at a cost that was heavy in labor and shore life. Ten thousand tons of detergent were used. It was the detergent, not the oil itself, that proved toxic to a wide variety of intertidal plant and animal life on the rocky coast of Cornwall. Where there is a shellfish industry and no seaside resort, it is best to put up with the awful smear for a while, to do some local steam cleaning or to keep the oil offshore with floating booms. The cleaned rocks seem to be quickly resettled by green algae, luxuriating in the absence of the animals that usually browse on them. As this report states, however, "oil on sandy beaches indeed presents an intractable problem." The treated oil sinks into the sand and is uncovered much later.

The text ends: "We are progressively making a slum of nature and may eventually find that we are enjoying the benefit of science and industry under conditions which no civilized society should tolerate." We have been warned.

BIO-MEDICAL TELEMETRY: SENSING AND TRANSMITTING BIOLOGICAL INFORMATION FROM ANIMALS AND MAN, by R. Stuart Mackay. John Wiley & Sons, Inc. ($12.50). A field so patently lying athwart the usual boundaries of academic research is sure to attract unusual minds. This fascinating and helpful text, part practical handbook, part survey and review, is a clear demonstration. It is dedicated to T. O. M., who turns out to be the author's pet ocelot, and it devotes a chapter to the charming use of telemetry as a zoo exhibit, one example being the provision of a temperature signal the visitor can pick up on his transistor set (or the zoo's), the signal coming from the inside of a caiman that "has swallowed a . . . transmitter that . . . does not harm [it]."

The field is about a decade old; the author, a pioneer, begins the book with the simple, small and reliable circuit he used then. The book continues (at a level of detail that would probably enable a fairly experienced amateur to complete the work) to discuss the basic transistor circuitry used for these intriguing studies. The detail goes beyond circuits to battery sizes and uses, to the plastics and potting compounds and cements and ways of assembling the little broadcasters to keep them working in an alligator's stomach or a rabbit's eye. If you want to use a commercial receiver, as is often economical, select one by "entering a radio store with a small transmitter." The transmitters come in marvelous variety; one sits on the back of a cockroach (a rather sturdy one), signaling by means of accelerometer whether the beast is walking, running or merely sitting and breathing. Another, quite standard, is about the size of a navy bean, has a range of half a meter and has a lifetime of three months with the smallest commercial battery. It has been used to monitor the temperature of the human brain through the skull. A flexible box of plastic containing tiny coils, all in a volume two millimeters in diameter and one millimeter thick, signals pressure from the eye of a rabbit. The flexing of the box lid moved the coils, whose resonant frequency was measured by an outside scanning oscillator that could detect the changing load.

There are even more ingenious, if not as simple, schemes. One Belgian group runs a tiny funicular railway along a nylon thread in the gastrointestinal tract, pulling thermometers and other sensors to the site of choice. Another group has made a kind of artificial flagellate, a small magnet enclosed in a rubber coat with a rubber tail. This device will swim along the blood vessels under the impetus of a biased oscillating magnetic field. Grizzly bears and whales with external transmitters represent the other end of the range of problems that have been tackled; transponders, passive radar reflectors with frequency-shift possibilities, and many another trick still remain to be worked out thoroughly. There is even a table of how much drug to use to induce a Bengal tiger to hold still for the broadcast in-



stallation. The law is here too: British regulations limit an entirely internal radio transmitter to a power of five milliwatts.

The volume is an exemplar of book design.

RADAR ASTRONOMY, edited by John V. Evans and Tor Hagfors. McGraw-Hill Book Company ($19.50). Even more than extragalactic astronomy and high-energy physics, radar astronomy is a sophisticated science practiced at only a few installations, scattered from the Mojave Desert to the Crimea. Big dishes, high power and the elegant and insightful treatment of data are the indispensable equipment of those who would conduct an active astronomy, touching with a microwave finger the planets and the sun, and mapping the moon about as well as the optical competition can (but the moon, after all, yields real samples these days). The radar-echo intensity falls off with two inverse-square laws, out and back; if it takes no petty dish to see airplanes, how can one be intrepid enough to aim for Mars? This book, the product of the noted group of workers at the Lincoln Laboratory of the Massachusetts Institute of Technology, sets out the entire subject in four categories: the fundamentals of the treatment of the signal to extract information in time, intensity, frequency and polarization; the nature of the problems to be studied, to learn both of surfaces and of distances and motions; a review of results in the various fields, and a knowing survey of the choice and design of the radar systems used. The methods are complex and expensive; they have to be. The signal power from Mars is about the same fraction of the transmitted pulse power as a few atoms are out of the mass of a gram of matter. This heroic measurement demands repetitions with careful timing—tens of thousands of pulses added in phase to beat the noise. It expends a peak power equal to that of a whole town in the brief outbound pulse; it uses digital sampling and elaborate numerical data treatment instead of the more familiar physical filters to define its bandwidths and response curves. All of this has grown out of the military needs of missile detection and the more peaceful problems of space-tracking.

The book is an advanced text; its many authors and uneven detail do not make it easy reading, but there is probably no better entry into the field. The epoch of writing is a bit uncertain; the text was formally closed about two years ago, and much has happened since that time. The best radar moon pictures are

not here. Here, however, is what our knowledge of the curious spin of Venus and Mercury and of our distance from the sun, of a still uncertain new test for the gravitational delay of photons moving past the sun and of many another remarkable result rests on. The entire complex structure remains vulnerable to subtle unseen errors such as unexpected defects in the computer circuit, as the same group learned during the past year. The book is a somewhat rough but genuine sample out of a scientific world marked by big organizations, technical virtuosity and large ideas. Like the radar systems, the book is expensive.

THE BIOLOGY OF THE STRIPED SKUNK, by B. J. Verts. University of Illinois Press ($7.95). *Mephitis mephitis*, the striped skunk, is found all over the U.S. and southern Canada, except for the driest desert. "Chicago" means in Fox Indian "the place of the skunk." Forty or more years ago the skunk was hunted for its long-haired pelt, but nowadays the trade has fallen off by a factor of 100. This book is an interesting account of a five-year field survey of skunks based on field trapping and radio tracking in two rural Illinois counties. The task was a public health one: the skunk is host to rabies, and a doubling in the count of rabid skunks was reported the year this study began. Unlike bats, skunks do not seem able to spread the disease by biting without showing serious symptoms. Nor can biting alone maintain the epidemic among skunks; there are few such infections, and during three months of the year, just when the disease is most prevalent, the skunks are mainly holed up in their dens. There may be some other way to maintain the latent virus; the problem is still not solved. No other animals appear to infect the skunks.

The power of the skunk's butyl mercaptan musk (which has been detected 20 miles at sea) seems to have strongly affected skunk behavior. Skunks are intrinsically pretty clever; they feed largely on insects and grubs, although they also take small mammals, carrion, grains and fruits. They have been seen scratching on a hive to bring out some bees. They are gallant lovers, but the male is foreign to the family and a menace to his young. They are night creatures, sometimes foraging all night long, moving mostly within a region half a mile across. Their senses of sight, hearing and smell all appear to be poor, so that two skunks may pass each other at close range without indicating any awareness of it. Maybe this is just "single-minded-

ness," the author remarks. Skunks are unobtrusive, and docile except toward their own kind in the breeding season. They try to flee the lights of the oncoming cars that kill so many of them, but they are seldom fast enough. Then the skunk faces the fierce intruder and tries its one defense: it stamps its feet, arches its back and lifts its tail.

This is a study in considerable depth, which will be of interest both technically and to the general reader concerned with wild animals. It clearly provides insight into the long-term consequences of owning a strong deterrent.

Magnetic Recording in Science and Industry, edited by Charles B. Pear, Jr. Reinhold Publishing Corporation ($19.50). This modern handbook reviews tape recording on the practical engineering level in a dozen expert chapters aimed at users, designers and those who would enter the field. There is not much for the high-fidelity fan; the aim is not music. This year there will be sold a few million miles of thin, strong plastic tape, coated with needle-shaped ferromagnetic crystals of Fe_2O_3 a few microns long and aligned during the coating. It is the state of magnetization of these crystals that computers read and write, from which video programs flow and (the smallest use of all) audio records are made in homes and schools. How the tape is made, how linear signals are coaxed from this highly nonlinear magnetic stuff, how in a few milliseconds the jittery tape reels of the computers get up to speed and manage to stop again, and a bookful of similar genuine feats of the modern technique (the basic idea being as old as the century) are told in this volume. Good references.

Continental Drift, Secular Motion of the Pole, and Rotation of the Earth, edited by William Markowitz and B. Guinot. Springer-Verlag New York Inc. ($7.20). At the turn of the century four special stations were established around the 40th parallel in Europe, America and Japan. (There is now a fifth in the U.S.S.R.) By making precise and repeated observations of star positions they could fix the direction of the earth's axis of rotation to one part in 50 million. The results show that in that time the crust of the earth has moved with respect to the pole of rotation by about 10 meters. Meanwhile it has become possible for the geophysicist to measure the magnetic latitude of ancient rocks. He falls short of the astronomer's directional accuracy by a factor of

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THE NATIONAL CASH REGISTER COMPANY ® DAYTON, OHIO 45409 a million or so, but he studies a time interval 10 million times longer! Both astronomer and geophysicist are probably seeing the same motions: the continents drift an inch or two each year over the quasi-fluid interior. The relative motions are easiest to discern in the ancient rocks, but the motion as a whole is easier to perceive in the contemporary data from telescopes.

This brief book presents papers and summaries from a meeting that was held last year partly to confront the two groups of workers. Most of the papers concern the long and splendid series of astronomical measurements; a few take up new methods (satellite-tracking and corner reflectors on the moon for spotting by laser ranging), and there are two excellent and not very technical brief reviews of the geophysical background by G. D. Garland and by S. K. Runcorn.

It is a pity that the results of the new long-base-line radio interferometry, exploiting the natural hydroxyl masers in the sky, were too late for the meeting. These may well add new power to the work.

THE MEASURE OF MAN: HUMAN FACTORS IN DESIGN, by Henry Dreyfuss. Whitney Library of Design ($13.95). The second edition of a portfolio of succinct and up-to-date information on how big Americans are, including man and wife and kids; how far they reach, how strongly they grasp, how well they read dials, climb ladders, see out of the corner of their eyes, breathe cleansed or dirty air. The work is mainly presented in 30 page-sized charts, with two full-size blueprints of dimensioned figures, Joe and Josephine. Although they cannot compare in mastery of line with Leonardo's man in dimensional arcs, these pages are useful and often attractive. Well known to designers, they deserve a wider diffusion among readers in science and engineering.

A FIELD GUIDE TO WILDFLOWERS OF NORTHEASTERN AND NORTH-CENTRAL NORTH AMERICA, by Roger Tory Peterson and Margaret McKenny. Houghton Mifflin Company ($4.95). Here at last is the guide to wild flowers of this well-known series. Peterson's clear visual sense of how the unfamiliar is to be recognized is as useful here as it has been for decades in the recognition of birds. The book's apparatus and organization are a model of how to do it; the drawings are good, but there is an air of skimpiness in the use of color that is a disappointment.

Heredity, Evolution, and Society

I. MICHAEL LERNER,
University of California, Berkeley

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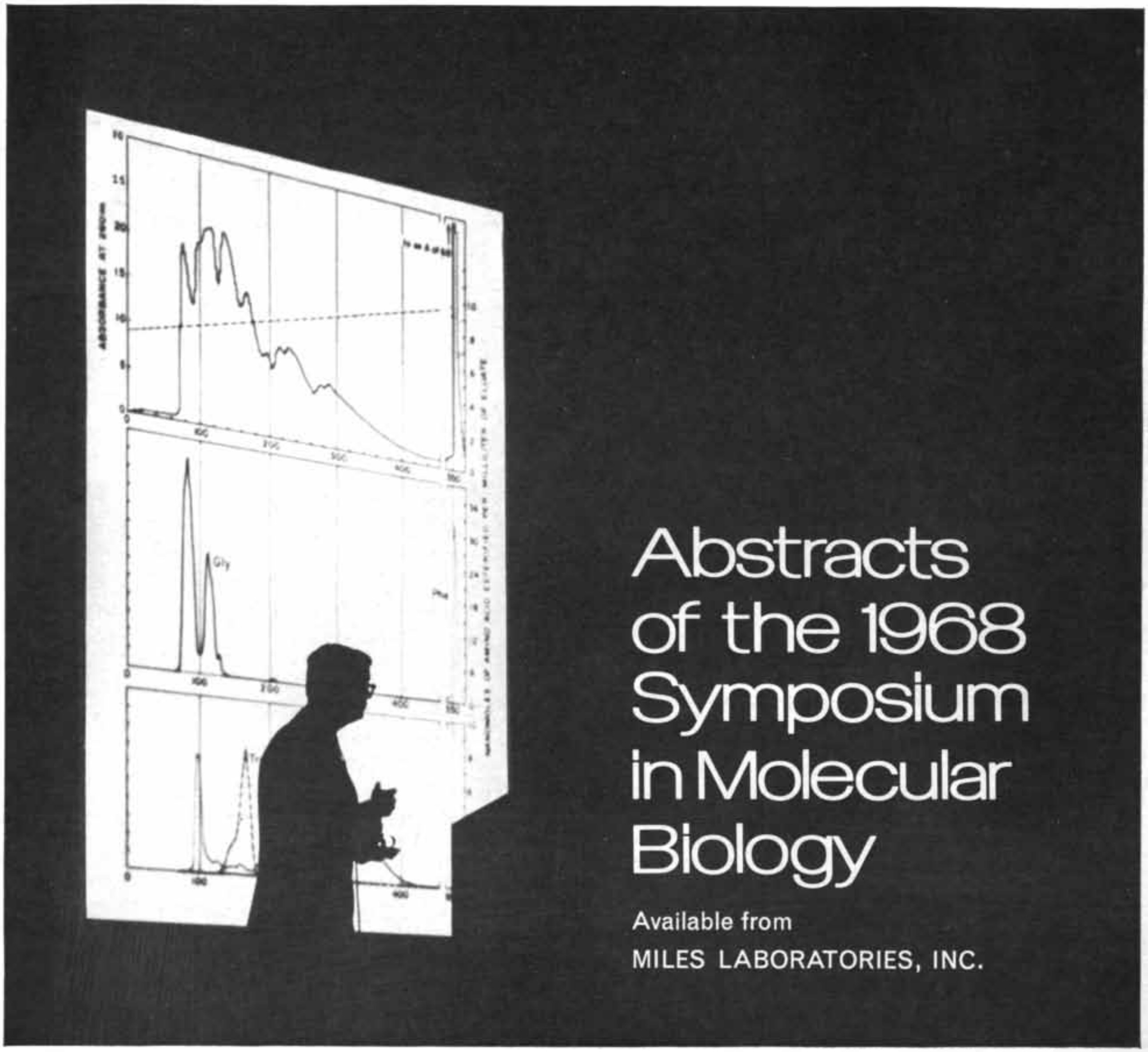

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