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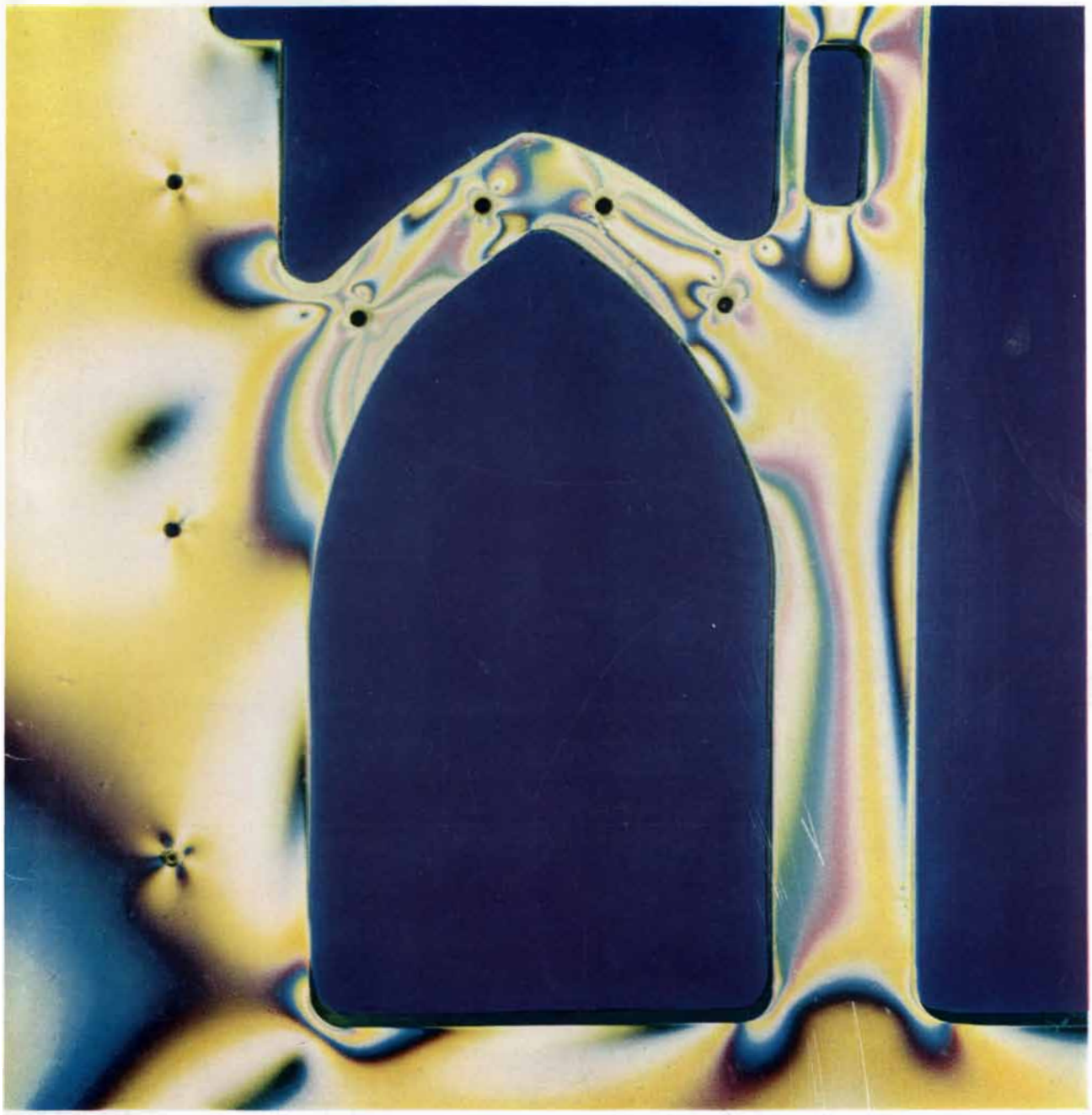

CATHEDRAL STRUCTURE

ONE DOLLAR

November 1972

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Flor—the remarkable cause of Sherry

Around the 1st Century B.C., a unique yeast started to materialize from the Spanish air quite suddenly, at vintage time. A snowy, whipped-cream-like surface bloomed over some, but not all wines. It looked like an enormous, white lily. So the Spanish called it *Flor* for flower. Gradually, all the lighter, finer wines thus began to flower...their bouquet changed, and their character deepened...they became dryer, crisper, and acquired more nose...the first Sherry was happening.

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The Sherry grape

The golden Palomino grape—the essential start of the best Sherry, was brought over from Jerez, Spain and planted in the rich soil of California. It was a perfect fit. At this point, two essential ingredients for fine Sherry had been brought to Almadén: *Flor* yeast and the Palomino grape. Next we swung our attention to method, and realized that the Solera system—that process used originally in Spain—was the only way to produce highest quality Sherry. And that required special barrels.

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The best wood for aging Sherry is white oak from Tennessee; even the Spaniards haven't found another oak as good. So we arranged to have white oak cut down and shipped regularly to Spain; there, with skilled hands, Spanish coopers shape it into butts or casks. These are returned to Almadén where they hold the wine in two important stages. The first is in what the Spaniards call a *Criadera* (literally, a nursery) where the dry, young Palomino wine takes on the *Flor* flavor. Next is the *Solera*.

The Solera System —2000 years old.

A vast, dim room holds tier over tier of small oak barrels—some 20,000 in all. The young wine is poured into the topmost tier. What is drawn off for Sherry comes from the bottom tier—and never more than a third of a barrel at a time; this is replenished from the barrel above, and that barrel from a still higher barrel. This is the Solera System: through the years, the young Palomino wine blends with the older wines, moving slowly, from barrel to barrel, until it takes on the richness and quality of its ancestors. It's easily the most expensive but definitely the best way to make Sherry. There are three Almadén Sherries, all made in this painstaking way, for you to try: *Cocktail Sherry*—as a dry aperitif to be served before dinner chilled or over the rocks; *Golden Sherry*—not quite so dry, to be served chilled on the rocks with walnuts; and *Cream Sherry*—for those who prefer a sweeter Sherry as a before or after dinner drink (or anytime for that matter).

The Port grape

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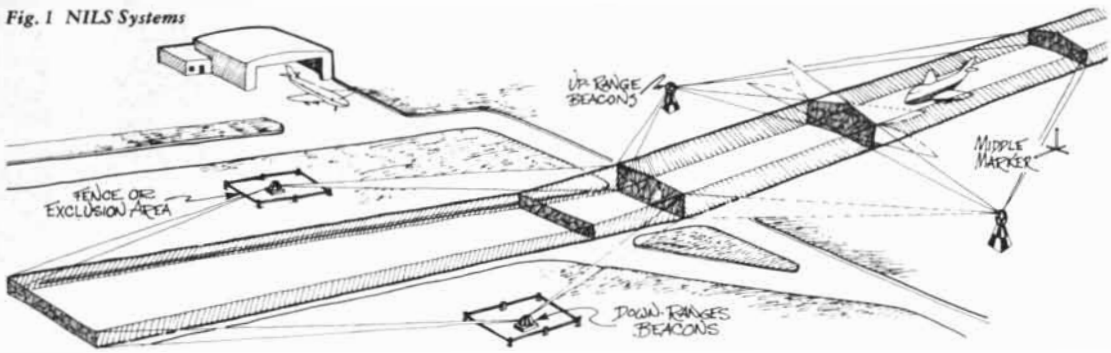
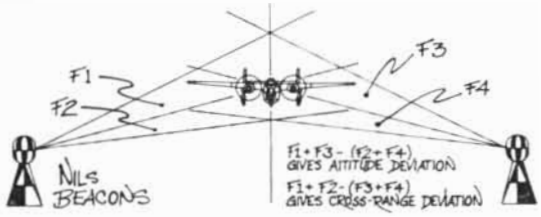


Fig. 2 NILS Beam Formation



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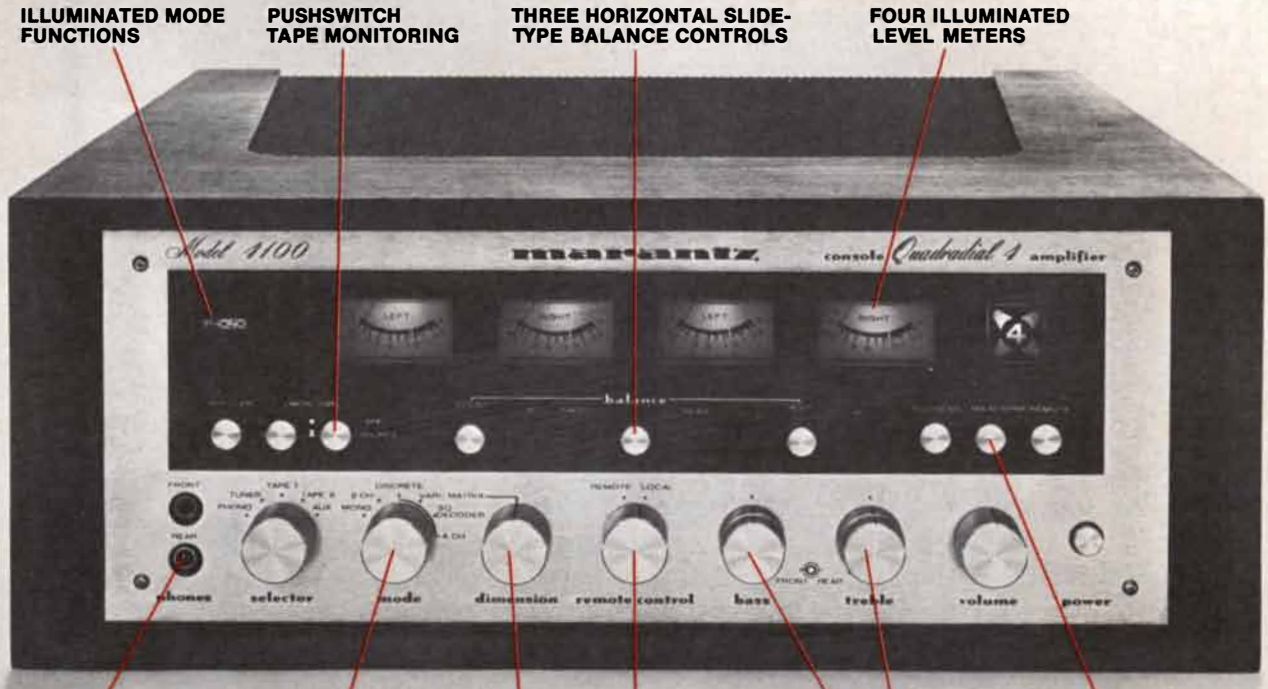

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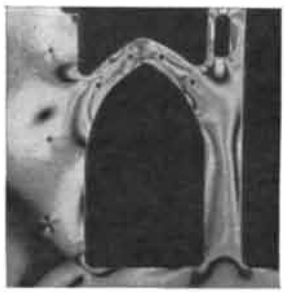

THE COVER

The photograph on the cover, showing the pointed arch characteristic of Gothic architecture, shows part of a plastic model of the cathedral of Bourges in France. The model was stressed at high temperature to simulate dead-weight loading and was then photographed in a polariscope; the effect of polarized light on the stressed plastic produced the interference pattern, which can be interpreted as a contour map of stress intensity (see "The Structural Analysis of Gothic Cathedrals," page 90). This part of the model represents the vaulting over a side aisle. The small holes in the plastic are used for attaching the weights with which stresses are simulated.

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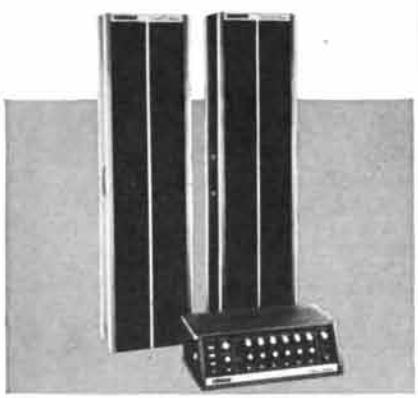

LETTERS

Sirs:

From this part of the world the situation in California seems quite unbelievable ["Alternative Hypothesis," "Science and the Citizen," August]. In five years of university teaching in that state I always began my discussion of evolution with the Creation in Genesis, not for religious reasons but as a fine example of the thinking of the ancients that is quite compatible with modern concepts—depending on one's definition of "God" and "day." However, being *required* to present the "alternative hypothesis" is another story, and I see the following possibilities: (1) As already mentioned in your report, there is the question of the violation of the separation of church and state. (2) There is now sufficient precedent from other fields of contention to be able to demand equal time, and force every Sunday-school teacher to present evolution on an equal basis. (3) Being required, I would opt for other ancient beliefs in "divine creation," involving the snake, the turtle or the bear. Rejection of these, or the insistence on the version of any one particular religion, must be considered a violation of the freedom of worship. (4) Speaking as a botanist, I should think that one must also include the history of Middle Earth, in order to be able to worship *Drimys*, the most recent scion of Telperion, Eldest of Trees.

STEPHEN S. TILLETT

Mérida, Venezuela

Sirs:

It was with some considerable interest that I read Professor Hess's account of his observations on "imprinting" in mallard ducklings in nature [" 'Imprinting' in a Natural Laboratory," by Eckhard H. Hess; SCIENTIFIC AMERICAN, August]. Unfortunately some of Professor Hess's allusions to the use of developmental age to calculate critical periods could cause some confusion to persons not having easy access to the original literature, and so I am writing in the hope of preventing that.

Developmental age in young birds is calculated from the onset of incubation rather than from the time of hatching, the latter being called posthatch age. Developmental age has been found useful in bracketing certain critical period phenomena in the *laboratory*. "Laboratory" requires emphasis because it is not possible to determine critical periods in the field. In order to determine a critical period for "imprinting," for example, young birds must be given a limited, age-related exposure to parental stimuli (auditory, visual or both) and later tested for the fidelity of their response to that same stimulation as a function of their age on the initial exposure. In nature ducklings are in unremitting contact with the parent bird, so that there is no way to calculate an optimum age period for the establishment of the attachment response under these circumstances, regardless of whether one wishes to use posthatch or developmental age. In view of this situation it is puzzling to read Professor Hess's remark that "actual observations of how a female mallard interacts with her offspring have pointed to the conclusion that imprinting is related to the age after hatching rather than the age from the beginning of incubation." Such a conclusion could come only from laboratory studies, not from field observations. In this con-

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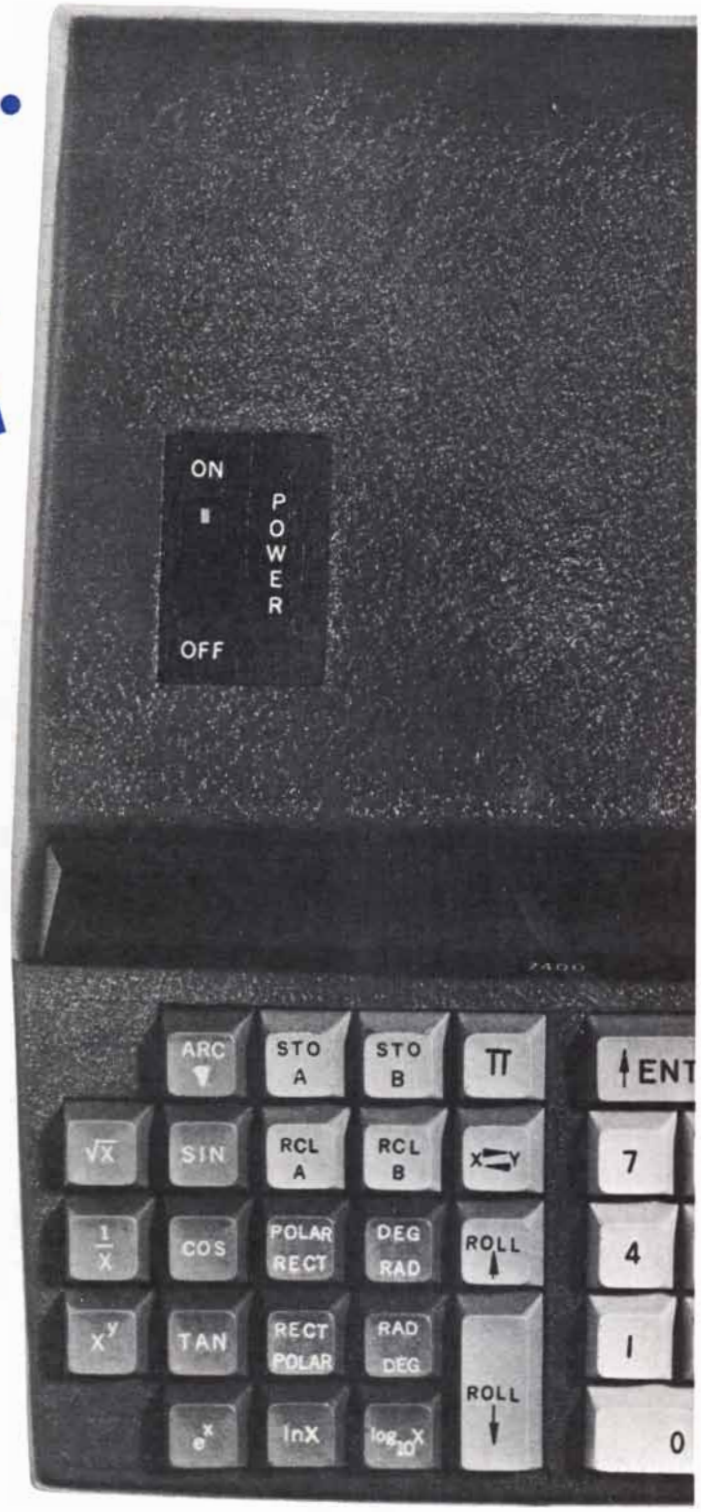

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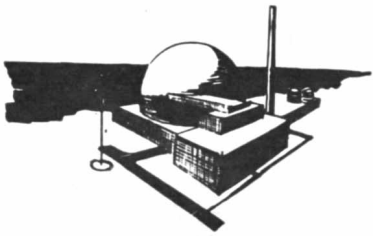

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nection Professor Hess does not deal with the fact that his laboratory studies show that from 13 to 16 hours after hatching is the critical period for imprinting in mallards where *following* the model during that time is related positively to strength of imprinting (the law of effort), whereas, according to Professor Hess's own observations, in nature mallard ducklings have no opportunity to follow the parent at that time. (They are still in the nest.)

Finally, Professor Hess makes a very unfortunate error when he tries to apply specific developmental-age data for Peking ducklings hatched in the laboratory to mallard ducklings hatched in the field in March (or any other month for that matter). Peking ducklings and mallard ducklings are not the same bird developmentally speaking. They have different developmental rates *under the same conditions of incubation,* whether in the field or in the laboratory, with the mallard *always* developing at a faster rate than the Peking under the same conditions. Consequently the specific developmental-age range of the critical period for one cannot be expected to hold for the other, as Professor Hess assumes in his mistaken comparison. Critical-period comparisons between the two would have to be relative rather than absolute.

GILBERT GOTTLIEB

Psychology Laboratory
Division of Research
North Carolina Department
of Mental Health
Raleigh

Sirs:

My refusal to accept Dr. Gottlieb's developmental-age concept in imprinting has been presented not only in my article but also at a meeting of the New York Academy of Sciences in the spring of 1971, where I discussed the misleading data on which Gottlieb has based his concept. The dubious value of his concept is also illustrated by a quote from John T. Williams, Jr., of the University of South Carolina in a recent *Psychonomic Science* article: "The original data upon which this hypothesis is based were reexamined and found to have been analyzed in a meaningless way. There seem to be no objective data supporting the idea that developmental age provides a more sensitive baseline."

Dr. Gottlieb's doctrinaire claim that "in nature... there is no way to calculate an optimum age period for the establishment of the attachment response" reflects his failure to appreciate not only the major thesis and data of my article but also the flourishing success of interdisciplinary analysis within behavioral biology. In addition, he does not distinguish between various levels of behavioral organization involved in imprinting. These different levels often require specific methodological techniques best suited for such analysis. Just as biochemical aspects of imprinting can best be studied in a suitable laboratory, so mallard imprinting must also be studied in a feral setting where it normally takes place.

Certainly my laboratory study of imprinting showed that from 13 to 16 hours after hatching is a critical period for imprinting in mallards. As I indicated in my article, laboratory methodology may generate data that are characteristic of the methodology and that are independent of the realities of the phenomenon under investigation. Thus I have become concerned that "almost all laboratory imprinting experiments, including my own, have been deprivation experiments.... The deprivation may have interfered with the normal behavioral development of the young ducklings."

In connection with the relationship between amount of following and imprinting strength in the laboratory, a relationship that I have termed the law of effort in my earlier writings, I took care to mention in the article that feral nest observations have revealed that "ducklings make a considerable effort to be near their parent." The same form of effort cannot occur in the artificial laboratory situation, and the following behavior in laboratory imprinting may be considered analogous to the effort expended in the feral nest.

Finally, I can assure Dr. Gottlieb that even my early publications dealt with the behavior-genetic components involved in the investigation of critical periods for imprinting in different breeds. I have always assumed that findings with highly domesticated Peking ducklings, or for that matter the white rat, offer very limited possibilities for behavioral generalizations. For that reason it is ironic to note that Dr. Gottlieb's findings with Peking ducklings have been used to question my results with mallards.

ECKHARD H. HESS

Department of Psychology
University of Chicago
Chicago

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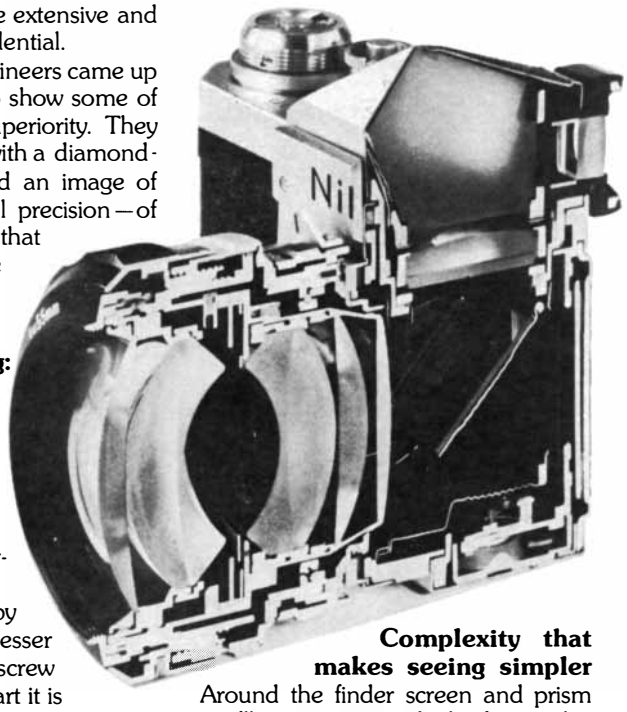
Anatomy of a Nikon Camera

Most Nikon photographers are content to enjoy their cameras for what they are, magnificent picture-taking instruments. But just what kind of technology is engineered into a Nikon that makes it perform so responsively, so precisely, so reliably year after year? The data is quite extensive and in some cases, confidential.

However, Nikon engineers came up with a different way to show some of the reasons for its superiority. They cut a Nikon in half, with a diamond-blade saw. It revealed an image of ingeniously purposeful precision—of wondrous complexity that belies the natural ease and speed with which the camera operates.



Precision threading: expensive, and important

Note the profusion of finely threaded components. The elements of every Nikkor lens, for example, are secured by threaded retaining rings, rather than by friction as they are in lesser lenses. Further, every screw is threaded into the part it is holding, not simply tightened against it. And, because screw holes are drilled before lens elements are mounted, you'll never find metal burrs inside a Nikkor lens. Precision of this sort is costly but the only real way to assure the permanent alignment accuracy required for such consistently sharp pictures, year after year.

The mount can make or break the lens.

One place a Nikkor lens has no threads is where it attaches to the camera body. Some cameras still have screw mounts which make changing lenses a slow process. Others use a breech-lock ring which can be mistaken for the aperture ring and allow the lens to come off accidentally. In contrast, the Nikon bayonet system requires only a quick 1/6 turn to remove a lens or lock it securely to the camera. The precision with which the body and lens are mated makes Nikon one of the very few cameras to accept an interchangeable f1.2 lens. (The extremely shallow depth-of-field of this lens demands meticulous mounting accuracy.)

Complexity that makes seeing simpler

Around the finder screen and prism you'll see a great deal of complex mechanics, quite unlike an ordinary single lens reflex. That's because, on the Nikon, both finder and finder screen are interchangeable. Naturally, this requires flanges and catches and releases which most cameras don't need. But as a result, you have your choice of any of 18 different finder screens and six different finders. You can tailor your choice of screen to the lens you're using, the subject you're shooting and the amount of light falling upon it. You can choose a finder that's perfect for ground level, action, available light or any other kind of photography. So you never have to compromise your view of the image. And that, after all, is really the great advantage of the single lens reflex system: to be able to frame and focus on any subject, near or far, quickly, easily and accurately.

Flatter film means sharper photographs

It's the function of the pressure plate to hold the film perfectly flat. Actually, it doesn't do that completely in *any* 35mm camera. Nikon designers have taken an extra step. The film winds onto the takeup spool in reverse, which counteracts the film's natural curl. The result is measurably flatter film and, as a direct result, sharper photographs. This reverse wind also pulls the film *around* the sprocketed roller instead of just across, so more sprockets are engaged and it becomes much less likely that you'll ever rip any sprocket holes out of the film, no matter how energetically you operate the winding lever or how fast a motor drive winds the film.

These are only a few of the design innovations harbored within Nikon FTN and F2 cameras. If space permitted, we could give you dozens of other insights into the care and ingenuity which is lavished on these exceptional cameras. Pick up a whole Nikon at any dealer, release the shutter, operate the winding lever, interchange the lens, the finder, the finder screen and you'll have some appreciation of the precision machining and assembly which also goes into every Nikon. (If, however, you'd like to see the actual cutaway camera, visit Nikon House in New York City, where it's on display, along with half Nikon movie and Nikkormat cameras.) Or write, and we'll send detailed literature. Nikon Inc., Dept. SA, Garden City, N.Y. 11530. Subsidiary of Ehrenreich Photo-Optical Industries, Inc. (Canada: Anglophoto Ltd., P.Q.)

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50 AND 100 YEARS AGO

SCIENTIFIC AMERICAN

NOVEMBER, 1922: "The intelligent manufacturer in this country realizes that his future prosperity lies largely in export trade. Unquestionably China offers us an opportunity that is quite unique. Geographically it lends itself more readily to export trade from this country than Europe. The present Republic of China has an area of approximately five million square miles, more than twice as large as that of the United States, and a population four times as great as ours. There are practical opportunities in China for the sale of nearly all American commodities."

"The great advantage in fuel economy that would be possessed by a successful Diesel locomotive is leading engineers to consider it as a possibility. The outstanding difficulty for such work is the Diesel's lack of flexibility, it being at present essentially a one-speed engine. New designs have, however, incorporated every feature of different existing Diesel types tending to increase flexibility, with most promising results. These include opposed pistons, hot piston heads, a constant-pressure cycle and every practicable device to control the fuel injection to suit different speeds."

"A. A. Michelson and F. G. Pease report further work with the interferometer on the 100-inch telescope on Mount Wilson. The angular diameters of the stars Arcturus, Aldebaran and Beta Pegasi are all close to .016 second, which would make the actual diameters about 20 million miles for Arcturus and 30 million for Aldebaran."

"It should not be any more difficult to conceive of transmitting motion pictures by radio waves than to understand transmitting sound. An apparatus built by C. Francis Jenkins includes at the sending end a pair of prismatic rings and a light-sensitive selenium cell in addition to the usual wireless apparatus. The function of the prism rings is to project a spot of light from the picture to be sent on the light-sensitive cell. The spot of light travels across the surface of the picture, each journey being its own width below the path of the previous journey; the strength of the light varies in strength according to the lights and shadows of the picture. The selenium cell translates these variations in light-strength into variations in current-strength, and these variations are transmitted by wire or wireless. At the receiving end similar apparatus translates the variation in the incoming radio impulse into variations in light-transmitting ability of a tube filled with carbon bisulfide. The spot of light thus produced is made to move across a sensitive screen in the same way as the original spot. This opens up the possibility of 'broadcasting' either from the original happening itself or from film."

"According to figures recently made public by the Census Bureau, more than 30 percent of the farms in this country have motor vehicles. Canadian registration figures published recently show that the farmers of Ontario own 36.8 per cent of all the automobiles in that province. And near Winnipeg there has been found a grain farm of 12,000 acres on which not a single horse is used, nor a single head of livestock raised. All the work is done with trucks and tractors. It was figured that 400 horses would be necessary to do all the work on the farm and 2,000 acres would be required to feed them."

SCIENTIFIC AMERICAN

NOVEMBER, 1872: "Next to our own country, there is no nation in the world that gives evidence of such rapid progress in industrial matters as Russia. Her mechanical and metallurgical interests are almost daily developing, and new means of utilizing her great resources are constantly coming into existence. A gigantic establishment has recently been founded by MM. Struve Brothers, situated near the city of Kolom, which, it is stated, rivals in magnitude the finest workshops of England or Belgium. It has been in operation but five years, and is at present engaged in the manufacture of iron bridges and railroad freight cars. Since its foundation it has completed 3,000 cars, and since it has begun the manufacture, 79 locomotives have left its shops."

"If 100 years ago a *savant* had expressed in a company of his peers the opinion that the earth was a million years old, he would have been laughed at, and if only 20 years ago a geologist had in a similar assembly asserted the great antiquity of mankind and the existence of fossil men, he would have been considered to be incredulous in religious matters and overcredulous in regard to geological evidences. Lyell estimated some 10 years ago the antiquity of man at 150,000 years or more, but we know now that the glacial period ended more than 200,000 years ago, and that man, with the reindeer, which retreated north, was already in existence at its termination."

"The Astronomer Royal of the Greenwich Observatory in England communicates to *Le Monde* the following: 'In a recent number of the *Comptes Rendus,* I find a paper by Father Scuhi regarding a remarkable explosion on the limb of the sun, visible in Rome for about three hours on the afternoon of July 7. Now, a magnetic tempest manifested itself at Greenwich at five o'clock on precisely the same day, diminishing by degrees until the evening of July 9, and, during a part of the time, was accompanied by an aurora. Though not wishing to commit myself on the question as to the connection which may exist between the solar explosion and the terrestrial magnetic storm, I have noticed that if there be such a connection, the transmission of influence from the sun to the earth ought to occupy about two hours and 20 minutes, or somewhat longer.' "

"The *Manufacturer and Builder,* in noticing the fact that Congress has appropriated $50,000 to pay for a 27-inch astronomical telescope, calls attention to the want of liberality usually shown by our public men in respect to expenditures for scientific instruments. It thinks there is no difficulty in obtaining money to build engines intended for destruction, such as monitors, but, when it comes to devices that are solely capable of adding to human knowledge and augmenting human happiness, then the purse strings are drawn tight and money grudgingly given. Our contemporary thinks that an appropriation of a million dollars to build a large telescope ought to be passed, and that science ought to be aided and encouraged in the same liberal style on all suitable occasions. The editor further believes that if such a telescope were to be capable of killing people at the rate of a thousand souls a minute, the million dollars would have been paid out and the machine constructed long ago."

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ALL SMALL CARS SOLVE THE PROBLEMS INHERENT IN THE BIG CAR.

OUR SMALL CAR SOLVES THE PROBLEMS INHERENT IN THE SMALL CAR.

This year, economics and the conditions of urban traffic will drive millions of Americans to the small car.

These American converts will discover, however, that most small cars, for all their virtues, can have two major problems of their own. First, lack of inside space. And second, compared to the 425-horsepower monsters Americans are used to driving, disappointing performance.

Which is why we thought you'd like to know about a small car that doesn't have those problems. The Fiat 128. One of the big reasons why in Europe, where they've been living with small cars for three generations, they buy more Fiats than anything else.

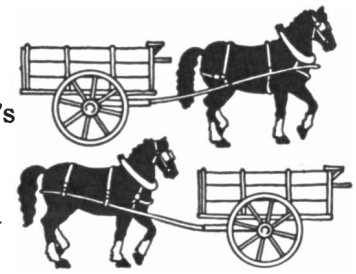
You see, ever since we invented the small car in 1936, our engineers have been designing small cars so European families who couldn't pay a big-car price could still have the roominess and performance they needed.

WE'RE SMALL, BUT NOT AT THE EXPENSE OF YOUR KNEES.

As for room, while the Fiat 128 is shorter outside than a VW Beetle, it's bigger inside than an Oldsmobile Cutlass and has a 13 cu. ft. trunk. In fact, 80% of the car's space is devoted to you and your luggage.

Space considerations aside, many small-car owners are reluctant about taking a corner fast or driving in a strong crosswind. That's why the Fiat 128 is built wider than the big-selling Japanese and German imports. And why it has standard radial tires (usually a $100 option). All-independent suspension. And the same responsive rack-and-pinion steering usually found on Ferraris, Porsches, and Jaguars.

What if you're trying to pass a giant truck or merge into fast moving highway traffic? If you've got to accelerate from, say, 40 to 70 mph to do it, the Fiat 128's overhead cam engine gives you an edge of more than six car lengths over America's favorite small car. And since stopping fast can be equally important, it has self-adjusting front disc brakes.


PULLING IS MORE EFFICIENT THAN PUSHING. THAT'S WHY WE HAVE FRONT-WHEEL DRIVE.

Lastly, there's another item that distinguishes the Fiat 128: front-wheel drive. This means superior handling and performance, because the wheels that move the car are also the wheels that turn the car. And because pulling is a more efficient way to move something than pushing.

(It also means superior traction in ice and snow. In fact, for the last two years the Fiat 128 has won the Canadian Winter Rally, which is run over ice and snow the likes of which we hardly ever see in the States.)

The Fiat 128 is available in 2-door, 4-door, and station wagon models. To appreciate just how good it is, you should know that in Europe, where each country is fiercely proud of the cars it makes, the Fiat 128 has won more international Car of the Year awards than any small car in car history.

Or any big car, too, for that matter.

FIAT

The biggest selling car in Europe.

Overseas delivery arranged through your dealer.

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A CHIEF EXECUTIVE OFFICER SPEAKS HIS MIND. PORTION OF AN INTERVIEW WITH JOHN O. LOGAN, PRESIDENT OF UNIVERSAL OIL PRODUCTS COMPANY, DES PLAINES, ILLINOIS

Q: Nuclear power is said to be one solution to the Energy crisis. What's UOP's role, Mr. Logan?

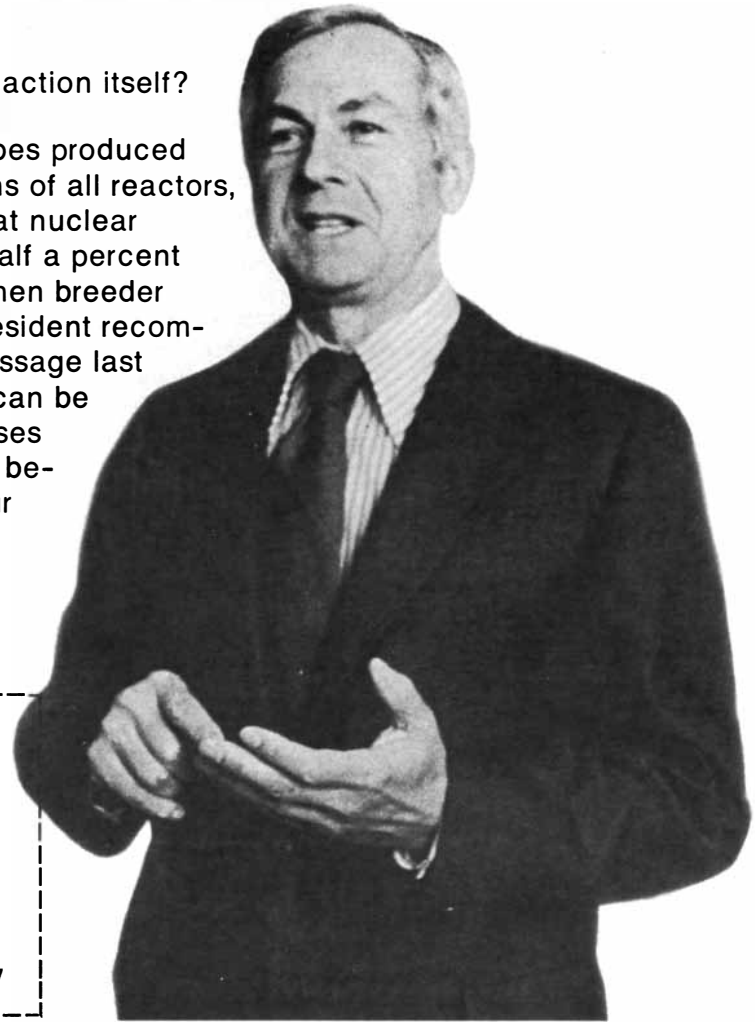
A: Ours is a potent but almost invisible role.

Q: For example?

A: We make seamless tubing for water-cooling in nuclear reactors. We sold 1,676 miles of this condenser tubing to TVA awhile ago and now all major fuel-core manufacturers specify the UOP product. Our half-century experience with chemical catalysts has led us to development of an off-gas nuclear recombiner that turns waste hydrogen and oxygen from the cooling process back into water—reducing the amount of radioactive xenon and krypton for easier liquid storage and treatment. UOP's secret in this case is an all-metal catalyst which can't be pulverized; can be recycled; and is unaffected by water.

Q: Anything closer to the nuclear reaction itself?

A: Yes, Zirconium fuel-cladding tubes produced by UOP are now used in three-fourths of all reactors, world-wide. You must understand that nuclear power right now supplies less than half a percent of the nation's energy supply. But when breeder reactors come on stream—as the President recommended in his State of the Union message last January—the nuclear power supply can be amplified a hundredfold. That increases UOP'S stake a hundredfold, too. We believe nuclear power can enhance our lives as well as ultimately help preserve our environment. It is most gratifying to me that UOP can contribute to that goal.



Write to Office of the President for details on:

( ) UOP's stakes in the Energy and Environment Crisis

( ) UOP's total Capabilities

UOP, Universal Oil Products Company
Ten UOP Plaza
Des Plaines, Illinois 60016

uop
The Answer Company

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THE AUTHORS

HERBERT F. YORK ("The Great Test-Ban Debate") is graduate dean and professor of physics at the University of California at San Diego, currently on leave. York had a long career as an administrator and a Government official: he was director of the Radiation Laboratory at Livermore from 1952 to 1958; chief scientist with the Advanced Research Projects Agency of the Department of Defense in 1958; director of defense research and engineering in the office of the Secretary of Defense from 1958 to 1961; chancellor of the University of California at San Diego from 1961 to 1964 (and again on an acting basis from 1970 to 1972), and twice a member of the President's Science Advisory Committee, serving as its vice-chairman in the latter years of the Johnson Administration. From 1962 to 1969 he was a member of the general advisory committee of the U.S. Arms Control and Disarmament Agency. York was graduated from the University of Rochester in 1942, receiving his master's degree there in 1943 and his Ph.D. from the University of California at Berkeley in 1949.

ROGER GUILLEMIN and ROGER BURGUS ("The Hormones of the Hypothalamus") are at the Salk Institute; Guillemin is resident fellow and dean and Burgus is senior research associate in the neuroendocrinology laboratory. Guillemin was born in France and received his degrees of bachelor of arts and bachelor of science from the University of Dijon in 1941 and 1942 respectively. His M.D. is from the faculty of medicine in Lyons, and his Ph.D. (in experimental medicine and surgery) is from the University of Montreal. He spent a number of years on the faculty of the Baylor University College of Medicine before going to the Salk Institute in 1970. His main outside interests are writing on the history of medicine and collecting pre-Columbian art. Burgus obtained his bachelor's degree in chemical technology at Iowa State University in 1957 and his master's and doctor's degrees in biochemistry from the same university in 1960 and 1962 respectively. He taught biochemistry at the Baylor College of Medicine before joining the Salk Institute in 1970. Burgus is a registered grower of avocados.

A. N. BROERS and M. HATZAKIS ("Microcircuits by Electron Beam") are at the Thomas J. Watson Research Center of the International Business Machines Corporation. Broers, who is manager of electron-beam technology, has been at the center since 1965, the year he received his Ph.D. in electrical engineering from the University of Cambridge. He has degrees of bachelor of science in physics and electronics from the University of Melbourne and bachelor of arts in electrical engineering from Cambridge. "My interest in microscopy," he writes, "extends beyond technological applications into biology." Hatzakis received his bachelor's and master's degrees in electrical engineering from New York University in 1964 and 1967 respectively.

A. HALLAM ("Continental Drift and the Fossil Record") is a member of the faculty of the department of geology and mineralogy at the University of Oxford and also a fellow of New College (founded in 1379). His bachelor's degree and his Ph.D. are from the University of Cambridge. Before going to Oxford he taught at the University of Edinburgh. In 1963 and 1964 he was a Harkness Fellow in the U.S., spending most of his time at Stanford University, and in 1970 he was visiting professor at McMaster University in Ontario.

HOWARD R. TOPOFF ("The Social Behavior of Army Ants") is assistant professor of psychology at Hunter College of the City University of New York and research associate in the department of animal behavior of the American Museum of Natural History. "These affiliations," he writes, "are a result of a new joint graduate program in animal behavior and biopsychology between the City University and the American Museum." Topoff received his bachelor's degree at the City College of the City University of New York in 1964 and his Ph.D. from the university in 1968. He was the last graduate student of the late T. C. Schneirla, who had been studying army ants since 1932; Topoff recently completed editing the book, *Army Ants: A Study in Social Organization,* that Schneirla was writing at the time of his death in 1968. Topoff writes of his concern about "the often uncritical application of concepts derived from studies on animal behavior to attempts to understand the origin of the problems of human societies." He has organized a new undergraduate course on the subject. Outside of science, he says, his principal interest is athletics.

JAN B. DEREGOWSKI ("Pictorial Perception and Culture") is lecturer in psychology at the University of Aberdeen. He has the degrees of B.Sc. (in engineering) and B.A. and Ph.D. in psychology from the University of London. He writes that his interest in cross-cultural work developed while he held a fellowship at the University of Zambia from 1965 to 1969. "I regard the work as important because cultures provide conditions that cannot be created in a laboratory and that are capable of throwing new light on psychological laws and processes."

ROBERT MARK ("The Structural Analysis of Gothic Cathedrals") is associate professor of civil engineering and architecture at Princeton University and codirector of the Princeton program on humanistic studies in engineering. He writes: "During college years I appeared for an interview for an engineering job carrying under my arm Sabartés' *Picasso,* with its brightly illustrated jacket. The interview was unsuccessful. Later, while I was waiting for an elevator, one of the engineers, apparently feeling sorry for my plight, emerged from the office to give me advice: 'Young man, never carry an art book when seeking *engineering* employment.' This dichotomy of interests continued to exist in my professional life until about six years ago, when several of my students, who were also taking a course on Gothic cathedrals, pointed to the need for scientific analysis of cathedral structure. A new, interdisciplinary field of study has emerged." Mark received his bachelor's degree in engineering from the College of the City of New York in 1952 and worked for several years as an engineer before taking up his work at Princeton in 1957.

CLYDE E. WIEGAND ("Exotic Atoms") is at the Lawrence Berkeley Laboratory of the University of California, where he has worked since 1941 except for the period from 1943 to 1946, when he was at the Los Alamos Scientific Laboratory. He received his bachelor's degree at Willamette University in 1940 after working for several years as a weather observer and an engineer with radio stations. His Ph.D., which he obtained from the University of California at Berkeley in 1950, is in physics. Wiegand writes that he and his wife "like to travel and have ranged from the jungle of Venezuela to the Himalayas of Nepal," where they hiked. "In 1967 we both learned to fly and bought a small plane, which has since been our main outside interest."

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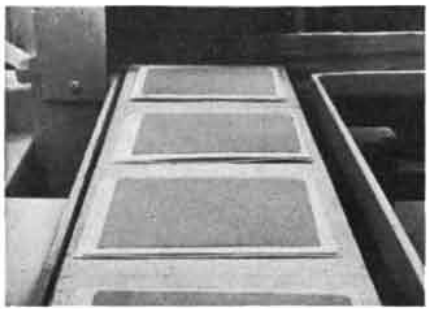
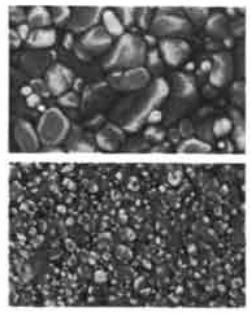
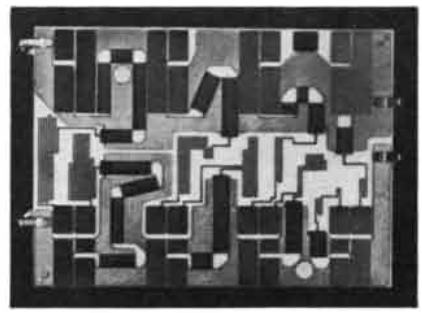
WESTERN ELECTRIC REPORTS



1500° C furnace was specially designed to fire these new substrates. The relatively low temperature results in smooth substrate surfaces for practically fault-free thin film bonding.



Electron micrographs show the great difference in grain size between new ceramic material (lower) and the previous material (upper).



Thin film integrated circuit shown here is part of a resistor network. It is one of many that benefit from the improved substrate. Metal leads on sides are bonded by thermocompression to tantalum nitride resistor film.

Smoothing the way for perfect thin film bonding.

Aluminum oxide, or alumina, is considered to have the best combination of properties for thin film circuit substrates. Until recently, however, the bonding of metal elements to gold-coated tantalum nitride resistor film on alumina was somewhat unpredictable.

Now, an advance at Western Electric has made it possible to get practically fault-free bonding of these materials.

This new perfection in bonding came through the development of finer grained alumina substrates.

The process has four basic steps: milling, casting, punching and firing.

During milling, alumina is combined with magnesium oxide, trichlorethylene, ethanol and a unique deflocculant. For 24 hours, this mixture is rotated in a ball mill. In a second 24-hour period, plasticizers and a binder are included.

The deflocculant plays a major role by dissipating the attraction forces that exist between the highly active alumina particles. This prevents thickening, which would ordinarily make an active alumina mixture unworkable.

The 48 hours of milling is followed by casting. When the material comes off the casting line, it is in the form of a flexible polymer/alumina tape, dry enough to be cut into easily handled sections.

After casting, a punch press cuts the material into the desired rectangles or other shapes. Holes can be punched at the same time.

Finally, because of the use of active alumina, the material is fired at an unusually low temperature which results in smooth substrate surfaces for reliable thin film bonding. The finished substrate is then ready for the various processes of thin film circuit production.

In developing this new process, engineers at Western Electric's Engineering Research Center worked together with engineers at the Allentown plant.

Conclusion: This new way to produce substrates is a truly significant contribution for thin film circuit production.

The ultimate gain from this smoother substrate is for communications itself. For through the achievement of nearly perfect bonding of metal leads to tantalum nitride, thin films can be produced with even greater reliability and economy.

Western Electric

We make things that bring people closer.

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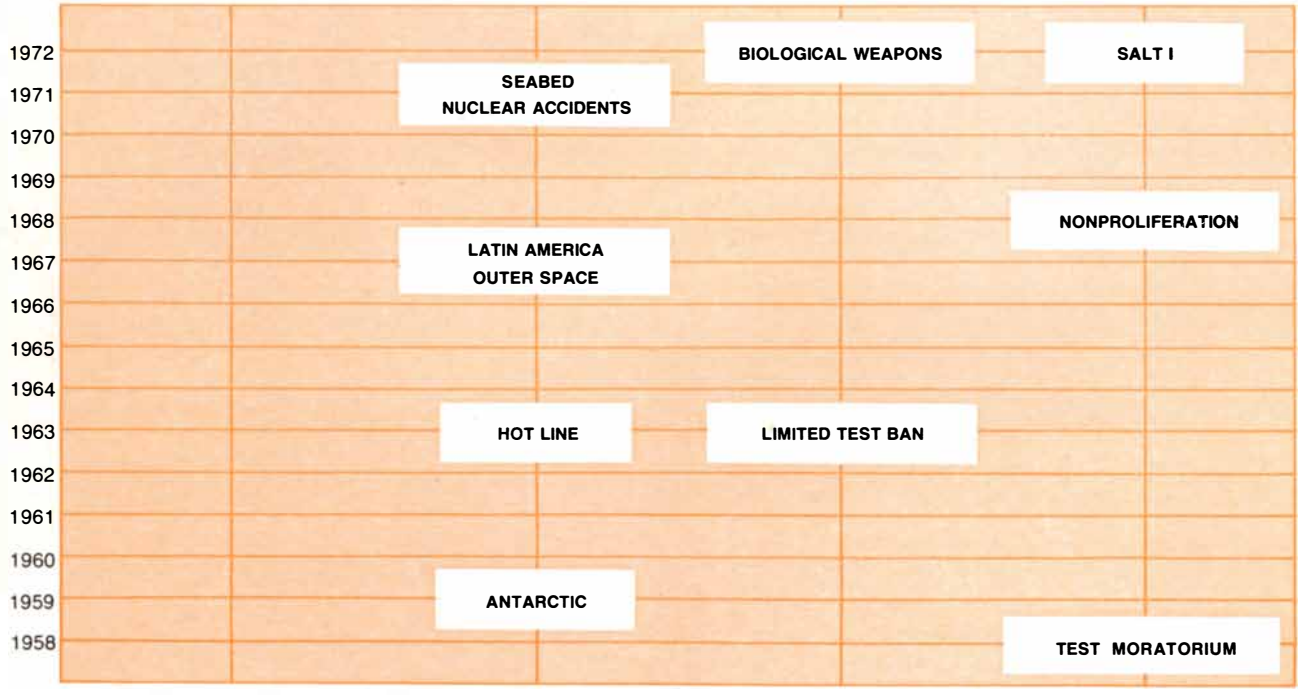
Established 1845 SCIENTIFIC AMERICAN November 1972 Volume 227 Number 5

The Great Test-Ban Debate

The trend of events in weaponry and in arms control tends to refute arguments presented a decade ago against a limited nuclear-test ban and to indicate that the time may be ripe for a comprehensive test ban

by Herbert F. York

The modest but significant progress toward the control of nuclear weapons that has been made during the past nine years has brought to the fore the question that was raised in the first place: Is the time ripe for a treaty prohibiting all tests of nuclear weapons? Indeed, both the limited-test-ban treaty of 1963 and the nonproliferation treaty of 1968 contain clauses obligating the signatories to seek to achieve a treaty establishing a comprehensive ban. The issue is therefore being debated again, as it was when Jerome B. Wiesner and I discussed the subject in these pages in October, 1964. This time, however, it is possible to employ hindsight to sharpen foresight, because most of the arguments being made against a comprehensive test ban now are essentially the same as the ones that were put



CHRONOLOGY OF ARMS-CONTROL AGREEMENTS adopted since 1958 is traced. The test moratorium lasted only from 1958 to 1961, but the work that went into it and the climate that it created provided the basis for all the other agreements. SALT stands for strategic-arms-limitation talks, which were conducted between the U.S. and the U.S.S.R. for more than two years and culminated in the agreements of last May limiting the deployment of anti-ballistic-missile systems and freezing strategic offensive missiles.

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forward in the long debate preceding the adoption of the limited test ban. An examination of how those arguments look in the light of experience will help to supply a basis for estimating how much weight they should be given in the present debate.

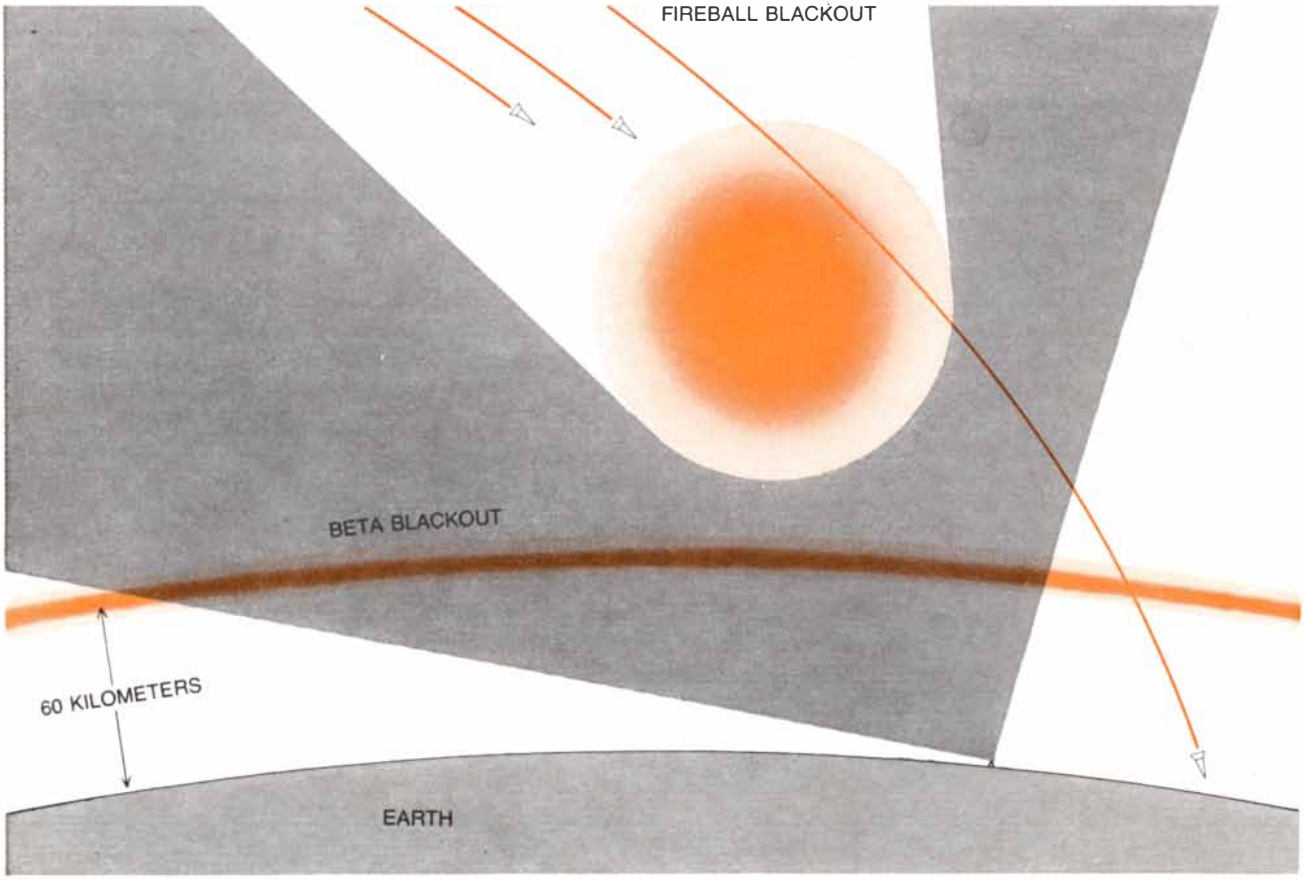
The questions involved are of two general types. One type has to do with the means for monitoring a test ban to ensure that the signatories are complying with the treaty. That subject was recently reviewed in these pages [see "Extending the Nuclear-Test Ban," by Henry R. Myers; SCIENTIFIC AMERICAN, January]. The other type has to do with the potential effects of a test ban on the national security of the parties to a treaty or any other agreement. I shall limit my discussion to questions of this type.

In the debates of a decade and more ago (from 1957 to 1963, to be more precise) the national-security matters most frequently raised by people who opposed or seriously questioned the test ban came under the following general headings: anti-ballistic-missile (ABM) systems, weapons effects, pure fusion bombs, improvement of the yield-to-weight ratio of nuclear weapons and new knowledge, possibly involving military surprises. Let us review the arguments and the subsequent developments under each heading.

In the early 1960's claims were made by Russian officials that the U.S.S.R. had solved the problem of intercepting and destroying incoming ballistic missiles. Not long afterward U.S. intelligence activity discovered that the Russians were indeed beginning to deploy an ABM system. Moreover, the extensive series of nuclear tests conducted by the Russians during 1961 and 1962 had included explosions at altitudes that would be of interest to designers of an ABM system. The U.S. had also conducted a number of high-altitude tests, leading certain scientists and military officials to assert that this country had enough knowledge to design an ABM system. Secretary of Defense Robert S. McNamara and other high officials did not agree, however, and so no ABM-system deployment was then authorized in this country.

Opponents of a test ban contended that the reason for the difference between the Russian decision to deploy and the U.S. decision not to deploy must be that the Russians knew something we did not know. They suggested that this something had been discovered during the Russian test series. Some opponents went on to speculate that the reason the Russians were now willing to consider a test ban was that they had learned some essential secret and saw the test ban as a way of preventing the U.S. from learning it.

For example, the physicist Edward Teller said: "I think there is a disparity in knowledge, and the disparity of knowledge today means a disparity of power tomorrow.... I believe that, because they have acquired this knowledge, they don't need any more atmospheric tests, and I believe that is why Khrushchev is willing to sign the treaty at present." Senator Strom Thurmond said: "All it will take to put the Soviets in a dominant nuclear position is two



BLACKOUT PHENOMENON was a possibility raised as an argument against the limited test ban. The concern was that a nuclear explosion at high altitude would produce ionized air that would for a time be opaque to the defender's radar. "Fireball blackout" would result when heat from the explosion stripped electrons from air molecules, and "beta blackout" would result from electrons released in the decay of fission products. Continued testing was said to be needed to produce a defensive missile system that could withstand such effects. The difficulty of creating any adequate antimissile system has made the blackout argument peripheral.

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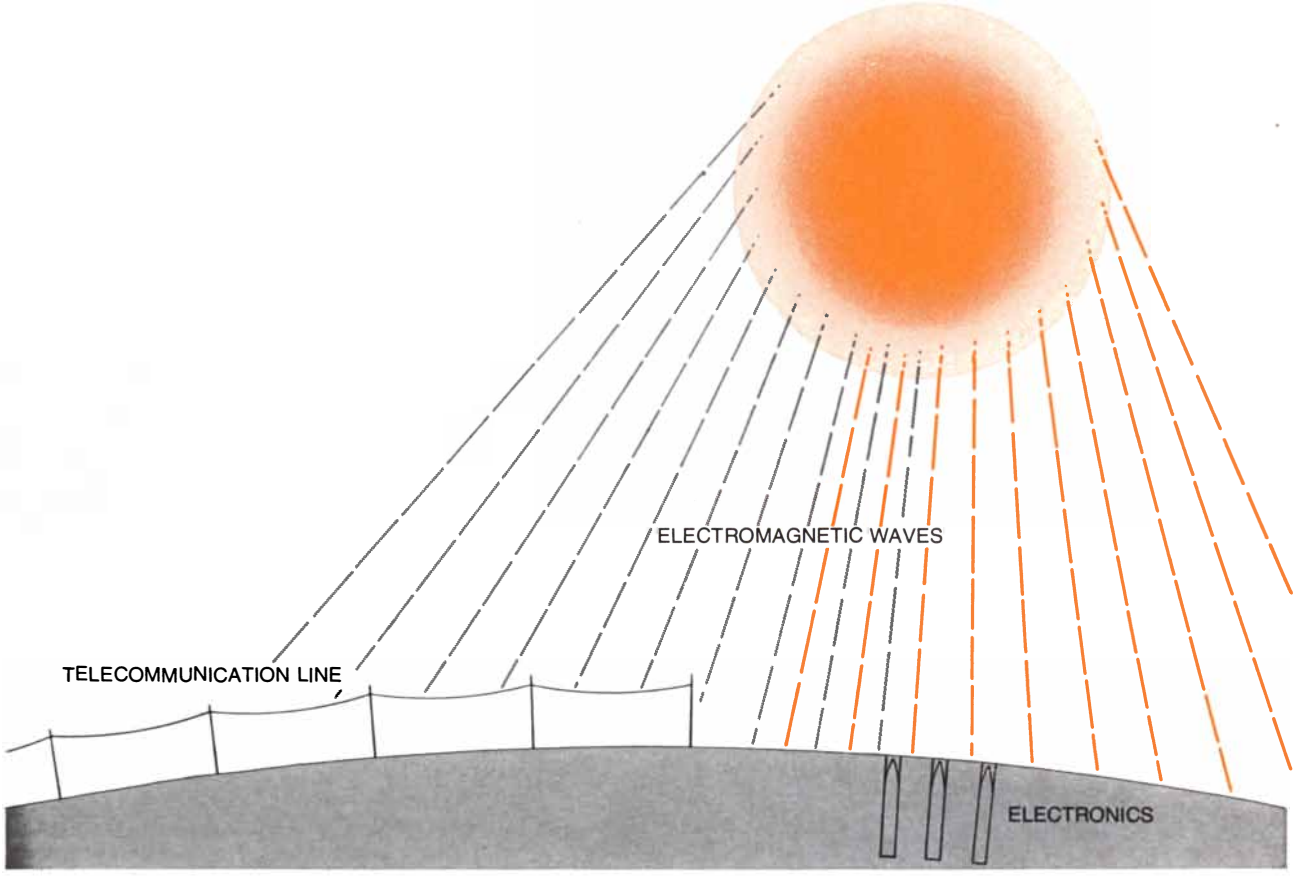
things: one, enough time to build up a stockpile of the already perfected Red antimissile missile, which will render our huge arsenal of ICBM's [intercontinental ballistic missiles] useless, and second, ratification of the test-ban treaty that will prevent the United States from high-altitude tests necessary for completion of our own Nike X antimissile-missile program, thereby leaving America defenseless against Red missiles."

When pressed for details, the opponents of the test ban commonly referred to several matters on which, they said, insufficient information existed, at least in the U.S. One matter was the blackout phenomenon, in which a nuclear explosion at high altitude produces a large volume of ionized air that is for a time opaque to radar. There were also allusions to certain long-range "kill" mechanisms that would work against incoming warheads. Here it was argued that tests were needed in order to design defensive warheads that would produce such effects and offensive warheads that would survive the effects.

On the other side of the argument it was contended that the U.S.S.R. had not gained any special advantage due to some private knowledge about high-altitude effects. Harold Brown, who was then Director of Defense Research and Engineering, said: "I feel rather strongly that they [the Russians] are not substantially ahead of us." He added that it was not a defect in nuclear knowledge that had prevented the U.S. from deploying ABM systems but rather that "the U.S. decided not to deploy the Nike Zeus because its effectiveness was inadequate against U.S. penetration aids . . . and we assume the same would be true of the Soviet penetration-aid capability." The U.S. Joint Chiefs of Staff said that "development of the U.S. [ABM] system does not depend on atmospheric testing and hence this treaty will not significantly influence any imbalance that may exist."

What have subsequent events revealed about these claims and predictions? The Russian ABM program proceeded erratically from the base described in 1963. After several periods of delay that indicated indecision and uncertainty, the Moscow ABM system (now called the Galosh system) was reported early this year to have fewer than 100 ABM vehicles ready for launching. The system was generally judged to be quite inadequate for coping with an attack against it by U.S. missiles. Russian ABM installations that had at one time been reported around Leningrad and Tallinn either were dismantled or turned out to have a different purpose. Nothing that has happened since the test-ban debate has confirmed the notion that the U.S.S.R. knew something the U.S. did not know. Indeed, the Russian decision to deploy the Galosh system seems to have been due to a poor understanding of just how easy it is to penetrate systems of that type and size.

On the U.S. side the development of an ABM system continued through the 1960's at a level of about $500 million per year. The system slowly evolved, as did the political situation both domestically and internationally. Finally, near the end of the Johnson Administration, a decision was made to deploy an ABM



"TREE" AND "EMP" PHENOMENA have been raised as arguments for continued testing. TREE stands for transient radiation effects on electronics, and EMP stands for electromagnetic pulse. They both arise from nuclear explosions. The phenomena can disrupt electrical communications on the ground and can cause electronic equipment on missiles to malfunction. In this "pin-down" tactic the defending nation supposedly could not launch its missiles. The weakness of the argument is that the tactic would be ineffective in view of the large variety of retaliatory weapons that would be available to the defender and the extent of their dispersal.

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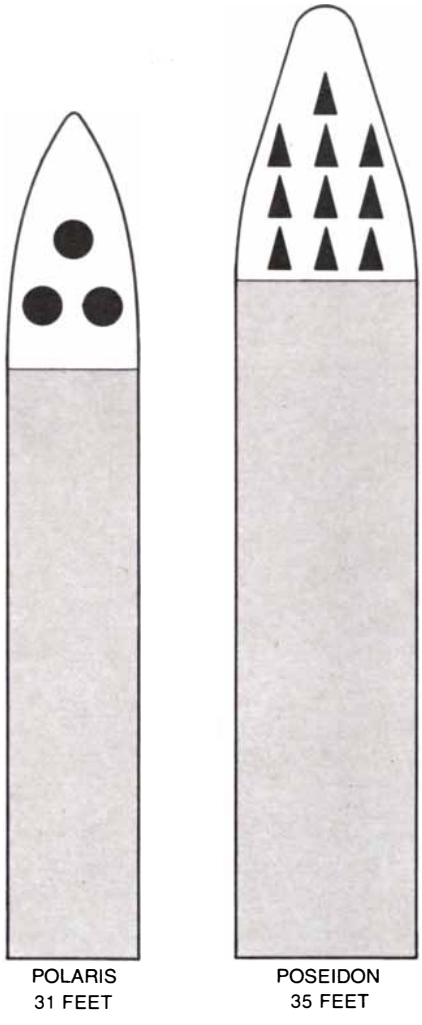
system called Sentinel around certain cities. The main reason given was that it would provide protection against a prospective Chinese missile force.

After considerable public reaction this decision was rescinded, and a deployment of the same equipment under a new name (Safeguard) was proposed by the Nixon Administration. The Senate accepted the proposal after a long debate about the effectiveness of the system and the problems being met in developing it. In the entire debate developments in nuclear weaponry were never cited as having a crucial role in the various decisions concerning deployment. The serious questions that were raised about the feasibility of the system all had to do with such matters as the computers, the radar and the problems posed by decoys and MIRV's (multiple independently targetable reentry vehicles). When nuclear problems such as blackout were mentioned, it was only peripherally and never as constituting a major problem.

None of this proves that nuclear-weapons development and weapons-effect research are entirely irrelevant to ABM development, but it does indicate that recent research and development in this field have been far from essential. Apparently any lack of perfection in weapons can be overcome in the design of other parts of the system. Moreover, as the ABM program has shifted from Sentinel to Safeguard and now to the site-defense system (sometimes called Hardsite), the emphasis has shifted from interception at great distances and high altitudes to interception near the target at relatively low altitudes, where the phenomena to be dealt with are much better known.



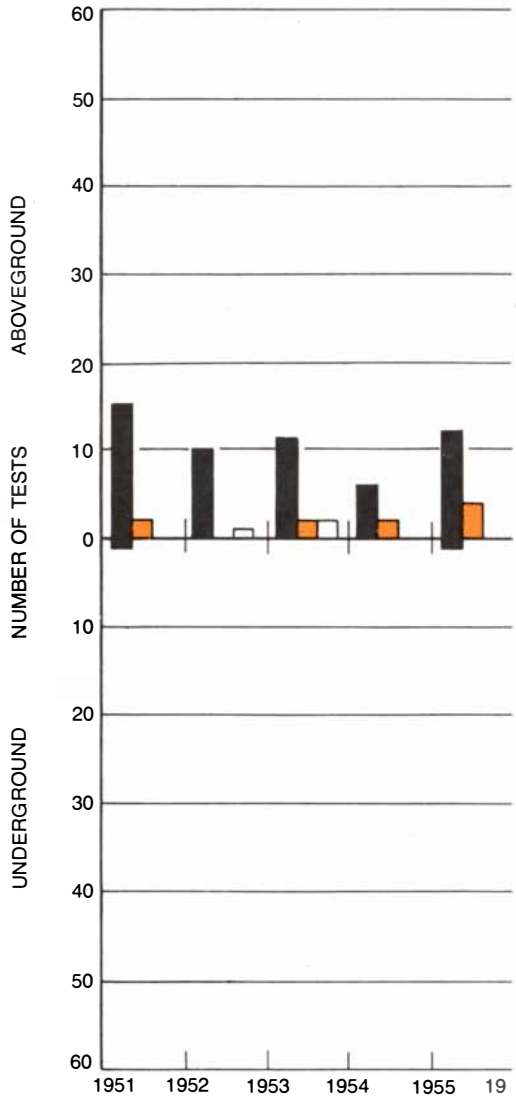
POLARIS AND POSEIDON missiles are compared. The older Polaris has three reentry vehicles that are not independently targetable, whereas the Poseidon has 10 MIRV's (multiple independently targetable reentry vehicles). It has been said that the Poseidon warhead could not have been developed under a comprehensive test ban. The author argues that the Polaris warhead could have well been adapted for the Poseidon missile.

I turn now to weapons effects. During the years when nuclear weapons were tested aboveground, the basic effects—blast, radiation, fallout—that kill, injure and destroy were studied in great detail. These are the weapons effects that matter; the entire concept of deterrence, which all sides cite as the main reason for maintaining nuclear forces, is based wholly on the threat of unacceptable levels of death and destruction through these effects. For decades the phenomenology of these effects has been known with a precision that far exceeds the practical use of the information.

In addition to these basic phenomena one hears of a few other more exotic effects that are of technical interest in connection with certain duels between nuclear weapons. Uncertainties about such effects are sometimes raised as an issue in test-ban debates. Among the effects are "TREE" and "EMP."

TREE stands for transient radiation effects on electronics. It is an old problem that has become relatively more important as more complex devices have been introduced into nuclear-weapons systems. It is also mainly of interest in connection with duels in outer space, where there is nothing to attenuate radiation, which therefore would far outreach other effects such as blast.

EMP stands for electromagnetic pulse. It refers to the fact that a nuclear explosion produces a large electromagnetic field, which in turn can induce large electric currents in conductors at substantial distances. Such currents, if nothing is done about them, can sometimes produce destructive effects in insufficiently protected equipment.



NUCLEAR TESTING by the U.S. (*black*), the U.S.S.R. (*color*) and all other nations

Some of the people who work on nuclear weapons have envisioned an attack in which an enemy explodes a series of warheads high over U.S. missile fields, producing a series of TREE and EMP phenomena (or other long-range effects) timed in such a way that the U.S. could not launch its missiles while the barrage continued. (The tactic is known as "pin-down.")

It is impossible to believe that real political or military leaders would consider such an effort in the face of the variety and dispersion of retaliatory weapons that could be employed. Even so, the claim that further research was

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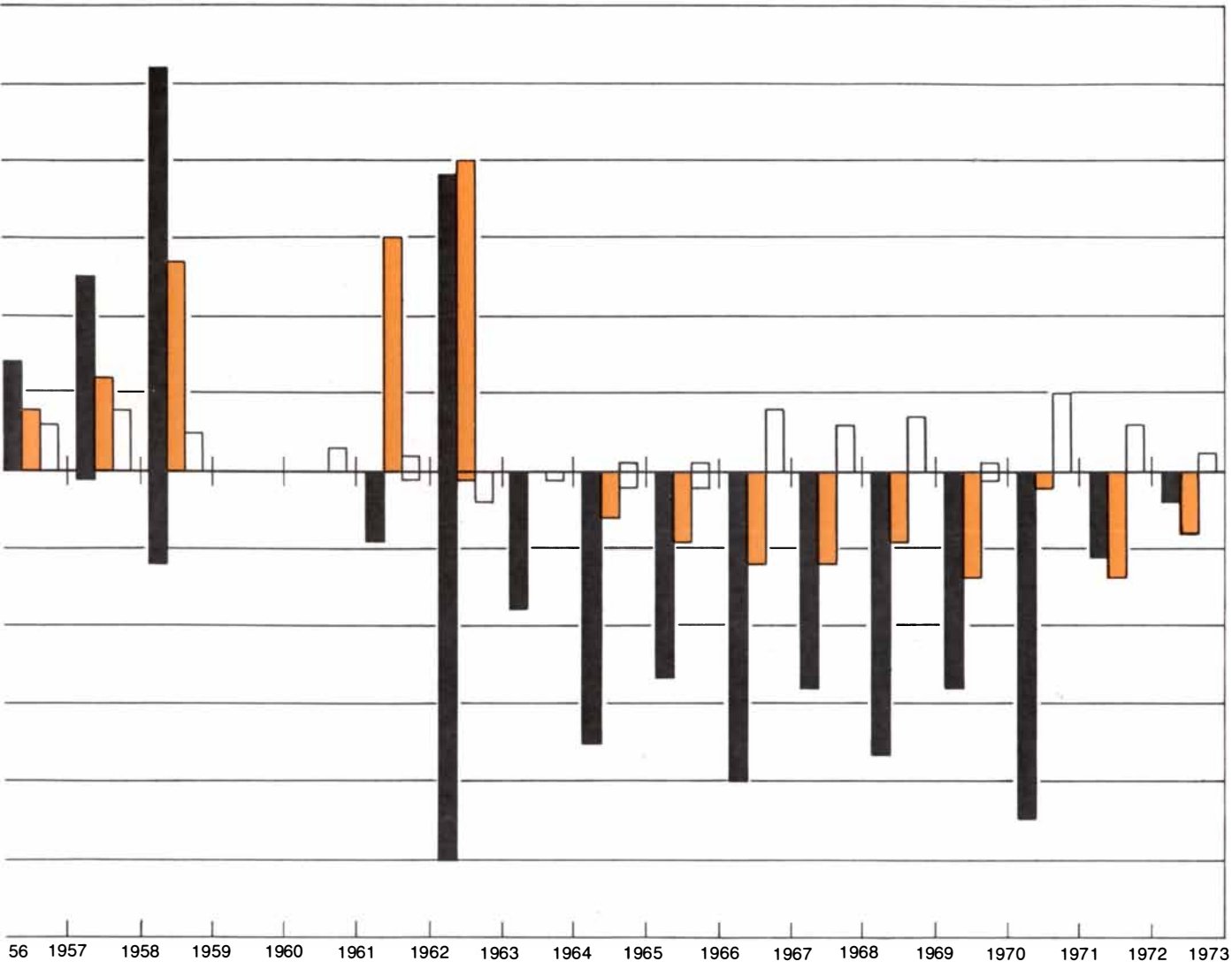

(*open bars*) is charted from 1951 to the fall of 1972. The gap near the center reflects the moratorium on testing nuclear weapons from 1958 to 1961. The figures were obtained from various sources by the Stockholm International Peace Research Institute (SIPRI).

needed on this matter was advanced in the early 1960's as an argument against the test ban. (At the time the argument was largely conducted behind the curtain of secrecy that surrounds much military activity; public discussion of the issue became possible only later.)

All the more exotic effects were observed before the partial test ban went into effect. They were not as thoroughly studied as the basic effects, however, and in addition certain new forms of interaction between these phenomena and specific weapons systems have been found since 1963. At first it was thought that it would be difficult to learn more about the exotic effects in underground explosions, and that possibility was raised as an argument against the partial test ban. Later it turned out that a good deal can be learned about the effects from underground testing and by other means. In 1968 Vice-Admiral Lloyd M. Mustin, director of the Defense Atomic Support Agency, reported to Congress: "We think we have the interaction of threats with these two systems [Minuteman and Polaris] well understood and identified and very carefully developed and sophisticated countermeasures far advanced."

In sum, no really new phenomena produced by the explosion of nuclear weapons has been discovered in about 15 years, and there is no good reason to expect that any will be forthcoming. In those years the U.S. has refined its knowledge of the effects of specific systems and in specific environmental situations. Even at that level of detail we have long since passed the point of diminishing returns. The remaining uncertainties are small compared with the other uncertainties about any nuclear attack: the kind, number, yield and accuracy of the weapons; the targets selected; the timing, the relation to other attacks or to political moves, and so on. These are the uncertainties that will dominate the thinking of any statesman who may one day be considering the use of nuclear weapons. No doubt there is more to be learned about weapons effects, but the matter is largely of interest to specialists, and concern about it should have no bearing on important political questions such as whether or not to ban further nuclear tests.

Pure-fusion bombs and bombs with a high ratio of fusion to fission (also called neutron bombs) were seen in the late 1950's as offering a number of ad-

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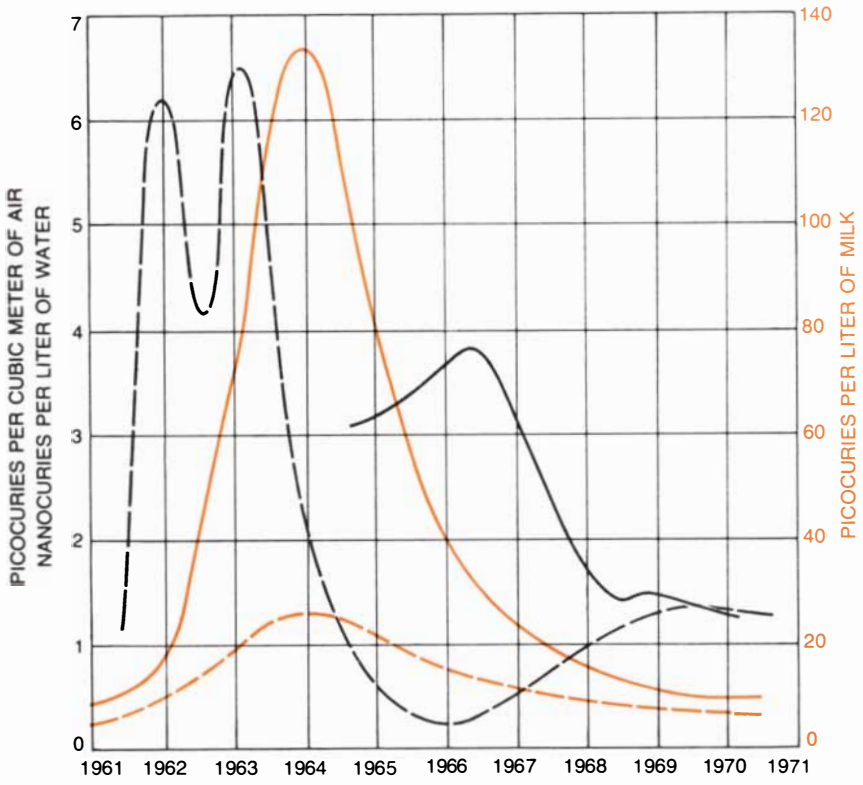
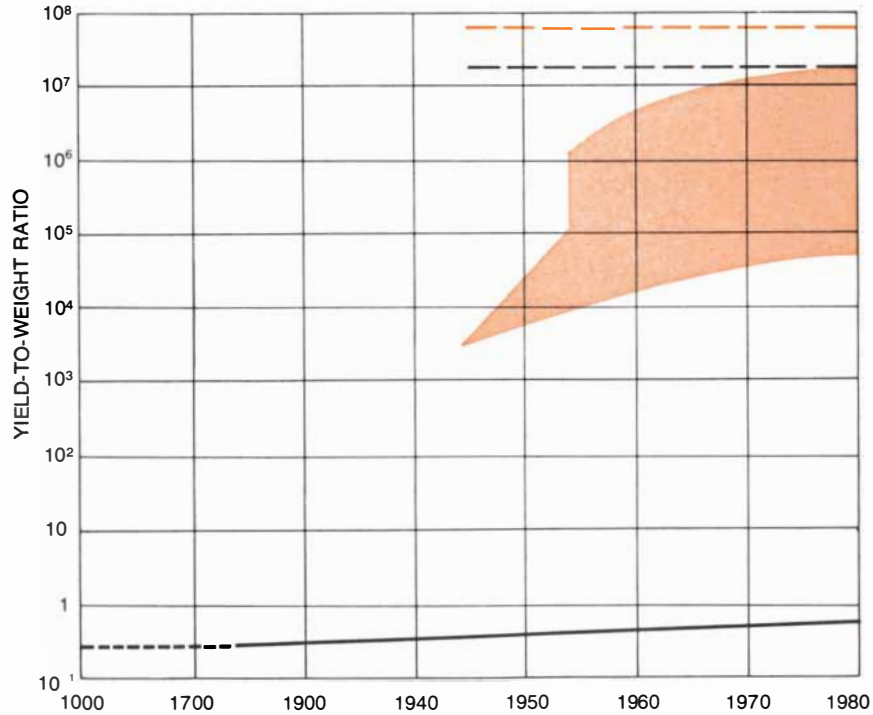


RADIOACTIVE FALLOUT has declined since nuclear testing by the U.S. and the U.S.S.R. has been done underground as a result of the limited test ban. The chart, based on data from the U.S. Environmental Protection Agency, shows gross beta radiation in the air (*broken black curve*), tritium in water (*solid black curve*), strontium 90 in milk (*broken colored curve*) and cesium 137 in milk (*solid colored curve*). Some of the radioactivity is natural.



RATIO of yield to weight of nuclear weapons (*colored band*) and conventional weapons (*black line*) is charted. Lower part of nuclear-weapon band represents fission bombs; upper part, thermonuclear bombs. Broken lines represent theoretical maximum for fusion (*color*) and fission (*black*). The slowness of the rise in recent years is due in part to emphasis on other matters such as dimensions and decreasing vulnerability to nearby explosions.

vantages, and the need to develop them was therefore raised as an argument against a test ban. Teller, for example, was reported to have said to a Republican committee on nuclear testing in 1963: "We have started the development of clean and cheap nuclear explosives. We need more tests to complete this development. Clean and cheap nuclear explosives are needed for battlefield use, for peaceful applications and for missile defense." John A. Wheeler of Princeton University was reported as telling the same group: "As a physicist and specialist on nuclear fission I see a decisive loss to national security from a test ban. It will prevent us from developing a technology of pure hydrogen devices free of fission fallout.... The new technology will have important peacetime applications in mining and earth-moving and will revolutionize ground warfare. ... It is unconscionable to renounce for the free world a revolutionary device which others will then make without our knowledge."

On the other side, William C. Foster, director of the U.S. Arms Control and Disarmament Agency, said that the expert advice he had received was that pure-fusion weapons would not be of great advantage. The reason, he said, was that "they would constitute primarily a cheaper substitute for the explosive components in our already large stockpile of nuclear weapons."

How did matters turn out? The pure-fusion bomb remains undeveloped, and responsible people no longer talk much about it as being the basis of a new revolution in weaponry. When officials of the Department of Defense and the Atomic Energy Commission present arguments for continued testing now, they do not rate the need for fission-free bombs any higher than the need for other and more orthodox modifications and improvements.

A pure-fusion explosion may yet be achieved as a result of all the effort that has been expended. It would be a technological accomplishment, but the likelihood that it would have any large military or political value seems small. The basic fact is that the nuclear capability of the major nuclear powers is already supersaturated in the sense that it can produce more varieties of death, destruction and horror than anyone can seriously contemplate seeking to inflict.

It was also stated during the debate preceding the test ban of 1963 that further improvement in the yield-to-weight ratio of nuclear weapons was in prospect

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and that certain other improvements and modifications were both possible and necessary. Among them were decreased vulnerability to nearby nuclear explosions and increased safety of weapons. Substantial progress has indeed been made along these lines since 1963. The important question, however, is: How important and how relevant has the progress been?

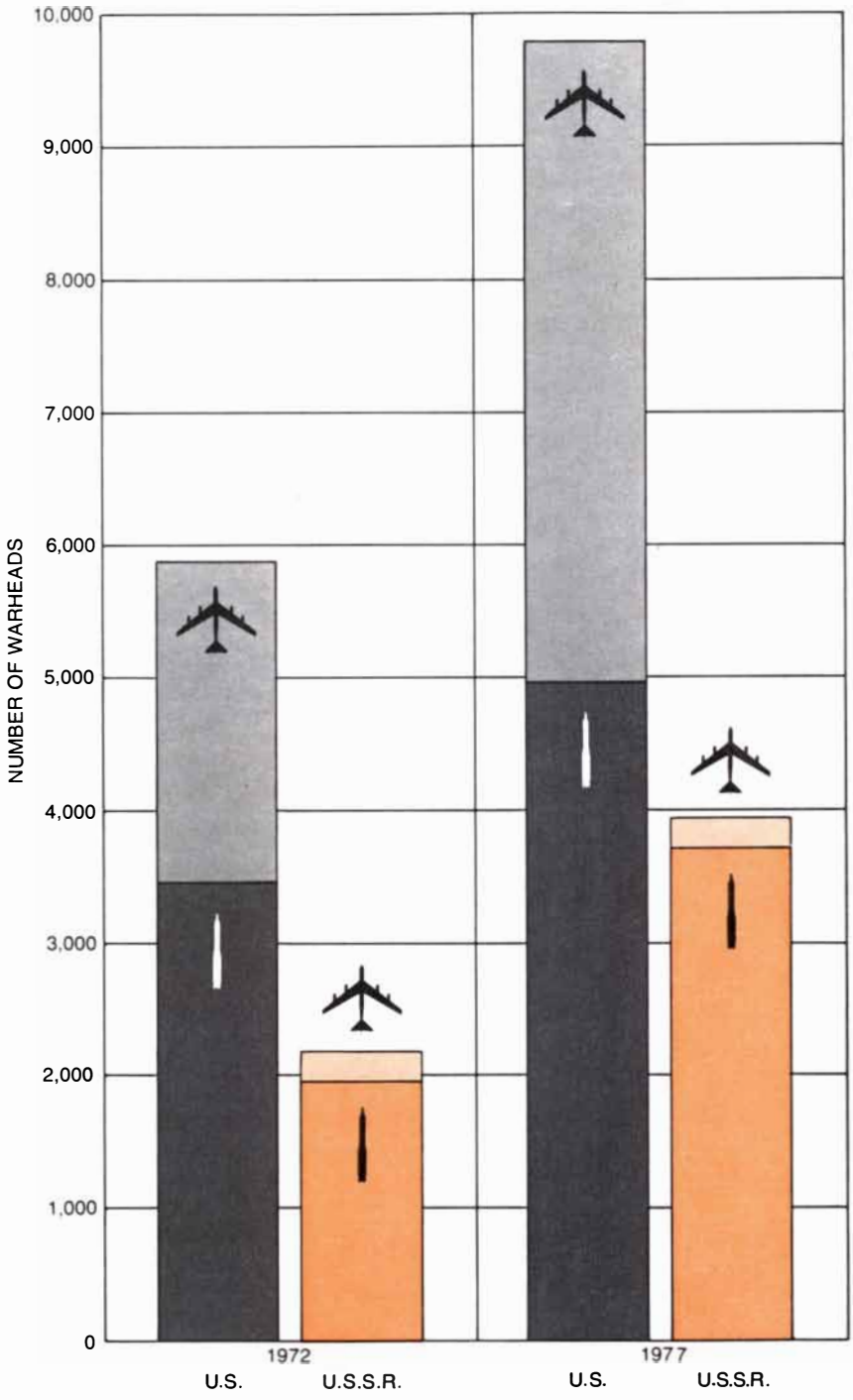
The Poseidon missile provides a basis for discussion. It is more advanced than its predecessor, the Polaris A-3, in many ways. It is bigger, it can carry a larger payload a longer distance and it has improved accuracy. Moreover, its payload is of the MIRV type: each missile launches a "bus," which has on board a large number of reentry missiles, each of which can be accurately and independently targeted. None of these advances depended on nuclear tests.

M. Carl Walske, Jr., assistant to the Secretary of Defense for Atomic Energy, recently stated that the warhead for the Poseidon MIRV was developed after the limited test ban went into effect, and he argued that if the ban had been comprehensive, nothing like the present Poseidon MIRV could have been developed. I believe his statement is highly misleading. If a pre-1963 warhead such as the one for the Polaris A-3 had been adapted for the Poseidon, the Poseidon MIRV would have had either lower multiplicity (fewer independent missiles) or a shorter range, but it could have had a higher total yield.

Presumably the new Poseidon warhead has been further modified so as to reduce its vulnerability to attempts to intercept it. These modifications apparently resulted in a reduction of the yield-to-weight ratio. In any case such modifications were superfluous, since the basic multiple-warhead feature is in itself the most effective means for penetrating anti-ballistic-missile defenses of the kind that now exist. It does so simply by overwhelming the defense with larger numbers. The only requirement is that the individual warheads be hardened enough and separated enough so that one interceptor must be launched for each reentry vehicle. An A-3 warhead on a MIRV bus of the Poseidon type would easily satisfy this requirement.

Defense penetrability beyond what could be achieved in 1963 is needed only against an ABM defense consisting of very large numbers of relatively sophisticated interceptors. No such defense now exists—nor, I believe, is there any serious prospect of one in the foreseeable future. To say the least, deployment of the post-1963 Poseidon warhead is premature.

It is small wonder that the concern over surprises and new knowledge persists. One need only recall the early years of nuclear development to realize that surprises and new knowledge abounded at that time. The phenomenon of nuclear fission was discovered in 1938. The first nuclear-test device was exploded only seven years later, which was also the first (and so far the only) time that nuclear bombs were employed in warfare. In terms of energy output those bombs



BALANCE OF POWER between the U.S. and the U.S.S.R. is charted in terms of nuclear warheads in 1972 and 1977, the end of the period for which the SALT I agreements are to remain in effect. The missile symbol represents missile-launched warheads and the airplane symbol represents bomber-launched missiles. The chart is based on data from the U.S. Arms Control and Disarmament Agency, which points out that the U.S. has more but smaller missiles than the U.S.S.R. and that the megatonnage represented is approximately equal.

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were 1,000 times larger than the biggest chemical bombs.

Seven years later the first thermonuclear device was exploded. It was 1,000 times as large in output of energy as the first atomic bombs. Both of these huge technological steps can be characterized as breakthroughs, and they had major political and military consequences. No such huge gains in yield were made thereafter, but during the next seven years fundamentally important factors such as yield-to-weight ratio continued to improve radically. By 1960 the yield-to-weight ratio of fission bombs was two orders of magnitude (100 times) larger than it had been at the beginning. Means also had been found for both reducing the size and increasing the yield-to-weight ratio of thermonuclear weapons, again by order-of-magnitude amounts.

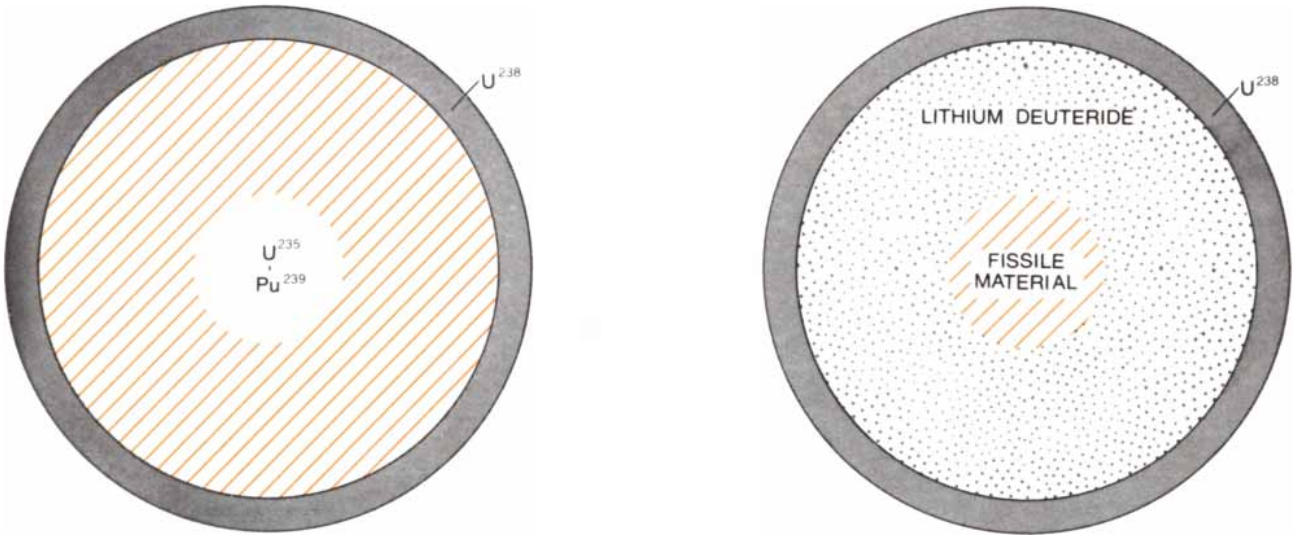
As a result of such developments many people came to believe politically significant technological breakthroughs had become the norm for nuclear technology. One thus finds many leaders in the field emphasizing the likelihood and importance of further technological surprises and arguing that no bars should be raised against obtaining new knowledge. In 1963, questioning the limited-test-ban treaty, John S. Foster, Jr., then director of the Lawrence Radiation Laboratory (he is now director of defense research and engineering in the Department of Defense), said: "We are involved in a field of technology that is not fully understood, nor its applications, and hence new experiments frequently bring surprises." Teller said a ban would "prohibit future science" and was "directed against knowledge." In 1961 Representative Chet Holifield, then chairman of the Joint Committee on Atomic Energy, expressed concern about "the ultimate general effect on weapons technology of a continuing test ban," which would "inevitably stifle developments undreamed of at the present time." He added: "Concepts are now being considered by our scientists which could be as revolutionary as the H-bomb [was] in 1949." General Curtis E. LeMay, as Chief of Staff of the U.S. Air Force in 1963, said: "We are just at the beginning of our investigations into the nuclear-weapons field."

On the other side, proponents of a test ban expressed doubt about the importance of specific potential breakthroughs and saw as unlikely the possibility that any such development would upset the balance of power. William Foster of the disarmament agency, supporting the limited test ban, suggested that nuclear science was maturing. "The point of diminishing returns in improving weight-yield ratios is fast approaching," he said.

At the time of the debate on the partial test ban the issue of surprises and new knowledge was still difficult to resolve. On the one hand there was the record of a remarkable series of discoveries, technological advances and politically significant applications. On the other hand no further breakthroughs were then in sight, with the possible exception of the pure-fusion bomb, and of that many experts said it would be technologically novel but without great political or military significance.

Now, however, it seems to me that this issue has been resolved. Nuclear weapons have been further refined, and there is greater understanding of the details of certain effects, but no new knowledge or surprises remotely similar in kind or importance to those of the first two nuclear decades have been reported or claimed. Moreover, the nuclear arsenal is so large and varied that the significance of new inventions is small in any case. Compared with the danger of further proliferation of nuclear weapons, the danger that the U.S. will be overwhelmed by an unsuspected breakthrough seems vanishingly small.

Let us turn now to the arguments that were made in 1963 and earlier in support of the limited test ban. Five principal points were made and can be set forth here in quotations of participants: (1) "A nuclear test ban treaty would constitute a significant step in the



NUCLEAR WEAPONS are depicted schematically. At left a fission bomb is shown just as the nuclear explosion starts. A supercritical mass of fissile material has been rapidly assembled by means of high explosive, which is not shown, and a chain reaction is initiated by a neutron from a source near the mass. The uranium 238 reflects some neutrons and provides some additional inertia but does not otherwise participate importantly in the reaction. The drawing of a thermonuclear bomb (*right*) explains its known properties, although no detailed design has ever been made public. Fissile material in the central core explodes, producing much heat and many neutrons. The neutrons convert some of the lithium 6 surrounding the core to tritium, and the heat causes thermonuclear deuterium-deuterium and deuterium-tritium reactions to take place in the lithium deuteride. These reactions in turn produce neutrons having enough energy to cause the surrounding uranium 238 to fission, thus releasing still more energy and additional quantities of neutrons.

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direction of slackening the arms race" (Dean Rusk). (2) It would preserve for a "longer period our present nuclear advantage" (William Foster). (3) "The treaty will curb the pollution of the atmosphere" (President Kennedy). (4) It would create a political climate in which "new opportunities for further steps toward turning the arms race downward might well be more within the realm of possibility than at present" (Rusk). (5) "A nuclear test ban would constitute a significant first step in achieving control over the further spread of nuclear weapons" (Foster).

Each of the statements also amounted to a prediction. Let us see how the predictions stand up in 1972. The limited test ban probably did slow down the arms race between the U.S. and the U.S.S.R., but it cannot be considered to have been outstandingly successful in this respect. It probably has severely limited the further development of very large thermonuclear weapons, but the rate of nuclear testing has continued at about the same level—although the tests are now underground.

Similarly, the treaty does not appear to have done much to preserve the "nuclear advantage" of the U.S. Since the treaty was signed, the U.S.S.R. has achieved rough parity with the U.S. in strategic weapons. In any event, the degree of "overkill" in the nuclear capability of both countries is such that further technological advances would make little political or military difference.

The treaty has been quite effective in curbing radioactive pollution of the atmosphere. Although France and China have continued to conduct nuclear tests in the atmosphere, the tests are far less frequent than was the case when the U.S. and the U.S.S.R. were conducting them. Moreover, without the treaty there would be no hope of persuading those nations and other potential nuclear powers to accept similar restraints. Meanwhile, in the absence of a comprehensive test ban such hazards as underground contamination, earthquakes and leakage of radioactive substances into the atmosphere remain possible.

The record of the treaty in creating an environment that made further moves toward arms control possible is excellent. The treaty has been followed by agreements to prohibit nuclear weapons in space (1967), make Latin America a non-nuclear zone (1967), bar further proliferation of nuclear weapons (1968), rule out the seabed for the emplacement of nuclear weapons (1971) and prohibit the use of biological weapons (1972). One might also cite the "hot line" agreements of 1963 and 1971 and the recent strategic-arms-limitation talks (SALT) that resulted in agreement by the U.S. and the U.S.S.R. to put ceilings on their offensive and defensive missiles.

One should also recognize, however, that many of the treaties are peripheral to the main problem and in effect prohibit actions that no nation particularly wanted to undertake anyway. The British disarmament expert Philip J. Noel-Baker, reviewing the results of the 1959 treaty that demilitarized Antarctica, commented that "while disarming Antarctica, we put 7,000 nuclear weapons in Europe; we should have disarmed Europe and put those weapons in Antarctica." Nonetheless, all the agreements are steps in the right direction, and collectively they add up to something significant. Moreover, they help to make arms-control and disarmament measures seem more feasible.

Probably the most important result of the limited test ban has been its contribution to inhibiting the further proliferation of nuclear weapons. Since the treaty was signed, only China has begun testing nuclear weapons, and the Chinese program to develop nuclear weapons had been set in motion long before 1963. The cause was greatly aided by the nonproliferation treaty, which now has some 70 signatories in addition to the original adherents (the U.S., the United Kingdom and the U.S.S.R.). It also seems evident that the treaty has deterred nonsigners from testing.

Indeed, the most important reason for moving now toward a comprehensive ban on testing nuclear weapons is that it would strengthen and reinforce the nonproliferation treaty. The present situation contains elements of hypocrisy and unfairness, since the two major nuclear powers are trying to persuade other nations that nuclear weapons are unnecessary while at the same time both are conducting test programs.

To sum up, a decade of hindsight on the debates preceding the limited-test-ban treaty of 1963 suggests the following main conclusions:

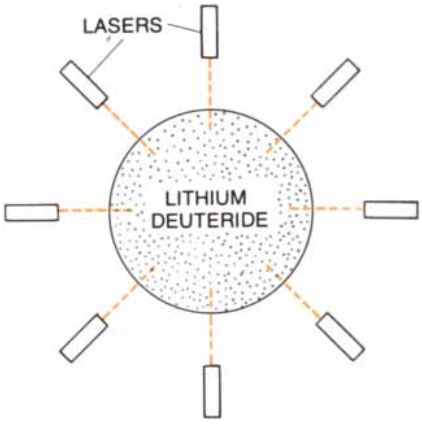
1. The predictions of major surprises and ominous developments were wrong. There has been no "third revolution" in nuclear weapons. The atmospheric tests before 1963 and the underground tests since then have not produced a solution to the problem of developing an ABM system that would be likely to have more than limited success.

2. On the other hand, the passage of time has confirmed the more moderate claims that there was substantial progress to be made in improving the yield-to-weight ratio, hardening weapons against interception, making better fits to new delivery systems and so on. The questions to be asked, however, are how progress in these areas has affected the nuclear balance and whether such technical progress is politically significant. The answers seem to be that, if anything, continued testing has further degraded whatever nuclear advantage the U.S. still had in 1963 and that the political significance of nuclear weapons is derived from the huge numbers of such weapons rather than from their technical sophistication.

3. The limited test ban has not done much to slow the main arms race between the two superpowers. The reason is the limited nature of the agreement. A comprehensive ban in 1963 probably would have done much more.

4. On the other hand, the limited ban has accomplished several of the most important objectives that were were set for it. In ascending order of importance they are cleaner air, the establishment of a political climate conducive to much additional progress in arms control and disarmament and the distinct slowing of the spread of nuclear weapons.

On balance, therefore, the limited test ban can be described as a success. Clearly, however, it needs to be extended to prohibit underground testing. A comprehensive treaty may now be within grasp; we must reach for it while we can.



PURE-FUSION BOMB, which has yet to be developed, would entail heating the fusion material without the use of a fission explosion. Lasers could perhaps produce the necessary initial conditions, but the technology seems to be formidable. Achieving such a bomb would be a technological feat, but it seems probable that the achievement would not have any great political or military value beyond the present nuclear bombs.

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THE HORMONES OF THE HYPOTHALAMUS

The anterior pituitary gland, which controls the peripheral endocrine glands, is itself regulated by "releasing factors" originating in the brain. Two of these hormones have now been isolated and synthesized

by Roger Guillemin and Roger Burgus

The pituitary gland is attached by a stalk to the region in the base of the brain known as the hypothalamus. Within the past year or so, after nearly 20 years of effort in many laboratories throughout the world, two substances have been isolated from animal brain tissue that represent the first of the long sought hypothalamic hormones. Because the molecular structure of the new hormones is fairly simple the substances can readily be synthesized in large quantities. Their availability and their high activity in humans has led physiologists and clinicians to consider that the hypothalamic hormones will open a new chapter in medicine.

It has long been known that the pituitary secretes several complex hormones that travel through the bloodstream to target organs, notably the thyroid gland, the gonads and the cortex of the adrenal glands. There the pituitary hormones stimulate the secretion into the bloodstream of the thyroid hormones, of the sex hormones by the gonads and of several steroid hormones such as hydrocortisone by the adrenal cortex. The secretion of the thyroid, sex and adrenocortical hormones thus has two stages beginning with the release of pituitary hormones. Studies going back some 50 years culminated in the demonstration that the process actually has three stages: the release of the pituitary hormones requires the prior release of another class of hormones manufactured in the hypothalamus. It is two of these hypothalamic hormones that have now been isolated, chemically identified and synthesized.

One of the hypothalamic hormones acts as the factor that triggers the release of the pituitary hormone thyrotropin, sometimes called the thyroid-stimulating hormone, or TSH. Thus the hypothalamic hormone associated with TSH is called the TSH-releasing factor, or TRF. The other hormone is LRF. Here again "RF" stands for "releasing factor"; the "L" signifies that the substance releases the gonadotropic pituitary hormone LH, the luteinizing hormone. A third gonadotropic hormone, FSH (follicle-stimulating hormone), may have its own hypothalamic releasing factor, FRF, but that has not been demonstrated. It is known, however, that the hypothalamic hormone LRF stimulates the release of FSH as well as LH.

Studies are continuing aimed at characterizing several other hypothalamic hormones that are known to exist on the basis of physiological evidence but that have not yet been isolated. One of them regulates the secretion of adrenocorticotropin (ACTH), the pituitary hormone whose target is the adrenal cortex. Another hormone (possibly two hormones with opposing actions) regulates the release of prolactin, the pituitary hormone involved in pregnancy and lactation. Still another hormone (again possibly two hormones with opposing actions) regulates the release of the pituitary hormone involved in growth and structural development (growth hormone).

That the hypothalamus and the pituitary act in concert can be suspected not only from their physical proximity at the base of the brain but also from their development in the embryo. During the early embryological development of all mammals a small pouch forms in the upper part of the developing pharynx and migrates upward toward the developing brain. There it meets a similar formation, resembling the finger of a glove, that springs from the base of the primordial brain. Several months later the first pouch, now detached from the upper oral cavity, has filled into a solid mass of cells differentiated into glandular types. At this point the second pouch, still connected to the base of the brain, is rich with hundreds of thousands of nerve fibers associated with a modified type of glial cell, not too unlike the glial cells found throughout the brain. The two organs are now enclosed in a single receptacle that has formed as an open spherical cavity within the sphenoid bone, on which the brain rests.

This double organ, now ensconced in the sphenoidal bone, is the pituitary gland, or hypophysis. The part that migrated from the brain is the posterior lobe, or neurohypophysis; the part that migrated from the pharynx is the anterior lobe, or adenohypophysis. Both parts of the gland remain connected to the brain by a common stalk that goes through the covering flap of the sphenoidal cavity. For many years after the double embryological origin of the pituitary gland was recognized the role of the gland was no more clearly understood than it had been in the old days. Indeed, the name "pituitary" had been given to it in the 16th century by Vesalius, who thought that the little organ had to do with secretion of *pituita:* the nasal fluid.

We know now that the anterior lobe of the pituitary gland controls the secretion and function of all the "periph-

HYPOTHALAMIC FRAGMENTS of sheep brains were the source from which the authors' laboratory extracted one milligram of TRF, the first hypothalamic hormone to be characterized and synthesized. The photograph is of about 30 frozen hypothalamic fragments; some five million such fragments, dissected from 500 tons of sheep brain tissue, were processed over a period of four years.

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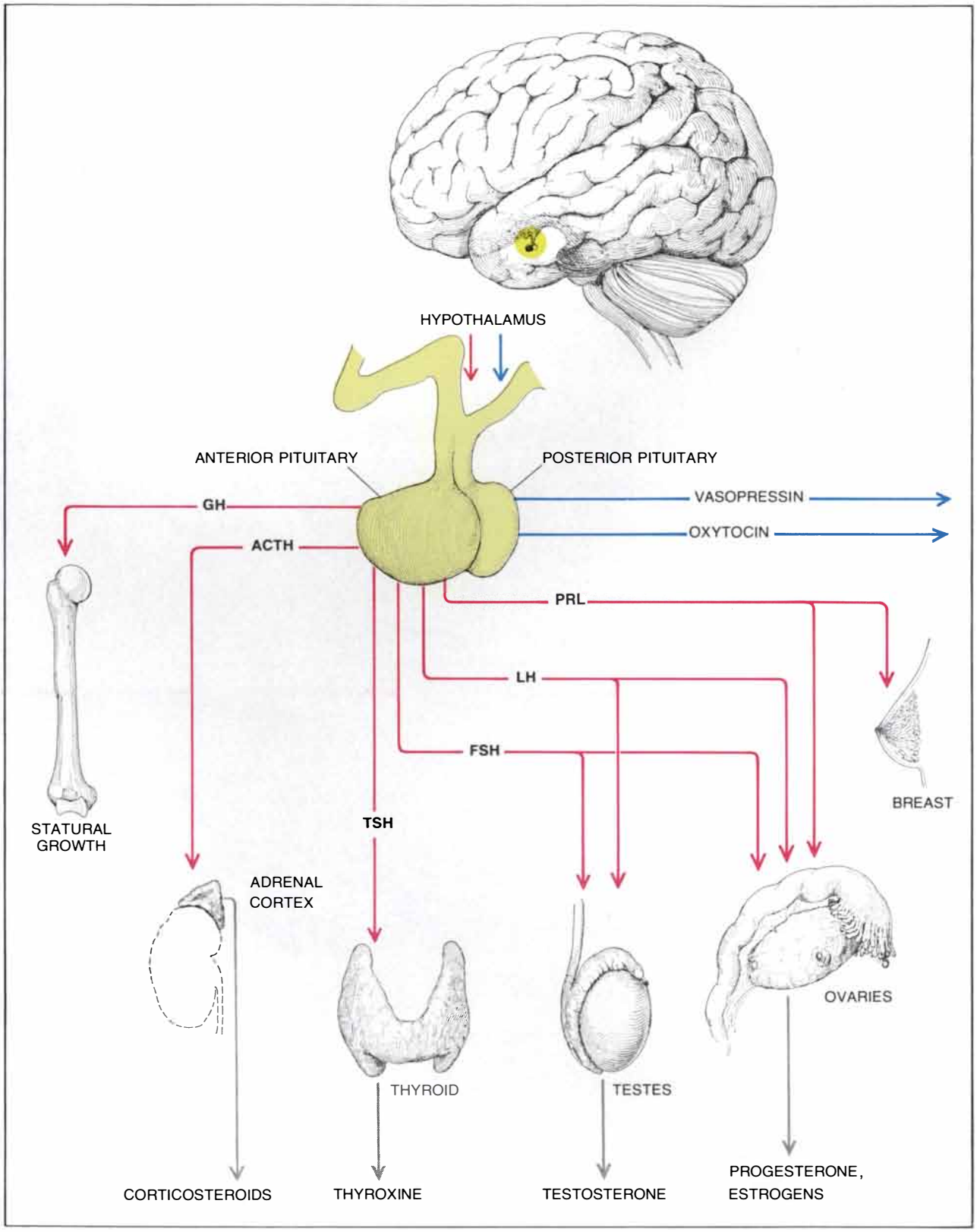

PITUITARY GLAND, connected to the hypothalamus at the base of the brain, has two lobes and two functions. The posterior lobe of the pituitary stores and passes on to the general circulation two hormones manufactured in the hypothalamus: vasopressin and oxytocin. The anterior lobe secretes a number of other hormones: growth hormone (GH), which promotes statural growth; adrenocorticotropic hormone (ACTH), which stimulates the cortex of the adrenal gland to secrete corticosteroids; thyroid-stimulating hormone (TSH), which stimulates secretions by the thyroid gland, and follicle-stimulating hormone (FSH), luteinizing hormone (LH) and prolactin (PRL), which in various combinations regulate lactation and the functioning of the gonads. Several of these anterior pituitary hormones are known to be controlled by releasing factors from the hypothalamus, two of which have now been synthesized.

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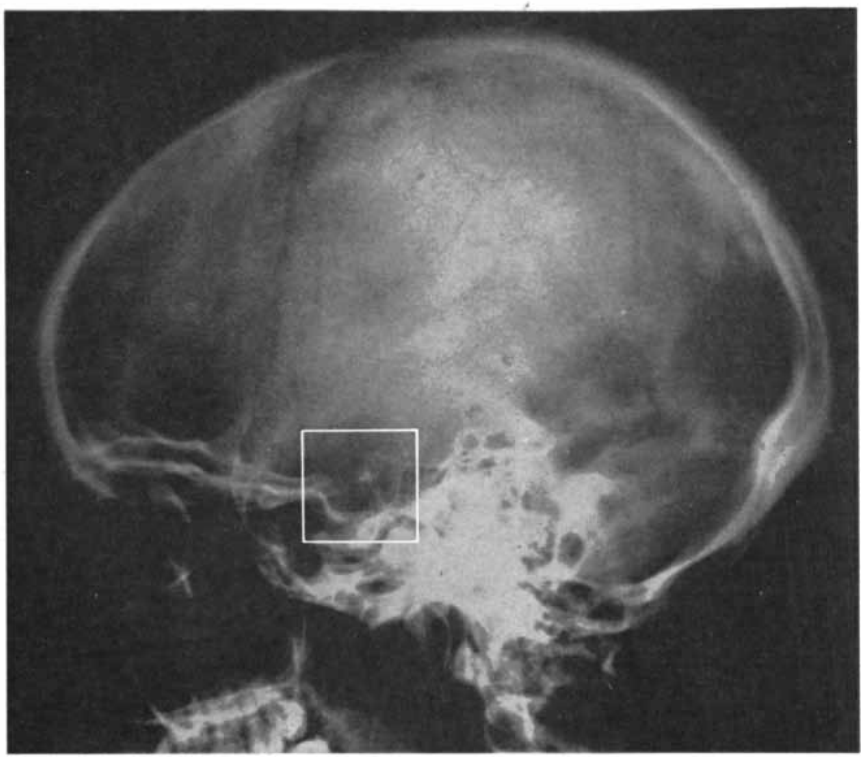
eral" endocrine glands (the thyroid, the gonads and the adrenal cortex). It also controls the mammary glands and regulates the harmonious growth of the individual. It accomplishes all this by the secretion of a series of complex protein and glycoprotein hormones. All the pituitary hormones are manufactured and secreted by the anterior lobe. Why should this master endocrine gland have migrated so far in the course of evolution (a journey recapitulated in the embryo) to make contact with the brain? As we shall see, recent observations have answered the question.

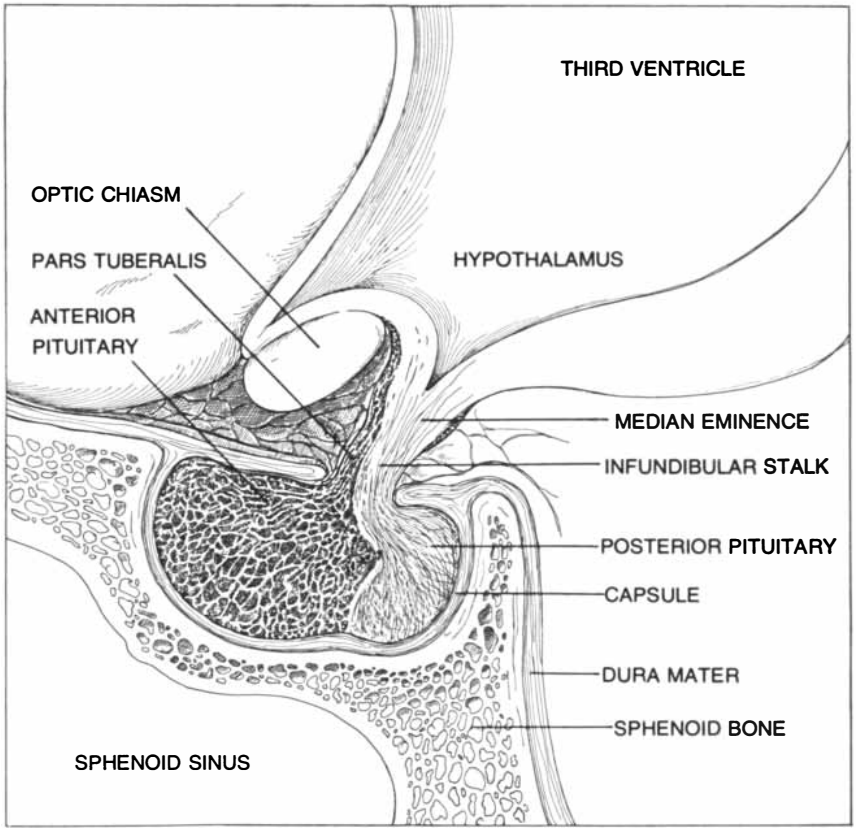
The posterior lobe of the pituitary has been known for the past 50 years to secrete substances that affect the reabsorption of water from the kidney into the bloodstream. These secretions also stimulate the contraction of the uterus during childbirth and the release of milk during lactation. In the early 1950's Vincent Du Vigneaud and his co-workers at the Cornell University Medical College resolved a controversy of many years' standing by showing that the biological activities of the posterior lobe are attributable to two different molecules: vasopressin (or antidiuretic hormone) and oxytocin. The two molecules are octapeptides: structures made up of eight amino acids. Du Vigneaud's group showed that six of the eight amino acids in the two molecules are identical, which explains their closely related physicochemical properties and similar biological activity. Both hormones exhibit (in different ratios) all the major biological effects mentioned above: the reabsorption of water, the stimulation of uterine contractions and the release of milk.

As early as 1924 it was realized that the hormones secreted by the posterior lobe of the pituitary are also found in the hypothalamus: that part of the brain with which the lobe is connected by nerve fibers through the pituitary stalk. Later it was shown that the two hormones of the posterior pituitary are actually manufactured in some specialized nerve cells in the hypothalamus. They flow slowly down the pituitary stalk to the posterior pituitary through the axons, or long fibers, of the hypothalamic nerve cells [*see top illustration on page 29*]. They are stored in the posterior pituitary, which is now reduced to a storage organ rather than a manufacturing one. From it they are secreted into the bloodstream on the proper physiological stimulus.

These observations had led several



BONY RECEPTACLE in which the pituitary gland is enclosed is a cavity in the sphenoid bone, on which the base of the brain rests. White rectangle shows area diagrammed below.



HYPOTHALAMUS AND PITUITARY are connected by a stalk that passes through the membranous lid of the receptacle in the sphenoid bone in which the pituitary rests. The double embryological origin of the two lobes of the pituitary is reflected in their differing tissues and functions and in the different ways that each is connected to the hypothalamus.

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biologists, notably Ernst and Berta Scharrer, to the striking new concept of neurosecretion (the secretion of hormones by nerve cells). They suggested that specialized nerve cells might be able to manufacture and secrete true hormones, which would then be carried by the blood and would exert their effects in some target organ or tissue remote from their point of origin. The ability to manufacture hormones had traditionally been assigned to the endocrine glands: the thyroid, the gonads, the adrenals and so on. The suggestion that nerve cells could secrete hormones would endow them with a capacity far beyond their ability to liberate neurotransmitters such as epinephrine and acetylcholine at the submicroscopic regions (synapses) where they make contact with other nerve cells.

Even as these studies were in progress and these new concepts were being formulated other laboratories were reporting evidence that functions of the anterior lobe of the pituitary were somehow dependent on the structural integrity of the hypothalamic area and on a normal relation between the hypothalamus and the pituitary gland. For example, minute lesions of the hypothalamus, such as can be created by introducing small electrodes into the base of the brain in an experimental animal and producing localized electrocoagulation, were found to abolish the secretion of anterior pituitary hormones. On the other hand, the electrical stimulation of nerve cells in the same regions dramatically increased the secretion of the hormones [*see illustration below*].

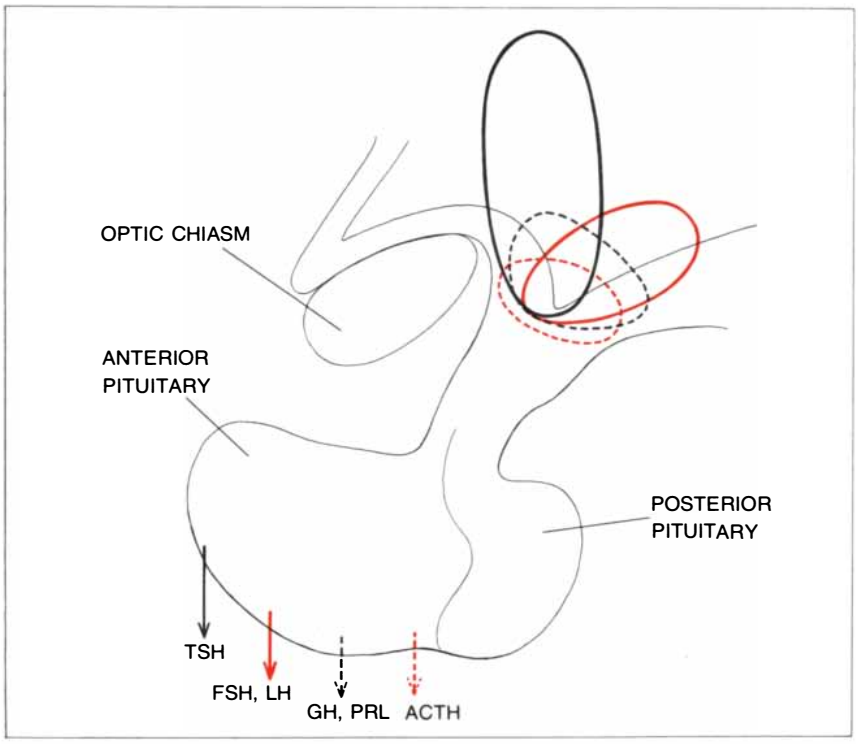
Thus the question was presented: Precisely how does the hypothalamus regulate the secretory activity of the anterior pituitary? The results produced by electrocoagulation and electrical stimulation of the hypothalamus suggested some kind of neural mechanism. One objection to this theory was rather hard to overcome. Careful anatomical studies over many years had clearly established that there were no nerve fibers extending from the hypothalamus to the anterior pituitary. The only nerve fibers found in the pituitary stalk were those that terminate in the posterior lobe.

A way out of the dilemma was provided by an entirely different working hypothesis, suggested by the discovery in 1936 of blood vessels of a peculiar type that were shown to extend from the floor of the hypothalamus through the pituitary stalk to the anterior pituitary [*see bottom illustration on opposite page*]. If these tiny blood vessels were cut, the secretions of the anterior pituitary would instantly decrease. If the capillary vessels regenerated across the surgical cut, the secretions resumed.

Accordingly a new hypothesis was put forward about 1945 with which the name of the late G. W. Harris of the University of Oxford will remain associated. The hypothesis proposed that hypothalamic control of the secretory activity of the anterior pituitary could be neurochemical: some substance manufactured by nerve cells in the hypothalamus could be released into the capillary vessels that run from the hypothalamus to the anterior pituitary, where it could be delivered to the endocrine cells of the gland. On reaching these endocrine cells the substance of hypothalamic origin would somehow stimulate the secretion of the various anterior pituitary hormones.

The hypothesis that pituitary function is controlled by neurohormones originating in the hypothalamus was soon well established on the basis of intensive physiological studies in several laboratories. The next problem was therefore to isolate and characterize the postulated hypothalamic hormones. It was logical to guess that the hormones might be polypeptides of small molecular weight, since it had been well established that the two known neurosecretory products of hypothalamic origin, oxytocin and vasopressin, are each composed of eight amino acids. Indeed, in 1955 it was reported that crude aqueous hypothalamic extracts designed to contain polypeptides were able specifically to stimulate the secretion of ACTH, the pituitary hormone that controls the secretion of the steroid hormones of the adrenal cortex.

It was quickly demonstrated that none of the substances known to originate in the central nervous system (such as epinephrine, acetylcholine, vasopressin and oxytocin) could account for the ACTH-releasing activity observed in the extract of hypothalamic tissue. It therefore seemed reasonable to postulate the existence and involvement in this phenomenon of a new substance designated (adreno)corticotropin-releasing factor, or CRF. Several laboratories then undertook the apparently simple task of purifying CRF from hypothalamic extracts, with the final goal of isolating it and establishing its chemical structure. Seventeen years later the task still remains to be accomplished. Technical difficulties involving the methods



RELATION between the hypothalamus and anterior pituitary was established experimentally. Lesions in specific regions of the hypothalamus interfere with secretion by the anterior lobe of specific hormones; electrical stimulation of those regions stimulates secretion of the hormones. The regions associated with each hormone are mapped schematically.

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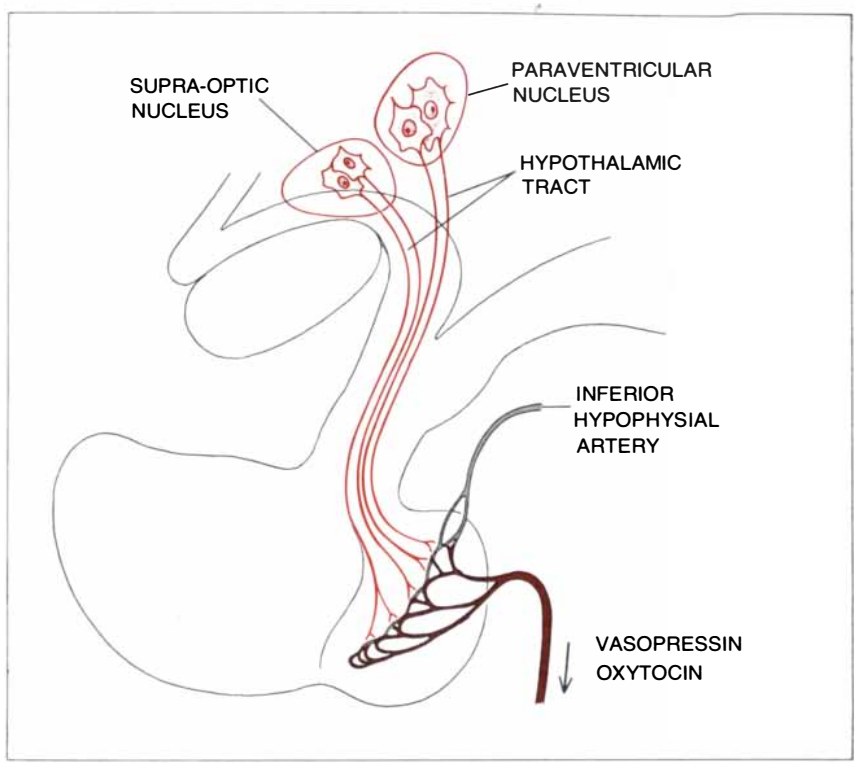
of assaying for CRF, together with certain peculiar characteristics of the molecule, have defied the enthusiasm, ingenuity and hard work of several groups of investigators.

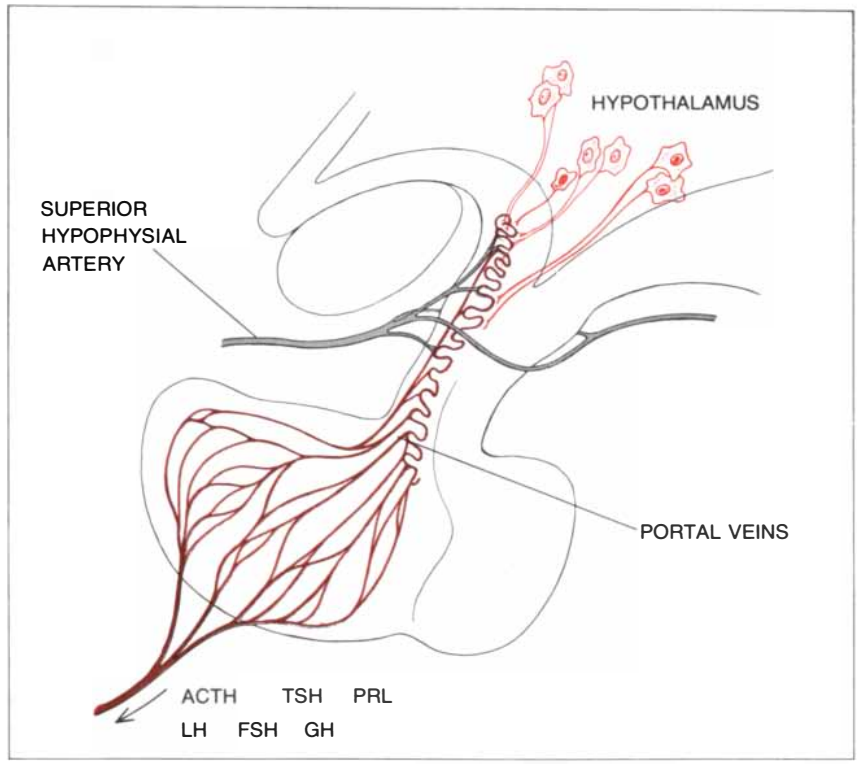
More rewarding results were obtained in a closely related effort. About 1960 it was clearly established that the same crude extracts of hypothalamic tissue were able to stimulate the secretion of not only ACTH but also the three other pituitary hormones mentioned above: thyrotropin (TSH) and the two gonadotropins (LH and FSH). TSH is the pituitary hormone that controls the function of the thyroid gland, which in turn secretes the two hormones thyroxine and triiodothyronine. LH controls the secretion of the steroid hormones responsible for the male or female sexual characteristics; it also triggers ovulation. FSH controls the development and maturation of the germ cells: the spermatozoa and the ova. In reality the way in which LH and FSH work together is considerably more complicated than this somewhat simplistic description suggests.

Results obtained between 1960 and 1962 were best explained by proposing the existence of three separate hypothalamic releasing factors: TRF (the TSH-releasing factor), LRF (the LH-releasing factor) and FRF (the FSH-releasing factor). The effort began at once to isolate and characterize TRF, LRF and FRF. Whereas it was difficult to find a good assay for CRF, a simple and highly reliable biological assay was devised for TRF. At first, however, the assays for LRF and FRF still left much to be desired.

With a good method available for assaying TRF, progress was initially rapid. Within a few months after its discovery TRF had been prepared in a form many thousands of times purer. Preparations of TRF obtained from the brains of sheep showed biological activity in doses as small as one microgram. A great deal of physiological information was obtained with those early preparations. For example, the thyroid hormones somehow inhibit their own secretion when they reach a certain level in the blood. This fact had been known for 40 years and was the first evidence of a negative feedback in endocrine regulation. Studies with TRF showed that the feedback control takes place at the level of the pituitary gland as the result of some kind of competition between the number of available molecules of thyroid hormones and of TRF. Other significant observations were made on the gonadotropin-releasing factors when



NEURAL CONNECTIONS could not explain the relation of the hypothalamus and the anterior lobe. The only significant nerve fibers connecting hypothalamus and pituitary run from two hypothalamic centers to the posterior lobe. They transmit oxytocin and vasopressin, two hormones manufactured in the hypothalamus and stored in the posterior lobe.



VASCULAR CONNECTIONS between hypothalamus and anterior lobe were eventually discovered: a network of capillaries reaching the base of the hypothalamus supplies portal veins that enter the anterior pituitary. Small hypothalamic nerve fibers apparently deliver to the capillaries releasing factors that stimulate secretion of the anterior-lobe hormones.

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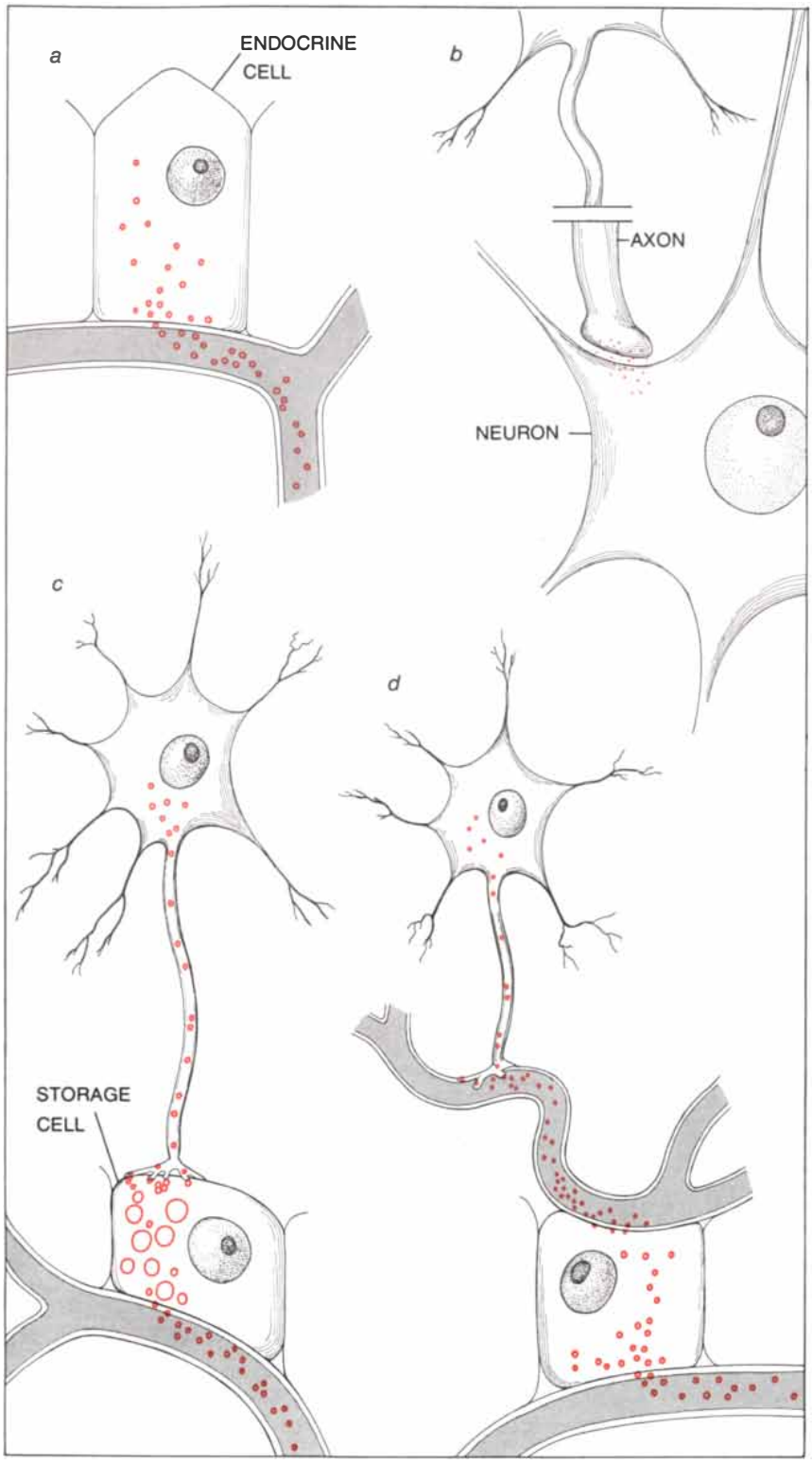

NEUROHUMORAL SECRETIONS involved in hypothalamic-pituitary interactions differ from classical hormone secretion and classical nerve-cell communication. A classical endocrine cell (such as those in the anterior pituitary or the adrenal cortex, for example) secretes its hormonal product directly into the bloodstream (*a*). At a classical synapse, the axon, or fiber, from one nerve cell releases locally a transmitter substance that activates the next cell (*b*). In neurosecretion of oxytocin or vasopressin the hormones are secreted by nerve cells and pass through their axons to storage cells in the posterior pituitary, eventually to be secreted into the bloodstream (*c*). Hypothalamic (releasing factor) hormones go from the neurons that secrete them into local capillaries, which carry them through portal veins to endocrine cells in the anterior lobe, whose secretions they in turn stimulate (*d*).

purified preparations, also active at microgram levels, were injected in experimental animals, for instance to produce ovulation.

It soon became apparent, however, that the isolation and chemical characterization of TRF, LRF and FRF would not be simple. The preparations active in microgram doses were chemically heterogeneous; they showed no clear-cut indication of a major component. It was also realized that each fragment of hypothalamus obtained from the brain of a sheep or another animal contained nearly infinitesimal quantities of the releasing factors. The isolation of enough of each factor to make its chemical characterization possible would therefore require the processing of an enormous number of hypothalamic fragments. Two groups of workers in the U.S. undertook this challenge: a group headed by A. V. Schally at the Tulane University School of Medicine and our own group, first at the Baylor University College of Medicine in Houston and then at the Salk Institute in La Jolla, Calif.

Over a period of four years the Tulane group worked with extracts from perhaps two million pig brains. Our laboratory collected, dissected and processed close to five million hypothalamic fragments from the brains of sheep. Since one sheep brain has a wet weight of about 100 grams, this meant handling 500 tons of brain tissue. From this amount we removed seven tons of hypothalamic tissue (about 1.5 grams per brain). Semi-industrial methods had to be developed in order to handle, extract and purify such large quantities of material. Finally in 1968 one milligram of a preparation of TRF was obtained that appeared to be homogeneous by all available criteria.

On careful measurement the entire milligram could be accounted for by the sole presence of three amino acids: histidine, glutamic acid and proline. Moreover, the three amino acids were present in equal amounts, which suggested that we were dealing with a relatively simple polypeptide perhaps as small as a tripeptide. In the determination of peptide sequences it is customary to subject the sample to attack by proteolytic enzymes, which cleave the peptide bonds holding the polypeptide chain together in well-established ways. Pure TRF, however, was shown to be resistant to all the proteolytic enzymes used. Since we could spare only a tiny amount of our precious one-milligram sample for studies of molecular weight, we could not obtain a

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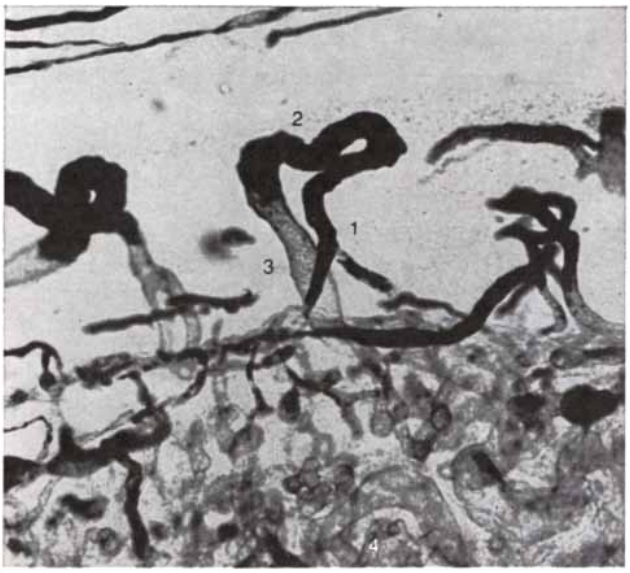
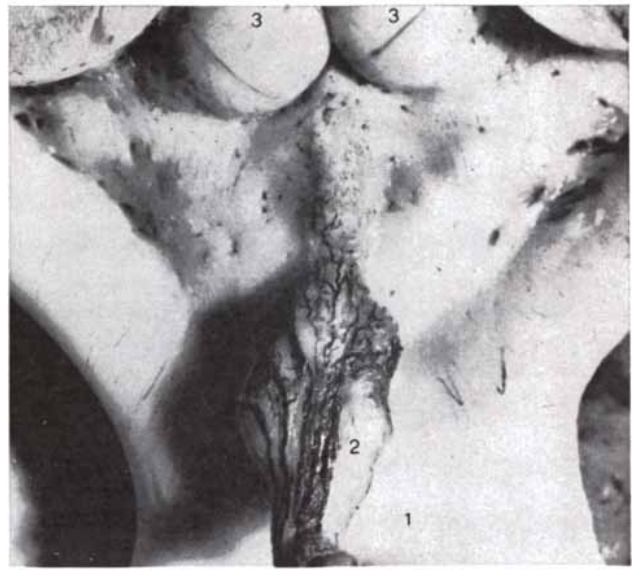




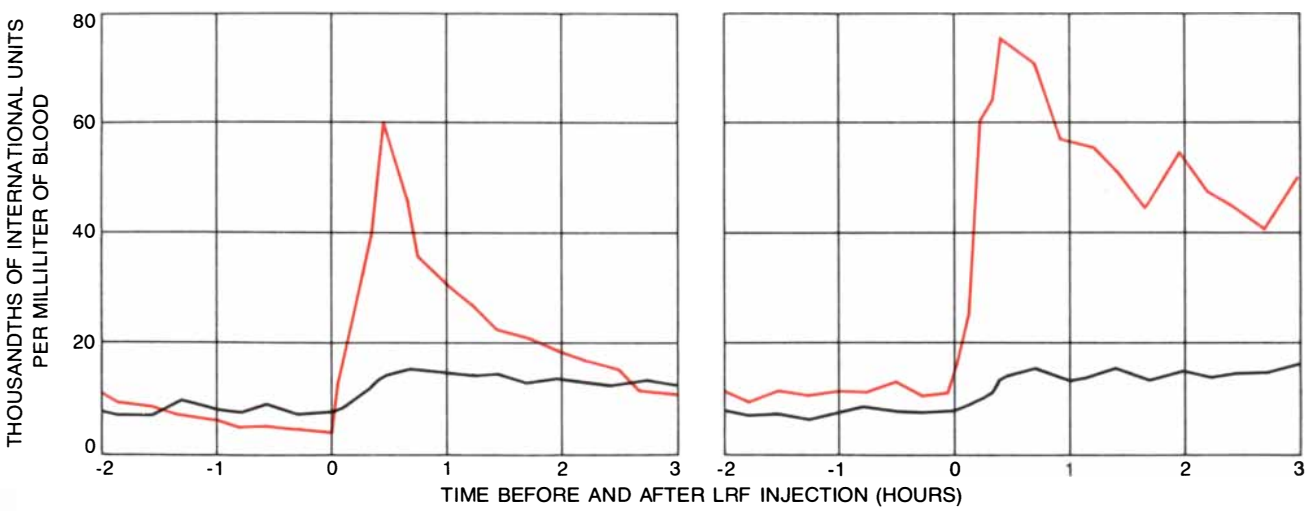
BLOOD VESSELS linking the hypothalamus and the anterior pituitary are seen in photographs made by Henri Duvernoy of the University of Besancon. The photomicrograph (*left*) shows some of the individual loops that characterize the capillary network at the base of the hypothalamus of a dog. The ascending branch of one loop is clearly seen (*1*); the loop comes close to the floor of the third ventricle (*2*) and then descends (*3*), carrying with it the releasing factors that are secreted by this region of the hypothalamus and entering the pars tuberalis of the anterior lobe (*4*). The photograph of the floor of the human hypothalamus (*right*) shows the optic chiasm (*1*), the posterior side of the pituitary stalk with its portal veins (*2*) and the mammillary bodies of the brain (*3*).

precise value for that important measurement. On the basis of inferential evidence, however, it seemed to be reasonable to assume that the molecular weight of TRF could not be more than 1,500.

With small molecules it is often possible to use methods based on the technique of mass spectrometry to obtain in a matter of hours the complete molecular structure of the compound under investigation. Because of the minute quantities of TRF available such efforts on our part were frustrated; the mass-spectrometric methods available to us in 1969 were not sensitive enough to indicate the structure of our unknown substance. Other approaches involve the use of infrared or nuclear magnetic-resonance spectrometry, which can provide direct insight into molecular structure. Here too the techniques then available were inadequate for providing clear-cut information about polypeptide samples that weighed only a few micrograms.

Confronted with nothing but dead ends, we decided on an entirely different approach to finding the structure of TRF. That approach was first to synthesize each of six possible tripeptides composed of the three amino acids known to be present in TRF: histidine (abbreviated His), glutamic acid (Glu) and proline (Pro). The six tripeptides were then assayed for their biological activity. None showed any activity when they were injected at doses of up to a million times the level of the active natural TRF.

Was this another dead end? Not quite. Our synthetic polypeptides all had a



HYPOTHALAMIC HORMONES have clinical implications and applications. For example, women with no pituitary or ovarian defect respond to the administration of synthetic LRF by secreting normal amounts of the hormones LH and FSH. Curves show effect of LRF on secretion of LH (*color*) and FSH (*black*) in a normal woman on the third (*left*) and 11th (*right*) day of menstrual cycle.

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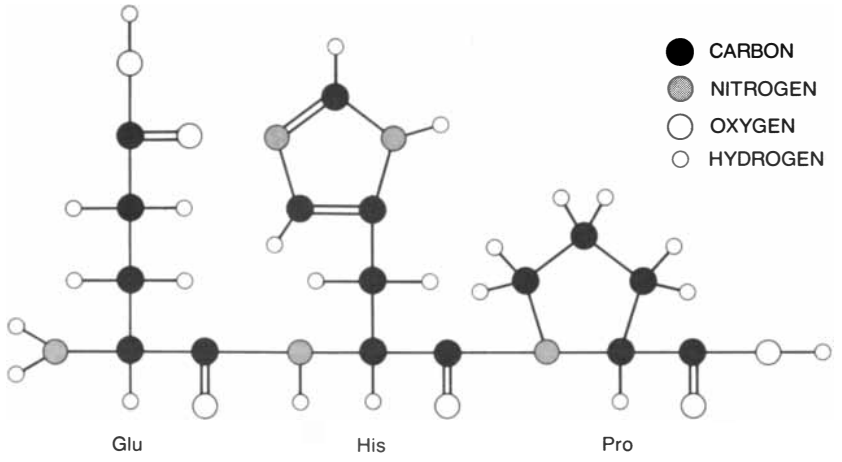


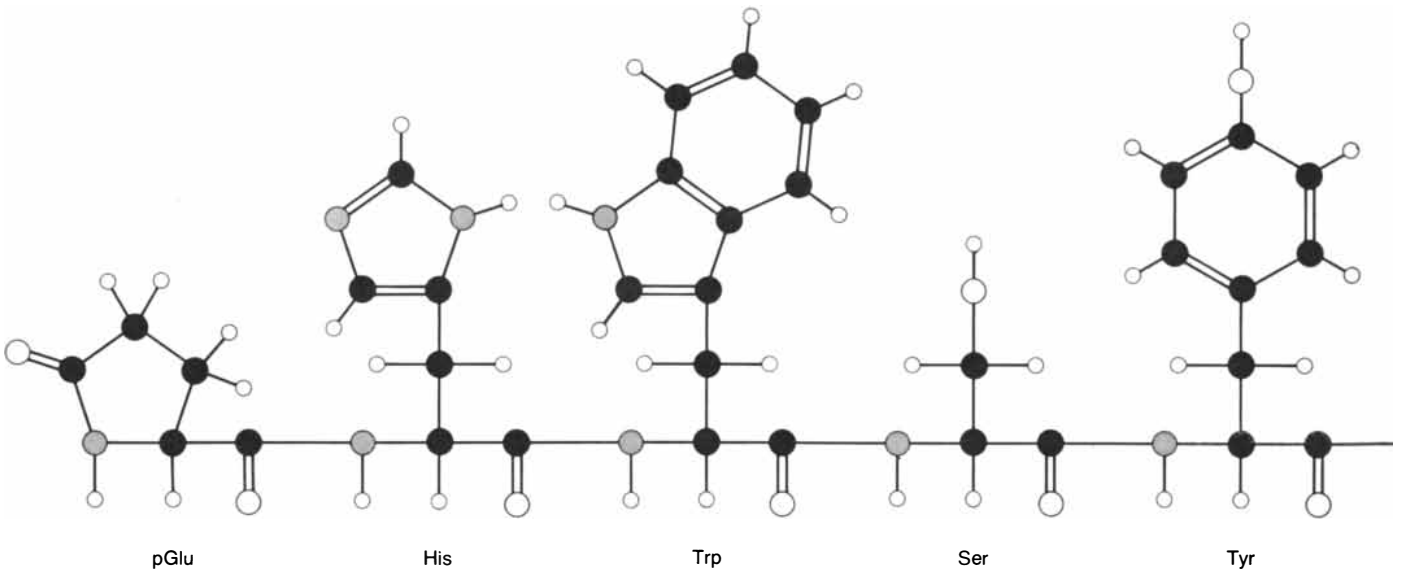
AMINO ACID CONTENT of TRF, the releasing factor for thyroid-stimulating hormone (TSH), was established: glutamic acid, histidine and proline in equal proportions. Each of six possible tripeptides was synthesized; one is diagrammed. None was active biologically.

free amino group (NH_2) at the end of the molecule designated the *N* terminus. We knew that in several well-characterized hormones the *N*-terminus end was not free; it was blocked by a small substitute group of some kind. Indeed, we had evidence from the small quantity of natural TRF that its *N* terminus was also blocked. To block the *N* terminus of our six candidate polypeptides was not difficult: we heated them in the presence of acetic anhydride, which typically couples an acetyl group (CH_3CO) to the *N* terminus. When these "protected" tripeptides were tested, the results were unequivocal. The biological activity of the sequence Glu-His-Pro, and that sequence alone, was qualitatively indistinguishable from the activity of natural TRF. Quantitatively, however, there was still a considerable difference between the synthetic product and natural TRF. Next it was shown that the protective effect of heating Glu-His-Pro with the acetic anhydride had been to convert the glutamic acid at the *N* terminus into a ring-shaped form known as pyroglutamic acid (pGlu).

We now had available gram quantities of the synthetic tripeptide pGlu-His-Pro-OH. (The OH is a hydroxyl group at the end of the molecule opposite the *N* terminus.) Accordingly we could bring into play all the methods that had yielded no information with the microgram quantities of natural TRF. Several of the techniques were modified, particularly with the aim of obtaining mass spectra of the synthetic peptide at levels of only a few micrograms.

Meanwhile, armed with knowledge about the structure of other hormones, we modified the synthetic pGlu-His-Pro-OH to pGlu-His-Pro-NH_2 by replacing the hydroxyl group with an amino group (NH_2) to produce the primary amide [*see top illustration on opposite page*]. This substance proved to have the same biological activity as the natural TRF. At length the complete structure of the natural TRF was obtained by high-resolution mass spectrometry. It turned out to be the structure pGlu-His-Pro-NH_2. The time was late 1969. Thus TRF not only was the first of the hypothalamic hormones to be fully characterized but also was immediately available by synthesis in amounts many millions of times greater than the hormone present in one sheep hypothalamus. TRF from pig brains was subsequently shown to have the same molecular structure as TRF from sheep brains.

Characterization of the hypothalamic releasing factor LRF, which controls the secretion of the gonadotropin LH, followed rapidly. Isolated from the side fractions of the programs for the isolation of TRF, LRF was shown in 1971 to be a polypeptide composed of 10 amino acids. Six of the amino acids are not found in TRF: tryptophan (Trp), serine (Ser), tyrosine (Tyr), glycine (Gly), leucine (Leu) and arginine (Arg). The full sequence of LRF is pGlu-His-Trp-Ser-Tyr-Gly-Leu-Arg-Pro-Gly-NH_2 [*see bottom illustration on these two pages*]. Although this structure is more compli-



LRF, the releasing factor for the luteinizing hormone (LH), which affects the activity of the gonads, was characterized and synthesized soon after. First the hormone was isolated and its amino acid content was determined. Then their intramolecular sequence was es-

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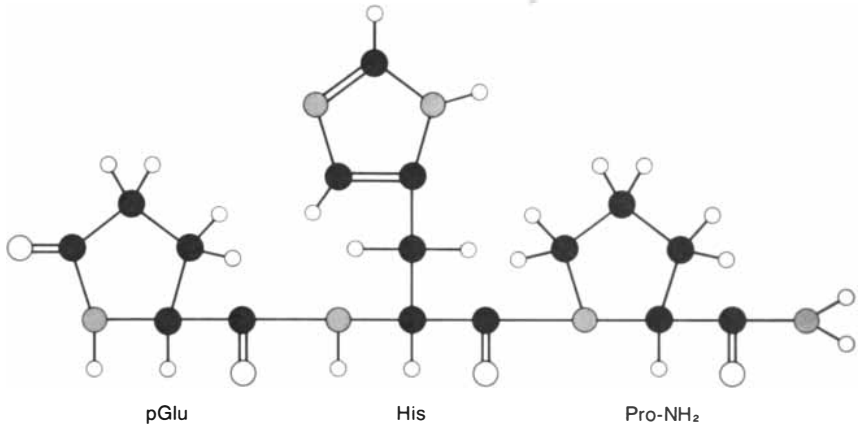
cated than the structure of TRF, it begins with the same two amino acids (pGlu-His) and has the same group at the other terminus (NH_2).

It turns out that LRF also stimulates the secretion of the other gonadotropin, FSH, although not as powerfully as it stimulates the secretion of LH. It has been proposed that LRF may be the sole hypothalamic controller of the secretion of the two gonadotropins: LH and FSH.

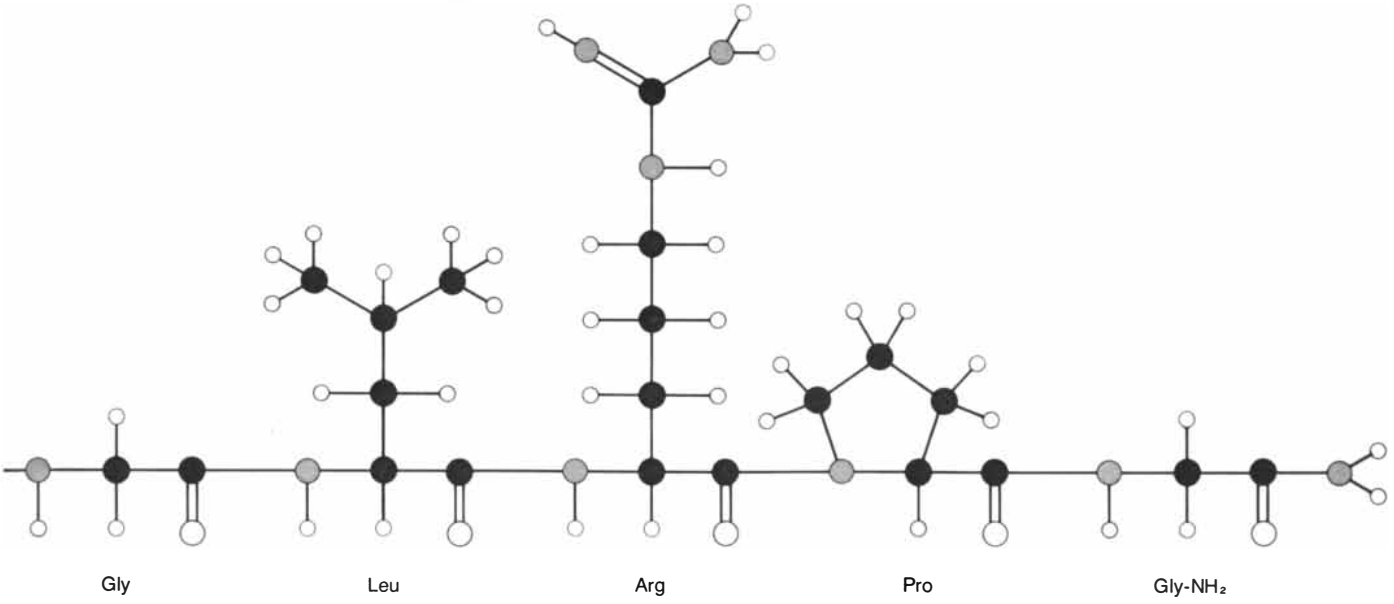
There is good physiological evidence that the hypothalamus is also involved in the control of the secretion of the other two important pituitary hormones: prolactin and growth hormone. Curiously, prolactin is as plentiful in males as in females, but its role in male physiology is still a mystery. The hypothalamic mechanism involved in the control of the secretion of prolactin or growth hormone is not fully understood. It is quite possible that the secretion of these two pituitary hormones is controlled not by releasing factors alone but perhaps jointly by releasing factors and specific hypothalamic hormones that somehow act as inhibitors of the secretion of prolactin or growth hormone. If it should turn out that inhibitory hormones rather than stimulative ones are involved in the regulation of prolactin and growth hormone, one should not be too surprised. The brain provides many examples of inhibitory and stimulative systems working in parallel.

The hypothalamic hormones TRF and LRF are both now available by synthesis in unlimited quantities. Both are highly active in stimulating pituitary functions in humans. TRF is already a powerful tool for exploring pituitary functions in several diseases characterized by the abnormality of one or several of the pituitary secretions. There is increasing evidence that most patients with such abnormalities (primarily children) actually have normally functioning glands, since they respond promptly to the administration of synthetic hypothalamic hormones. Evidently their abnormalities are due to hypothalamic rather than pituitary deficiencies. These deficiencies can now be successfully treated by the administration of the hypothalamic polypeptide TRF.

Similarly, an increasing number of women who have no ovulatory menstrual cycle and who show no pituitary or ovarian defect begin to secrete normal amounts of the gonadotropins LH and FSH after the administration of LRF. The administration of synthetic LRF should therefore be the method of choice for the treatment of those cases of infertility where the functional defect resides in the hypothalamus-pituitary system. Indeed, ovulation can be induced in women by the administration of synthetic LRF. On the other hand, knowledge of the structure of the LRF molecule may open up an entirely novel approach to fertility control. Synthetic compounds closely related to LRF in structure may act as inhibitors of the native LRF. Two such analogues of LRF, made by modifying the histidine in the hormone, have been reported as antagonists of LRF. It is therefore possible that LRF antagonists will be used as contraceptives.



TRIPEPTIDES were modified in an effort to characterize the releasing factor. When the sequence glutamic acid–histidine-proline was modified by forming the glutamic acid into a ring and converting the proline end (*right*) to an amide, it was found to be TRF.



tablished and reproduced by synthesis; the synthetic replicate shown here was found to have full biological activity. In addition to stimulating LH activity, LRF also stimulates the secretion of another gonadotropic hormone, FSH, although not so powerfully.

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MICROCIRCUITS BY ELECTRON BEAM

By using an electron beam to trace the patterns of electronic circuits it should soon be possible to put 100,000 transistors and similar devices on a silicon chip a few millimeters square

by A. N. Broers and M. Hatzakis

The size of electronic circuits has shrunk dramatically during the past decade. In the early 1960's three or four logic circuits, each incorporating perhaps a dozen transistors or other devices, were mounted on a plastic circuit board about three by five inches in size. Today upward of 1,000 similar circuits can be put on a chip of silicon a tenth of an inch square. Fairly straightforward extensions of present technology should make it possible to put 10,000 circuits on a similar chip within a few years.

The projected tenfold increase in the density of circuit components will be made possible in large part by substituting an electron beam for the ultraviolet beam now used in the preparation of large-scale integrated electronic circuits. Just as an electron microscope can provide much higher resolution than a light microscope, the new electron-beam technology can produce transistors and other circuit devices many times smaller than any that can be fabricated by present methods.

The reduction in circuit size already achieved has had two major benefits: a sharp decrease in the cost of circuits and a sharp increase in the speed with which logic operations can be performed. The reduction in cost is vividly demonstrated by numerous low-priced pocket-sized calculators now on the market, some of which contain more than 10,000 transistors. The ultimate speed of an electronic switching device usually comes down to the time it takes to build up an electric charge in some part of the circuit, in other words to the time it takes for the circuit to charge up a capacitance. In addition, the time it takes for a signal to travel from one circuit to the next is now a significant portion of the total delay time in the logic circuits of computers. The miniaturization of circuits reduces both sources of delay.

The rapid progress in the miniaturization of electronic circuits is a result of development of a set of fabrication procedures collectively known as silicon planar technology. In this technology complex circuits are built into and on the surface of a wafer of silicon in a series of steps. Each step begins with coating the silicon wafer with a photosensitive material known as a photoresist.

A pattern is impressed on the photoresist by shining ultraviolet radiation on it through a mask outlining the desired pattern. The areas in the photoresist that are exposed to light are made either soluble or insoluble to a solvent, which is the developer. In the first case the photoresist is called a positive resist; in the second, a negative resist. After development the area thus exposed on the silicon wafer is etched to remove a layer of oxide. The etching opens the surface to the diffusion of tiny amounts of impurities to produce the desired electrical characteristics or opens it to the deposition or removal of metal electrodes and interconnections. Complex circuits are built into the silicon by a succession of such procedures. Since the cost of processing varies more or less directly with the area of silicon wafer processed, the more circuits that can be squeezed into a given area, the lower the cost per circuit.

In the most advanced experimental circuits this process is approaching a limit established by the wavelength of light. The smallest dimension of these devices, usually set by the width of metal electrodes, is about one micron, or one thousandth of a millimeter. The wavelength of the ultraviolet radiation used to produce these lines is about .4 micron. If one tries to make the lines thinner than one micron, the radiation projected through the mask starts to give rise to a diffraction pattern consisting of a series of lines rather than one line. The result is a blurring effect that prevents the production of a line much less than one micron wide no matter how narrow the line in the mask is [*see top illustration on page 36*].

Several years ago a number of workers began looking into the possibility of using electrons to delineate structures smaller than those that can be made with ultraviolet radiation. Although electrons, like the photons of light, have the properties of both particles and waves, their wavelength is thousands of times shorter than the wavelength of visible light. For the purposes of microfabrication electrons can be regarded as particles. Their wavelength is so much smaller than the structures one would like to make that diffraction effects do not enter in.

Electrons have other potential advantages for producing patterns in a photoresist. Compared with a beam of light a beam of electrons has not only a short wavelength but also a large amount of energy. Therefore the aperture of the magnetic lenses used to focus the electrons can be small, and the depth of focus of an electron-optical system is far greater than that of a comparable optical system. This depth of focus is strikingly apparent in pictures made with the scanning electron microscope, which is in many ways very similar to the electron-beam fabrication apparatus originally used by many workers to make microcircuits. (Some of the photographs accompanying this article were made with an electron-beam fabrication apparatus that also serves as a scanning

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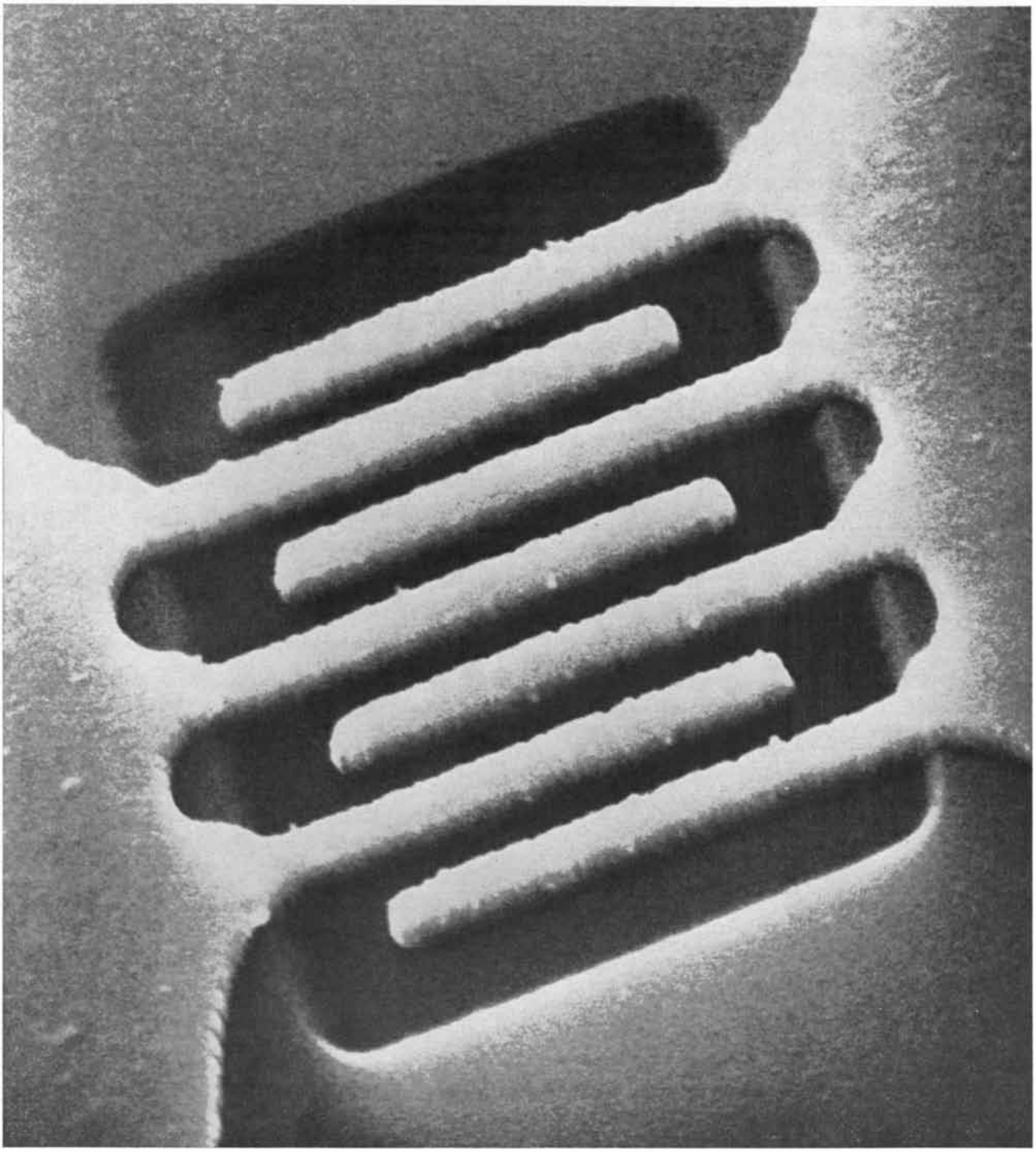
electron microscope.) The greater depth of focus considerably relaxes many of the stringent requirements optical projection systems impose on the position and the flatness of the silicon wafer on which the microcircuits are made.

Since electrons can be deflected by an electric or magnetic field, the geometry of the devices delineated by an electron beam can be controlled by electronic means. In some circumstances this kind of control can be an important advantage. Optical exposure calls for a mask permanently formed in a photographic plate or on a film of metal. Electronic control means that computer-generated patterns can be exposed and tested during the period when a circuit is being developed, eliminating the considerable cost of making masks for experimental circuits. It also means that



EXPERIMENTAL TRANSISTOR STRUCTURE was made with the electron-beam technology developed by the International Business Machines Corporation. By using an electron beam to delineate the geometry of the structure the dimensions of a transistor can be a factor of 10 smaller than can be achieved by prevailing methods, which use ultraviolet radiation and masks to establish the basic geometry. In this device the width of the aluminum fingers and the spacing between fingers is .5 micron, or 5,000 angstroms.

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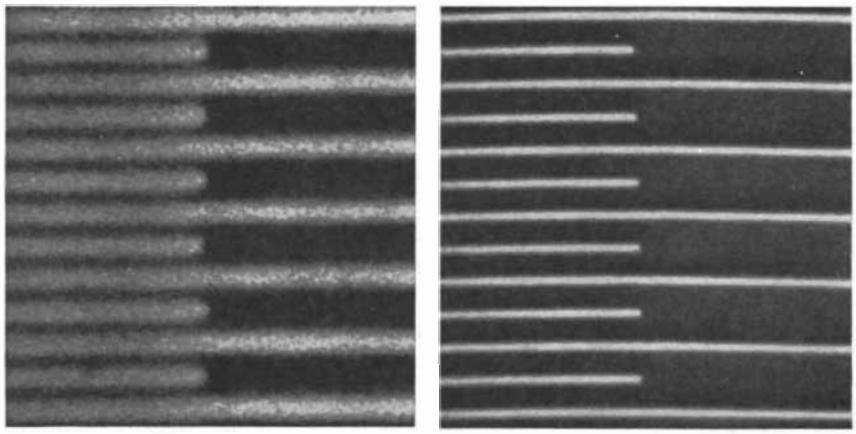
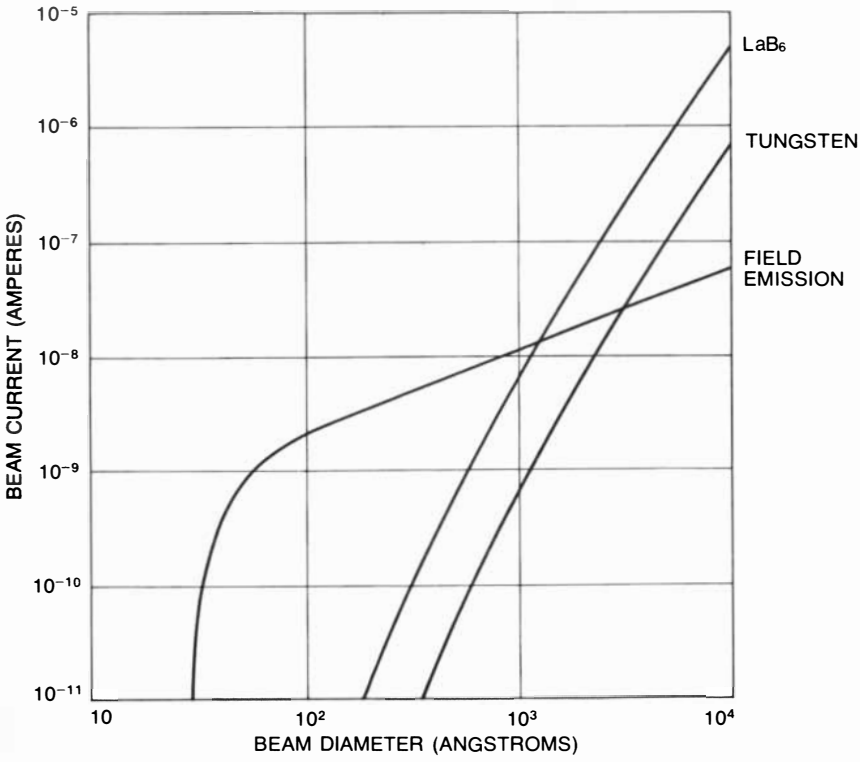


SUPERIOR RESOLUTION of electron-beam optics over conventional light optics is demonstrated by two micrographs of a device known as an acoustic-surface-wave transducer. The center-to-center spacing of the aluminum fingers in the device is one micron. The picture at left, made with a high-quality light microscope, exhibits the characteristic blurring effect produced by the diffraction of light. The picture at right was made with a scanning electron microscope. The device itself was fabricated by the electron-beam technology.

one can readily change the configuration of production circuits and even custom-mix circuit combinations on a single wafer. This flexibility may prove to be important as high levels of integration in logic circuits are attempted. When a significant fraction of a computer is contained on one chip, the number of identical chips becomes smaller, and the number of different kinds of chip needed for a complete product line becomes larger. This "part number" problem looms as probably the most serious eventual limitation on integration levels that can be usefully attained by present technology.

The major drawback in using electron beams for circuit fabrication is exposure time. It takes a long time to "cover" a two-inch silicon wafer with an electron beam less than a micron in diameter. In the past few years, however, the exposure speed has been significantly improved, first by the discovery of "brighter" electron sources and then by the development of electron-optical systems designed specifically for fabrication.



DIAMETER AND CURRENT OF ELECTRON BEAM used in fabricating microcircuits depend chiefly on the cathode used as an electron source. A new lanthanum hexaboride (LaB_6) thermal cathode provides about 10 times as much current in a given spot size as a tungsten cathode while providing 10 times the life. For beam diameters less than 1,500 angstroms a field-emission cathode provides a higher current than does either of the thermal cathodes. Curves apply to a system whose final lens has a focal length of five centimeters.

The commonest source of electrons in electron microscopes and related instruments is a tungsten "hairpin": a cathode wire bent into a narrow *V*. Current is passed through the wire to heat it to a temperature high enough to excite the electrons until they can be drawn away by an electric field. The sharper the point of the *V* is, the stronger the field at the point is. The field strength determines how large an electron current can be drawn from the cathode before the space charge, or mutual repulsion, of the electrons begins to widen the beam significantly. Beyond that point trying to draw additional current from the cathode simply makes the beam increasingly wider, and the brightness no longer increases. Brightness, which is the current density per unit of solid angle, is the parameter that fundamentally determines how much current can be focused on a given spot with an electron-optical system having a given operating aperture.

The tungsten hairpin has two main limitations. First, the sharpness with which it can be bent is limited, with the result that the space charge holds the available current to a rather low value. Second, it evaporates metal fairly fast at the high temperature required for it to emit reasonable numbers of electrons. Tungsten hairpins typically last about 30 hours in the electron microscope.

It was found some 20 years ago at the General Electric Research Laboratory that the compound lanthanum hexaboride (LaB_6) emits copious amounts of electrons at a temperature where its evaporation rate is quite small. Unfortunately it also becomes very reactive at the operating temperature and rapidly destroys anything on which it is mounted. In the mid-1960's a lanthanum hexaboride cathode was developed at the International Business Machines Corporation that gets around the chemical reactivity of the material by heating

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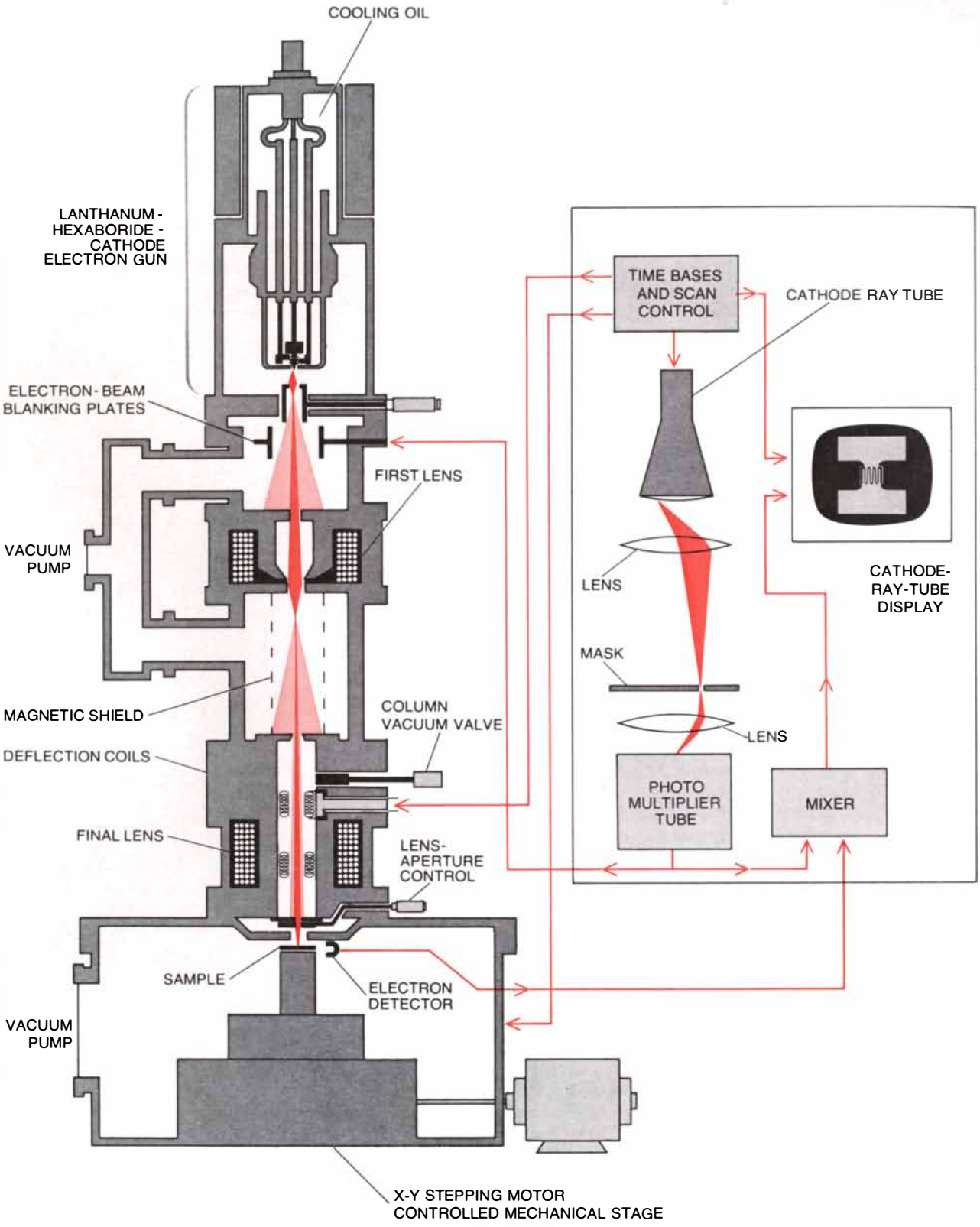

ELECTRON-BEAM FABRICATION SYSTEM can generate patterns either by means of the flying-spot scanner shown in this illustration or by a wholly computer-controlled system, which is illustrated on the next two pages. Basically, as the path of the electron beam in the column at left is guided across the sample, or workpiece, in a raster pattern, the beam is turned on and off under the control of a flying spot of light directed through a transparent mask that contains the desired circuit pattern. The spot of light is provided by a high-precision cathode ray tube. As the spot of light scans the pattern the electron beam is turned on or off, depending on whether the spot falls on a transparent portion of the pattern or on an opaque portion. A signal from a photomultiplier below the mask turns the electron beam on or off by activating electrostatic plates that deflect the beam on or off the axis of the column. The size of the exposed pattern on the sample is set by the magnitude of the current fed to the electron-beam deflection coil of the system.

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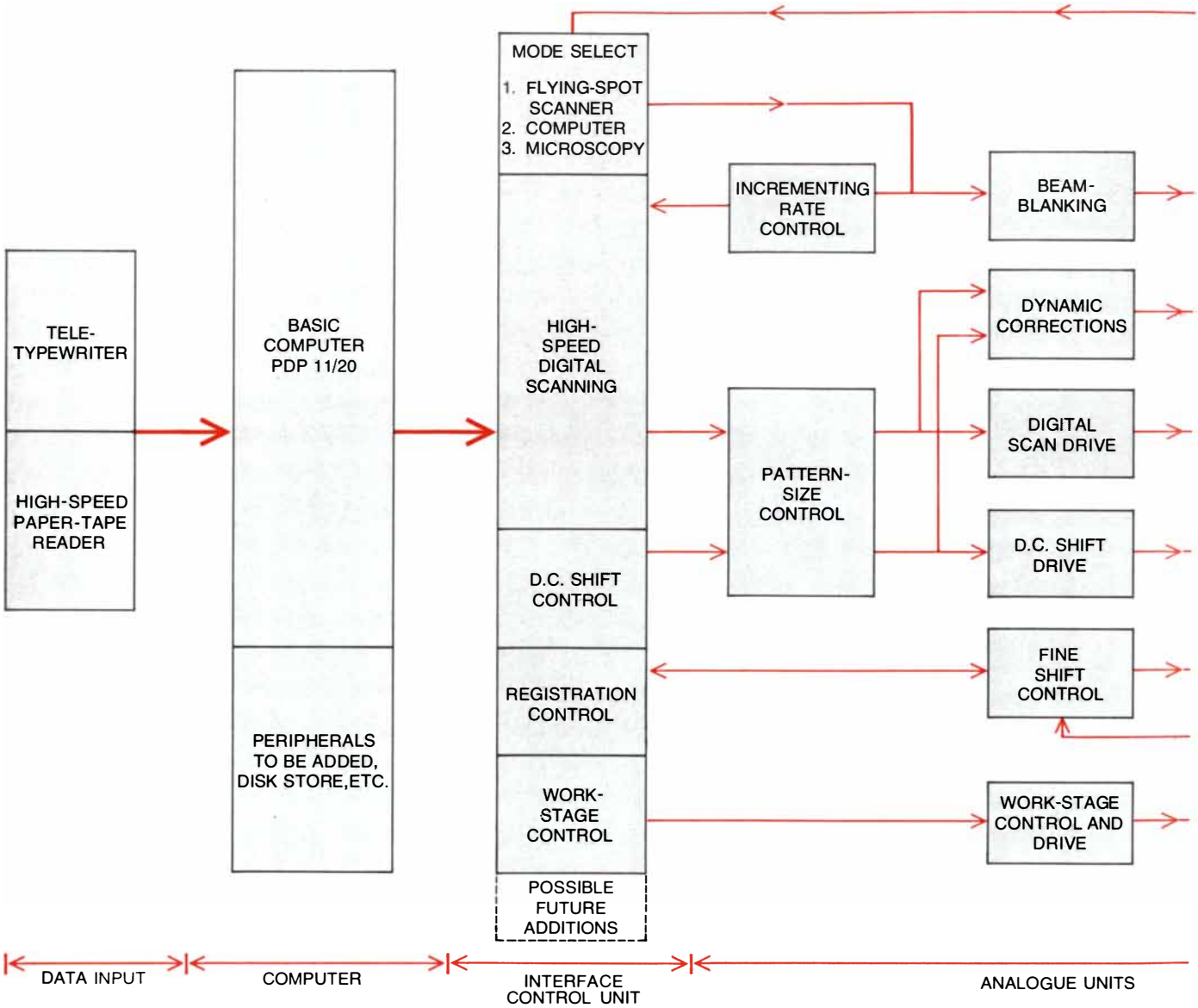
only the tip of a rod of it. The tip is heated either by radiant heat from a surrounding coil or by electron bombardment, and the base of the rod is clamped in an oil-cooled mount. When the lanthanum hexaboride electron gun is used in a scanning electron microscope, it provides considerable improvement in the resolution of the instrument, from about 100 angstroms (typical of the best commercial instruments) to about 30 angstroms. That resolution is the highest obtained so far with this type of electron microscope.

The improvement is attributable to two properties of the lanthanum hexaboride cathode that enable it to provide approximately 30 times greater brightness than a tungsten hairpin. First, it emits more electrons at its operating temperature than a tungsten cathode. Second, the rod can be ground to an extremely sharp point, which helps to overcome the space-charge limitation at greater emission densities. (The electron-current density is equivalent to the intensity of the electron beam.) The higher brightness provided by the lanthanum hexaboride cathode makes it possible to have smaller apertures in the magnetic lenses of the microscope. By using only electrons that have traveled near the axis of the lens system one can minimize the effect of aberrations in the lenses. From the viewpoint of device fabrication the lanthanum hexaboride rod has further advantages. It is much more massive than a tungsten hairpin, so that it is more stable mechanically. Moreover, it lasts for hundreds of hours compared with tens of hours for the hairpin.

A cathode that offers even greater brightness than the lanthanum hexaboride cathode is the tungsten field-



COMPUTER-CONTROLLED FABRICATION SYSTEM generates the desired circuit geometry directly without a mask, according to a stored program. The number of lines scanned in producing the desired circuit is limited only by the spreading of the electron beam as it travels to the corners of the field and by the accuracy with which the beam can be positioned. The number of lines that can be scanned in a single chip exceeds that attainable with the flying-spot scanning system illustrated on the preceding page because in that system the line density cannot exceed the number of lines the cathode ray tube can resolve. Present computer systems can po-

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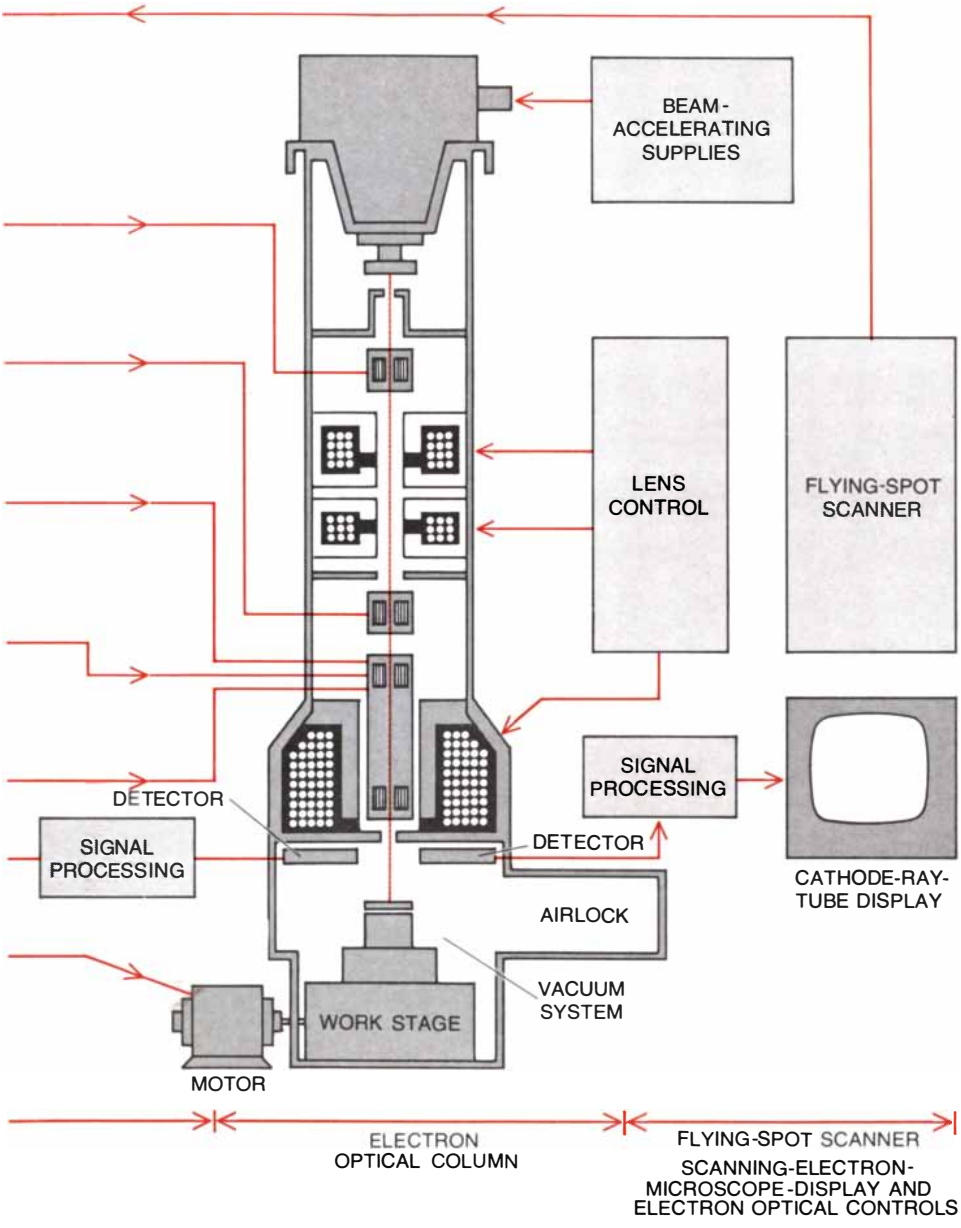
emission cathode. Field emission occurs when the electric field at the surface of a cathode becomes so great that the surface potential barrier, which normally prevents electrons from escaping, is depressed, so that electrons can pour straight out of the material. In practice the extreme electric field needed (10^7 volts per centimeter) is achieved by relying on the field concentration that occurs at the point of a fine tungsten wire. Such cathodes can produce luminosities about 40 times greater than lanthanum hexaboride and have been employed at the University of Chicago to obtain a resolution of five angstroms in a transmission scanning electron microscope [see "A High-Resolution Scanning Electron Microscope," by Albert V. Crewe; SCIENTIFIC AMERICAN, April, 1971].

Unfortunately, with today's field emitters the electron current available is not large enough to efficiently illuminate the large-angled beams used in many electron-beam fabrication systems. Such a system requires a final beam current of at least one microampere. Only when the beam diameter is smaller than about 1,500 angstroms and the current is smaller than about 10^{-8} ampere does the field-emission cathode offer any advantage [*see bottom illustration on page 36*]. Another drawback of the field-emission cathode is that for stable operation it requires ultrahigh-vacuum conditions (10^{-10} millimeter of mercury), and even then the current stability is worse than it is with thermal cathodes. Long-term stability is particularly important for electron-beam fabrication systems because they generally have to operate unattended.



tentially scan several thousand lines in a few seconds. The apparatus depicted in this illustration can also function as a flying-spot scanner and as a scanning electron microscope. The apparatus was originally designed at the Cambridge Scientific Instrument Company by a group under T. H. P. Chang. Chang is continuing his work on the development of electron-beam technology at the Thomas J. Watson Research Center in Yorktown Heights, N.Y.

The simplest electron-beam "column" used for the fabrication of microcircuits consists of an electron gun that produces a round beam between 10 and 100 microns in diameter and one or more magnetic electron lenses to reduce the beam diameter to its final size, which is generally five times smaller than the smallest structure to be fabricated. Such columns are similar to those used in scanning electron microscopes; in fact, all that is needed to convert a scanning electron microscope into a circuit-fabricating device is the addition of a pattern-generator.

The information required to generate the pattern is most commonly produced by a flying-spot scanner or by a computer. The flying-spot scanner is inexpensive and easy to implement but it has several limitations, which become apparent when its operation is understood. In the flying-spot scanner the electron beam and the spot on a cathode ray tube are scanned in synchrony [*see illustration on page 37*]. The spot on the cathode ray tube is imaged by an optical lens onto a transparent mask containing the pattern to be fabricated. As the light spot scans across the mask the electron beam is turned on and off according to whether the light spot falls on a transparent or on an opaque portion of the pattern. The signal for turning the beam on or off is obtained from a photomultiplier tube placed below the mask. The beam is turned on and off by deflecting it on and off the axis of the column with electrostatic plates. The pattern on the mask is thus reproduced by the beam. The size of the exposed pattern on the sample is set by the magnitude of the current fed to the electron-beam deflection coil. The major shortcoming of the flying-spot scanner is that the number of lines that can be included in the mask cannot be greater than the number of lines the cathode ray tube can resolve. Even with high-performance cathode ray tubes the number of lines is less than the electron beam is capable of resolving. Another serious restriction is the

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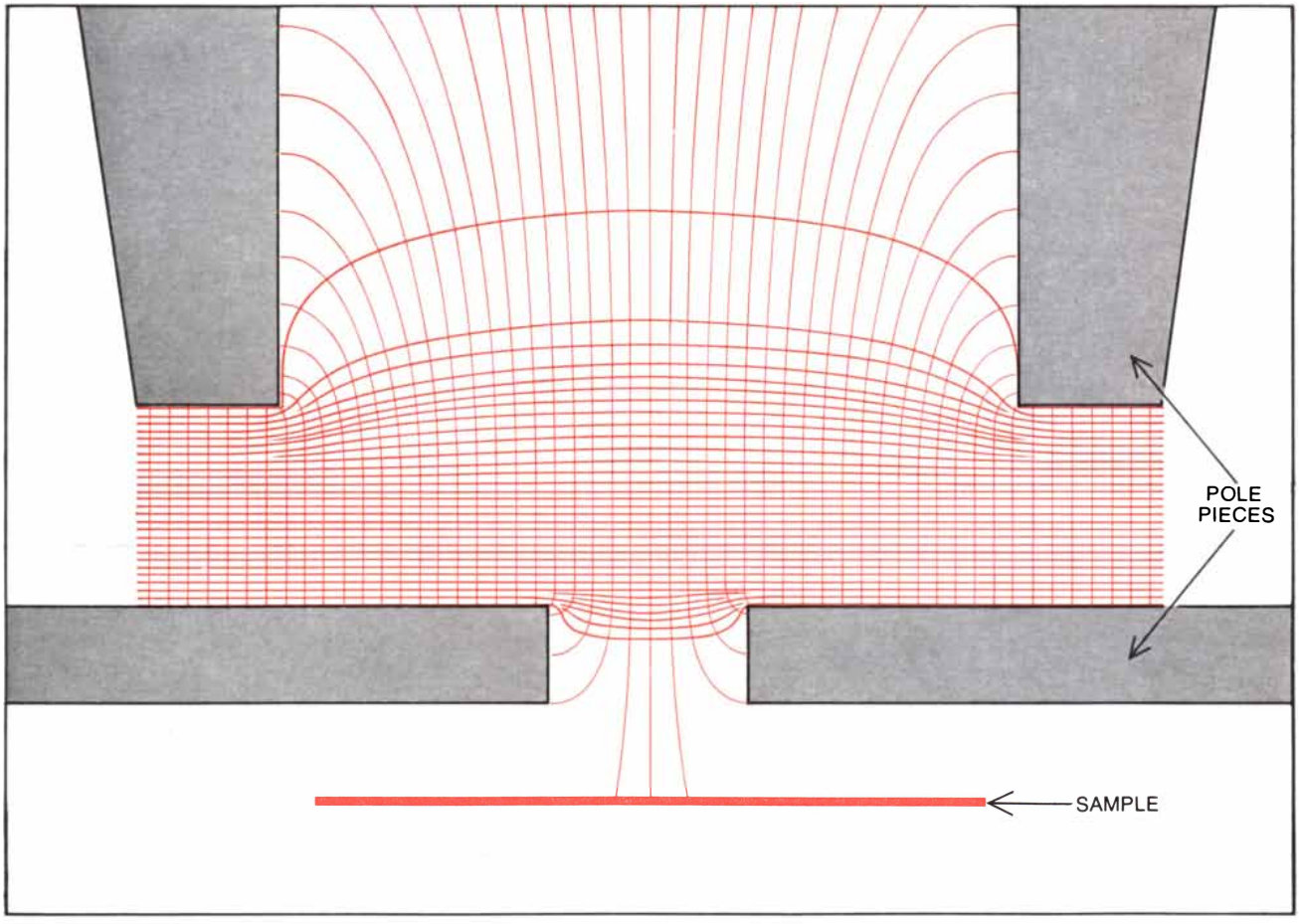
need for a mask, which negates the ability to generate the pattern "on line."

Computer control overcomes both problems. No mask is needed, and the number of lines that can be scanned is limited only by the increase in the size of the electron beam when it moves to the corners of the field and by the accuracy with which the beam can be deflected and positioned [*see illustration on preceding two pages*]. In typical systems these two restraints limit the size of the field to about 2,000 lines. In other words, if electronic devices are to be fabricated with minimum dimensions of one micron, the field over which they can be fabricated is two millimeters. The overall accuracy of the system has to be much better than one part in 2,000, because in most applications several steps are required and each pattern has to be exposed accurately on top of previously fabricated structures. The accuracy needed is generally a fifth of the minimum dimension. This means that 10,000 lines have to be scanned and that the stability of the deflection signals has to be better than one part in 10,000. Since many components contribute to the stability of the beam, including the power supply as well as the scan-generator and amplifier, individual components need a stability approaching one part in 100,000, which is close to the maximum precision attainable with today's electronic equipment.

With computer control two different techniques can be used to scan the beam. It can be scanned in a raster, as the image in a home television set is scanned, or it can be directed to scan only those areas requiring exposure. In the first case the beam passes over the entire sample and is turned on only when required. Exposure is inefficient, but the beam always traverses the same path and positional accuracy is easily maintained. The second approach is more efficient, but it can be used only in the absence of errors due to hysteresis and eddy currents. Hysteresis arises because of memory effects in the magnetic materials surrounding the coil that deflects the electron beam. If the beam is to be deflected from point A and point B, hysteresis makes point B vary in position according to the position of A. Eddy currents produce differences in the position of B if the speed of deflection is changed between A and B. To reduce these errors all conducting and magnetic materials must be kept as far away from the deflecting coil as possible.

Because the area that can be scanned at one time by an electron beam is only a few square millimeters across, many exposures are usually required on each circuit chip, typically between 100 and 200 on a silicon wafer two inches in diameter. This means that the wafer must be mechanically stepped between each exposure. After mechanical stepping the beam is repositioned with respect to the sample.

In all scanning systems the beam is positioned and focused by scanning the beam over the sample surface and detecting the change in the emission of



MAGNETIC FIELD OF ELECTRON LENS was calculated by a computer program written by M. B. Heritage of IBM. In designing an electron lens the designer begins by selecting a particular configuration for the pole pieces. He can actually build the pole pieces and measure the field they produce or he can calculate the field. A System/360 Model 91 computer is capable of generating a grid of 50 by 200 points, representing the geometry of a magnetic field with an accuracy of five parts per million, in some 30 seconds.

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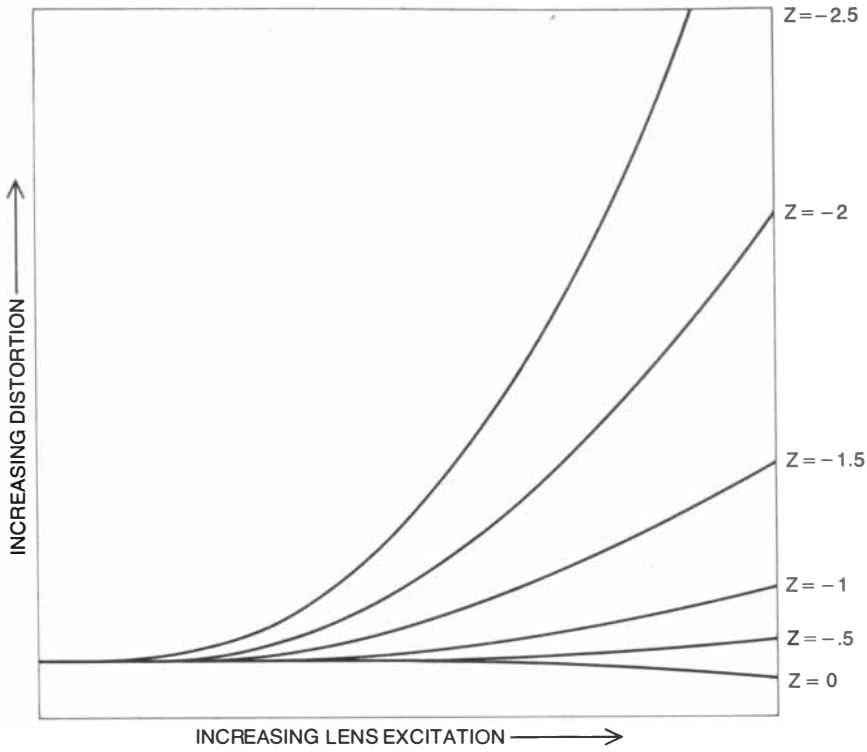
secondary and reflected electrons as the beam passes over surface detail. Changes in electron emission are detected by collecting the electrons emitted from the surface. In this mode the apparatus is really operating as a scanning electron microscope, although for reasons of speed and automatic control the information is generally processed electronically and not displayed pictorially. For integrated circuits, where several exposures are needed, each exactly located with respect to those preceding it, special registration marks are placed on the surface so that the beam position and the size of the scanned area can be checked. The beam scans these marks before exposing the required pattern. If a computer is used to provide pattern data, it can also be used to control the mechanical movements of the table and to monitor the electron beam for focus, current intensity and position. Such control is achieved in practice by setting aside time between exposures to correct for errors that may have developed during exposure.

The observation of registration marks is made difficult by the layer of resist that always covers the surface. This difficulty has led some workers to use an alternative approach: accurately positioning the mechanical table on which the sample rests. Here the beam has to be positioned with respect to the sample only once, and for subsequent exposures registration is achieved by accurately positioning the table with an optical interferometer. Unfortunately this method does not correct for drift in the position of the beam or compensate for changes in the size of the scanned image, both of which may occur before the sample is completely exposed. Since the accuracy that can be obtained is only about .1 micron, the method is limited to fabricating devices whose minimum dimensions are about .5 micron.

If it can be assumed that the pattern-generator imposes no speed limitations (a valid assumption for most computer systems), the time taken to expose a given area with an electron beam depends on the sensitivity of the resist and on the beam current. In order to indicate what this means in actual exposure time, let us imagine that one wants to expose an area two millimeters square with sufficient resolution to produce lines one micron wide. For this purpose a lens with a focal length of five centimeters is suitable. To attain the desired resolution the diameter of the beam must be .2 micron.



ELECTRON-BEAM DISTORTION increases rapidly as the lens aperture is moved fairly small distances (Z) from the center of the gap in a magnetic lens. There is an optimum position for the aperture that gives zero distortion; here it falls between $Z = 0$ and $Z = -.5$. Since it is usually desirable to use high lens excitation in order to reduce other lens aberrations, it is important that the lens aperture be optimally placed in order to minimize distortion. The curves were plotted according to a program developed by Heritage.

Although a beam current of 6×10^{-8} ampere can be obtained with a cathode of lanthanum hexaboride [*see bottom illustration on page 36*], this intensity of current is provided by a lens aperture that is suitable only when the field is less than a square millimeter or so. For larger fields one must reduce the aperture to minimize the additional aberrations that arise when the beam is deflected farther off axis. Thus for a field two millimeters square it is necessary to have an aperture that reduces the beam current to about 2.5×10^{-8} ampere.

The sensitivity of the resist is expressed as the total charge that needs to be deposited per unit area to expose the resist to the point where it can be developed. If we assume a typical value of 10^{-5} coulomb per square centimeter, the total exposure time for a field two millimeters square will be 17 seconds. This assumes that a standard television raster scan is used. If only the areas requiring exposure are scanned, the time will be reduced by a factor of at least two and perhaps as much as five. The time taken to position the sample and register the electron beam has to be added to the exposure time to arrive at the overall time per field.

Inasmuch as integrated circuits are commonly mass-produced on wafers two inches in diameter, equivalent to an area of some 2,000 square millimeters, it is apparent that one cannot afford to adopt the system just described for the commercial fabrication of circuits. The speed of the system is more than adequate, however, for building experimental devices and limited quantities of special high-performance circuits.

When the exposure speed of simple round-beam scanning apparatus is insufficient, one must turn to electron-optical equipment with "parallel" exposure capability. In other words, more than a single resolution element of the circuit must be exposed by the beam at one time. In the extreme case entire patterns can be exposed at once with what are called projection systems. These systems are really transmission electron microscopes working in reverse. Instead of a specimen there is a mask, and instead of magnifying the object formed by the specimen the object formed by the mask is demagnified. Such a system has been built at the University of Tübingen.

Because all the elements in the pat-

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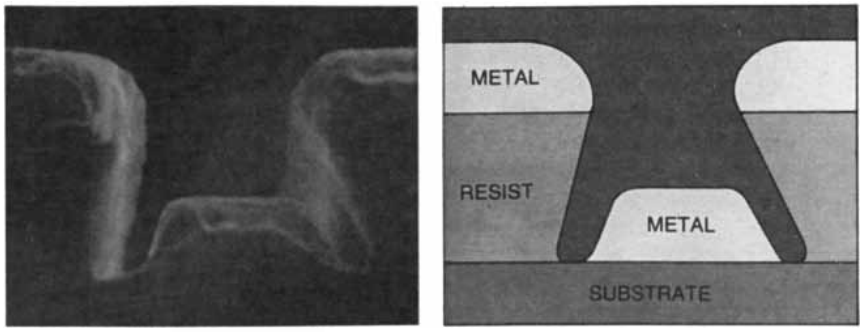

END VIEW OF METAL LINE about one micron wide is shown in the scanning electron micrograph at left. The line was deposited through an opening in a "resist" of polymethyl methacrylate (PMMA) that had been exposed to a sharp electron beam. When PMMA is bombarded by electrons, the plastic is partially depolymerized and can be dissolved away. The solvent tends to undercut the resist, however, as is depicted in the drawing at right. When a thin film of metal is later evaporated onto the surface of the workpiece, it bonds to the substrate wherever the resist has been removed and covers the resist in a thin layer elsewhere. Both the resist and the unwanted metal are then stripped away from substrate.

tern are exposed simultaneously, the exposure time is reduced by a factor that can be as high as the number of elements in the pattern. As a result a 1,000-line field with 5,000 by 5,000 resolution elements can in principle be exposed 25 million times faster than with a single round beam. In practice this performance is not possible, nor is it even useful. The high speed is not possible because even heated electron sources are not able to maintain their brightness over the large angles needed to illuminate the masks. The high speed would not be useful because exposure times smaller than about a tenth of a second become insignificant compared with the times needed to mechanically load and position the sample with respect to the electron pattern.

Problems with projection include the difficulty of positioning the pattern with respect to the sample and the lack of an electron-transparent substrate on which to support the mask. These problems are predominantly technological, however, and will probably be solved. If they are, projection over part or all of the pattern will almost certainly overcome problems of limited exposure speed. Flexibility will be sacrificed as more and more of the pattern is projected, because the pattern will no longer be completely generated on line from the pattern-generator. In many applications, however, such as the fabrication of computer memory devices, where billions of identical components are needed, this loss should not be important.

To extend the capability of any electron-beam fabrication apparatus to more complex arrays of devices, it would be highly desirable to relax the restriction that the electrons used to expose the resist be only those whose path is close to and almost parallel to the optical axis of the lens system. In other words, it would be desirable to be able to use larger apertures for more intensity, and to cover larger fields. To achieve this goal, however, the designer of magnetic lenses must deal with an entirely new set of aberrations that enter in when one tries to image points that are some distance away from the optical axis of the lens system.

The design of magnetic lenses not only is a new art in comparison with optical-lens design but also involves certain difficulties not present in optical systems. One of them is the fact that the shape of the lens, that is, the shape of the lines of magnetic force, is not arbitrarily chosen at the beginning as the shape of an optical lens is. The designer starts with his magnetic pole pieces and has to calculate or measure the field lines they produce. For achieving precision lenses this is not a trivial task. A second handicap is that there is no such thing as a diverging magnetic lens: a lens with a negative focal length. Therefore the magnetic-lens designer lacks an important tool of the optical designer for eliminating aberrations.

With the aid of modern numerical analysis techniques it is now possible to produce efficient programs for computing the lines of magnetic force produced by pole pieces with various geometries [*see illustration on page 40*]. The computation for a grid of 50 by 200 points, with an accuracy of five parts in a million, takes 25 seconds on an IBM System/360 Model 91 computer. The ability to compute rapidly and accurately the fields produced by a magnetic lens of a given configuration allows the aberrations of a lens to be determined by an additional straightforward computation. The aberrations can then be minimized. The class of aberrations represented by distortions, that is, aberrations that change the shape of the object being imaged, can be kept very small for any value of lens excitation by placing the aperture close to the center of the lens gap. If the aperture is placed farther away along the optical axis, the lens excitation must be kept small to minimize distortion [*see illustration on preceding page*].

The development of thin and bright beams of electrons that can be controlled to cover large areas is of course only the first step in the formation of small devices and circuits. In order to build a physical structure some medium must be used that is altered in the area where the electron beam is allowed to impinge. The medium can be the workpiece itself or a temporary layer applied to the surface of the workpiece. An example of the first approach is thermal machining, where the electron beam is used to vaporize part of the workpiece, thereby removing the unwanted portions for the formation of the desired pattern. The main disadvantage of thermal machining is that resolution is limited by thermal spreading in the sample to minimum dimensions of several microns. In the second approach a layer of material in solution is applied to the workpiece before exposure to the electron beam and is allowed to dry, forming a protective cover over the entire surface of the workpiece. This temporary layer is the resist; it is equivalent to the photoresists used in the semiconductor industry, where ultraviolet radiation produces the desired pattern.

Photoresists can also be used for electron-beam exposure, since the mechanism of exposure is the same whether ultraviolet radiation or electrons write the pattern. In general, photoresists consist of a polymer and a material called a sensitizer, which contains a substance that absorbs radiant energy instead of allowing it to pass through. When a photoresist is exposed to light or ultraviolet radiation, two effects can take place within the polymer. First, some of the chains that bind the molecules of the polymer together are broken and the size of the groups of molecules is reduced. Second, new chains are created between the existing groups, resulting in larger groups of molecules.

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If the first effect dominates, the average molecular weight of the polymer is reduced in the exposed areas, and these areas dissolve more readily in the developing solution. Resists of this type are the positive ones. If the second effect is dominant, the molecular weight of the material in the exposed areas is increased; these areas dissolve more slowly in the developer and remain after the unexposed areas are washed away. These are the negative resists.

Many of the commercially available photoresists of both the positive type and the negative type have been tested under electron-beam exposure in the search for a suitable electron resist. Unfortunately the resolution of all of them is unsatisfactory because the width of the thinnest line produced on the resist after development is limited by the exposure mechanism and not by the width of the electron beam that exposed the line.

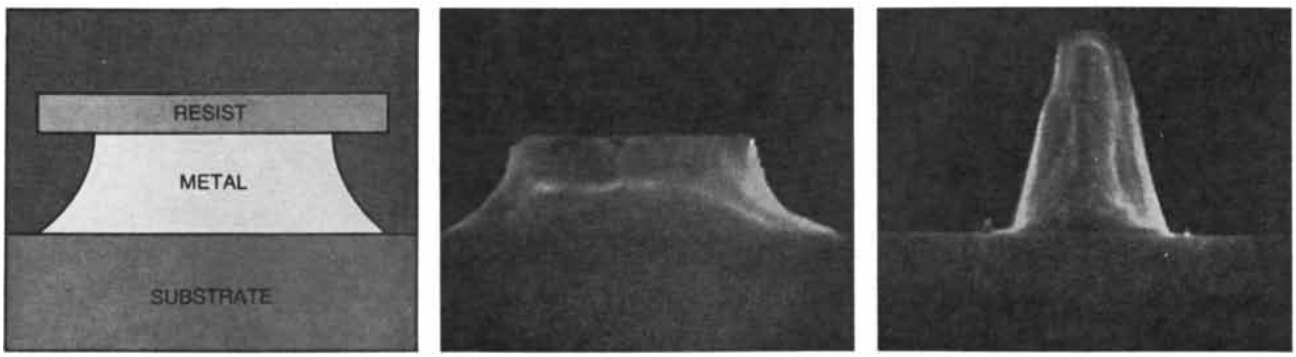
A key advance in electron-beam fabrication was the discovery at IBM that the polymer polymethyl methacrylate (PMMA) is an almost ideal resist for the electron-beam exposure of extremely fine patterns. PMMA is a positive resist; since it is a pure polymer and contains no sensitizer, it is not sensitive to light and can be handled without special lighting. The resolution of PMMA is superior to that of any other known resist: it is capable of producing line widths smaller than .1 micron. PMMA is available in the form of a solid or a powder and has to be dissolved in a solvent before it can be coated on the workpiece by spinning. The thickness of the resist layer after drying and baking is typically between .2 micron and one micron, depending on the particular processing to be used.

Most of the processing steps in semiconductor fabrication require that parts of the workpiece be removed. That is, after the resist has been developed and partially removed the exposed parts of the workpiece are etched away in a chemical solution. The parts protected by the resist remain unchanged and protect the surface below. The PMMA resist has been used to fabricate some of the smallest operating transistors yet built. The minimum width of the lines in these devices is 8,000 angstroms, or .8 micron.

In addition the PMMA resist offers a unique method for forming high-resolution structures. In this method a vapor of the material from which the structure is to be made is condensed in vacuum onto the workpiece through the exposed and developed pattern on the resist. This process is extremely useful in the formation of the metallic conductors that are used in semiconductor fabrication to carry current to or from a device or circuit. In conventional fabrication techniques with photoresists the required conductors are formed by first evaporating a metal layer over the entire sample, then coating it with photoresist and exposing the pattern. After exposure the resist is developed and the unwanted metal is etched away in a chemical solution, leaving only the parts protected by the resist. Unfortunately the chemical solution etches the sides of the remaining conductors while removing the unprotected metal. This effect, known as undercutting, puts a severe limitation on the minimum size of the conductors, particularly because the rate of undercutting is often nonuniform.

In the evaporation method using the PMMA resist the metal forming the conductors is added after the resist has been exposed and developed [*see illustration on opposite page*]. That is, the area where metal is wanted is first exposed to the beam so that on development the resist is removed. Because electrons entering the resist during exposure scatter sideways as they penetrate the resist layer, the line produced in the resist is wider at the bottom than at the top, so that when the metal is evaporated onto the surface of the sample, there is a physical discontinuity between the metal on top of the resist and the metal on the bottom of the line. The sample is then immersed in a liquid that dissolves the unexposed resist, and the entire resist layer with the metal on top of it is removed from the workpiece, leaving only the metal on the sample surface. This "lift off" process is possible only if the discontinuity between the metal on the resist and the metal on the sample is maintained, and if the thickness of the metal does not exceed about 80 percent of the thickness of the resist.

Metallic lines or lines of many other materials with widths of less than a tenth of a micron can be fabricated in this way [*see illustration on opposite page*]. Just as significantly the process allows the use of a thickness of metal at least equal to the minimum width of the required line. As a result metallic conductors can now be much narrower without reducing their current-carrying capacity so much that reliability suffers. This capacity is very important in the effort to pack more electronic circuits into a smaller area. For example, in a typical circuit fabricated conventionally an interconnection line one micron wide and .2 micron thick can carry a current of .02 ampere, equivalent to a current density of 10 million amperes per square centimeter. With the lift-off technique it



CONVENTIONAL METALLIC CONDUCTOR (*middle*) and a conductor made by the "lift off" method using a PMMA resist (*right*) are compared in two scanning electron micrographs. The drawing at left illustrates the conventional method of forming metallic conductors. Metal is deposited over the entire sample surface and then covered with a resist. The resist is dissolved away according to a pattern formed by exposure to ultraviolet radiation. When the metal is subsequently etched away, considerable undercutting occurs. The line shown in the middle picture was actually exposed with lines 3.5 microns wide. Because of undercutting the line itself is only 2.5 microns wide. The line at far right, made by the electron-beam technique, is three microns high and only one micron wide.

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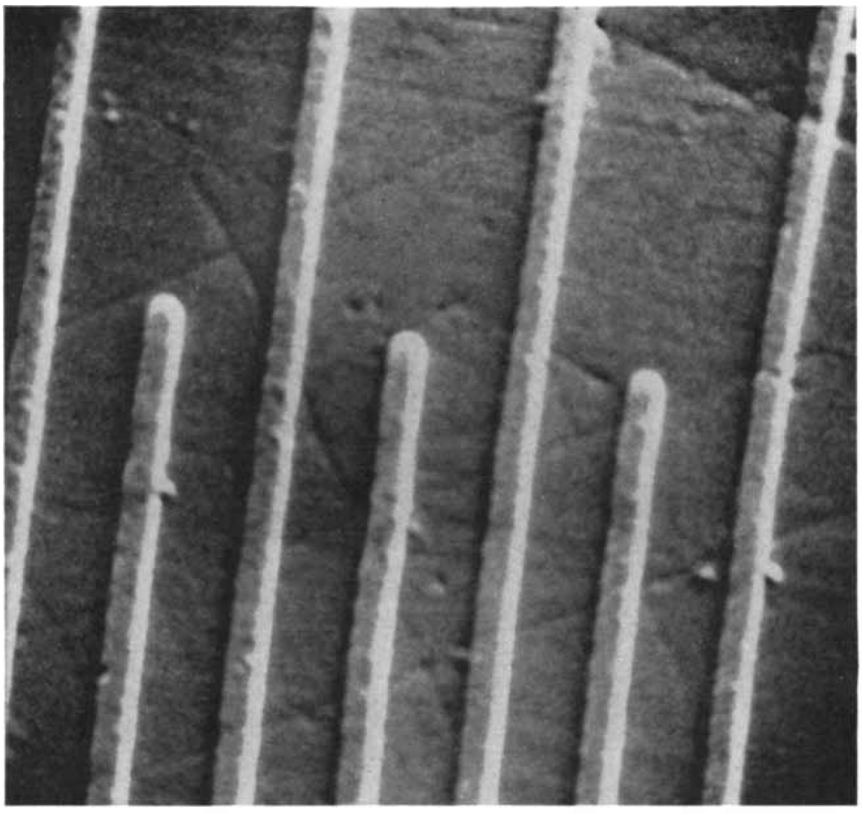
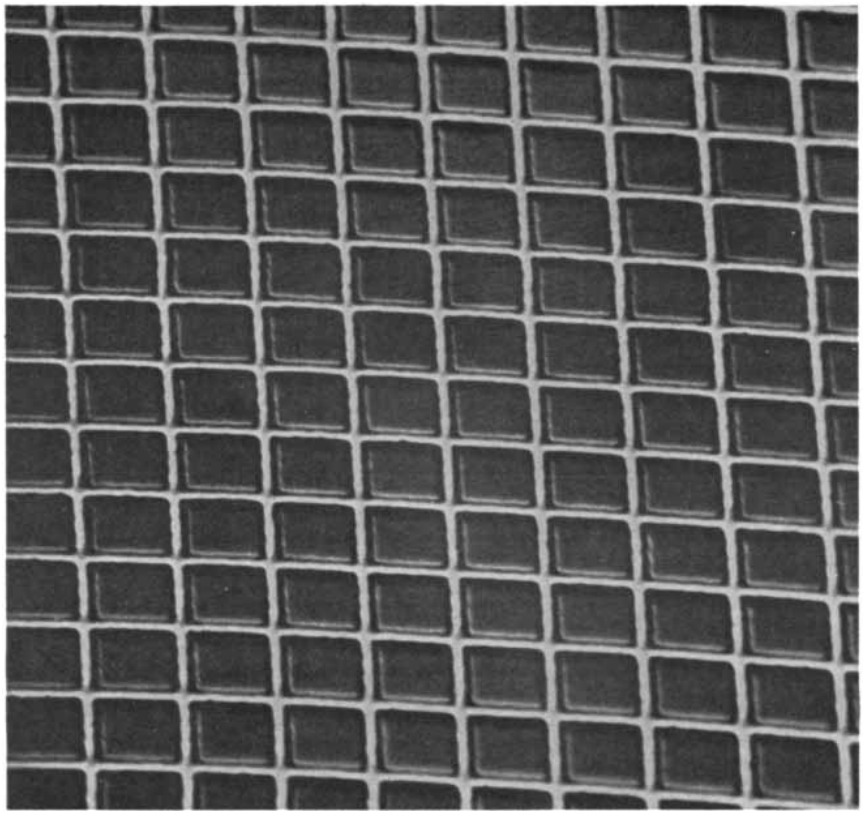


ACOUSTIC-SURFACE-WAVE TRANSDUCER made by the lift-off technique has the highest operating frequency yet achieved: 3.5 gigahertz (billion cycles per second). Aluminum lines are .14 micron (1,400 angstroms) wide with a center-to-center spacing of .5 micron.



CALIBRATION GRID STRUCTURE was made by evaporating a gold-aluminum alloy through a PMMA resist mask. The lines are about .1 micron wide and one micron apart.

is possible to make an interconnection line one micron wide that is also three microns thick [*see illustration on preceding page*]. A .02-ampere current in such a line has a current density of less than one million amperes per square centimeter.

Electron-beam fabrication with the PMMA resist has opened the way for new types of devices that could not be made previously because the dimensions needed were smaller than about one micron, the minimum available with conventional photolithographic techniques. One such case is the acoustic-surface-wave transducer, a device used for launching acoustic waves along the surface of piezoelectric substrates [see "Acoustic Surface Waves," by Gordon S. Kino and John Shaw; SCIENTIFIC AMERICAN, October]. Devices employing these transducers have found important applications in the processing of microwave signals. The line width and line spacing of the device determine the operating frequency. With conventional fabrication techniques the maximum operating frequency is limited to several hundred megahertz (million cycles per second). With electron beams it is possible to build devices that operate at frequencies 10 times higher. The highest frequency yet achieved in an acoustic-wave transducer is 3,500 megahertz (3.5 gigahertz). The device has a line width of .14 micron (1,400 angstroms) and a center-to-center spacing between adjacent lines of .5 micron [*see top illustration at left*].

Another example is an experimental transistor structure with aluminum lines .5 micron wide separated by a .5-micron gap [*see illustration on page 35*]. Extremely small grids that can be used for measuring purposes in scanning microscopes are readily made with electron beams. One such grid has wires only .1 micron (1,000 angstroms) wide with a center-to-center spacing of one micron [*see bottom illustration at left*].

It is certain that as the demand for smaller and smaller devices and electron circuits continues electron beams will find wider applications in the field of fabrication previously dominated by optical techniques. The experiments on device fabrication that have been carried out so far indicate that electron beams should make it possible to develop semiconductor circuits and other electronic devices with dimensions considerably smaller than those set by the wavelength of light. In addition the devices can be made directly under electronic control without the need for precise masks.

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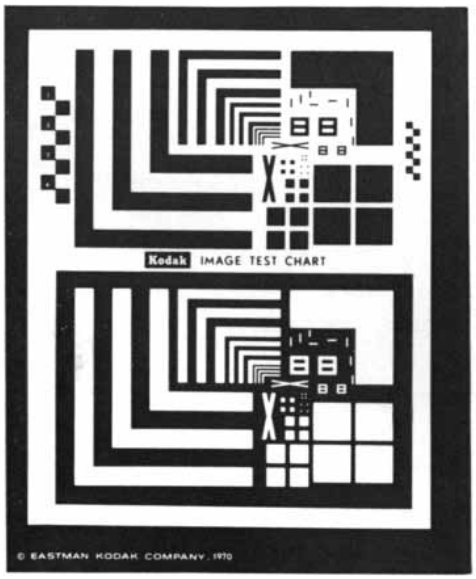
We want to be useful ...and even interesting



Note the vertical strips of checkerboard at upper left and upper right. The left-hand columns of black squares in both sizes contain clear-on-black numerals. What's more, the numbered squares vertically overlap by increasing amounts the diagonally adjacent unnumbered ones. On the original they do, anyway. When the target is photographed, on the negative the overlap shrinks. This gives a measure of the effective exposure for high-resolution materials. If the overlap is gone on the negative at square 2, one speaks of a No. 2 exposure.

How sharp

A hand magnifier will show you here a test of the reproduction chain that ends on this printed page, a test to the point of failure. The purpose here is not to question the quality of the printing in this magazine* but to offer the KODAK Image Test Chart. It comes on film in 96 x 116mm size as KODAK Publication P-301 and in 20 x 24-inch size as P-303. Whatever size original is convenient in testing a system involved in precision photography, the chart is intended to show limitations that come into play as the size of the reproduction goes down.

This yields a different kind of story from a mere statement of "resolving power" and perhaps a fuller story but not quite as quantitative.

If you bang your fist on the table and demand a simple answer to the question how many lines per millimeter, don't test with this chart. If you are interested in additional dimensions of photo-optical performance—rendition of corners, what you would gain and what you would lose by a small shift in focus, more or less exposure, a processing change, stray-light shielding—this chart and plenty of patience may provide the detailed answer that the table-banger has already rejected.

We devised the chart for the modern electronic-circuit manufacturing industry, which makes its microscopic products by photography. It can be ordered from dealers in technical photographic products.† (For more information, see Solid State Technology *for November, 1971, p. 34.)*

*Depends, for example, on whether your copy was printed early or late in the press run.

†Or at $1 for P-301, $20 for P-303, from Dept. 454, Kodak, Rochester, N.Y. 14650. Prices subject to change without notice.

Strange cations

About 20 years ago patents started flowing through the photographic industry for replacement of some of the silver ions in silver halide crystals by other cations. A few years later products appeared on the market which permitted a beam of light in an oscillograph to write at very high speeds without need for chemical development. Mere room light caused the written record to pop up. Then, despite the room light, the record stayed legible for longer than needed. The aerospace industry in full bloom consumed such paper voraciously.

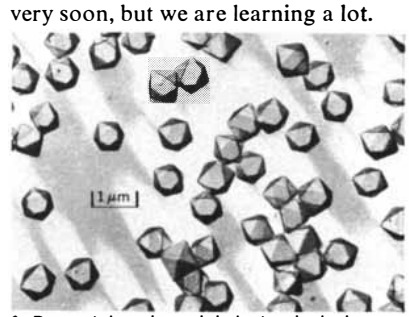
Though the newer cations continue to free the photographic process of old limitations, silver is not about to go. Though we and everybody else are trying, silver is very hard to beat.

In silver halide many cations wander interstitially through the lattice; one in every 10^7 Ag^+ ions is on the loose. If somewhere in the lattice there sits an electron that had somehow been lifted into the conduction band, perhaps by a photon of light, and has since been trapped at an anomaly, a wandering Ag^+ will join it soon. *This will deepen the trap for a subsequent photoelectron.* If none comes along within 10 seconds or so, the newly made neutral silver atom will give up the electron and wander off again. If the deepened trap does catch a second silver atom and then a third, a cascade starts that renders the entire crystal developable. Note that the need for that crucial second photoelectron makes the whole thing act like a coincidence circuit. Otherwise silver centers would soon form all over the crystal, light or no light.

For these reasons, silver halide emulsions can cover 15 orders of magnitude in light intensity—a picosecond laser flash or an atlas of the faintest astronomical objects perceptible by present technology.

Designing a photographic emulsion for short exposure or long, for high contrast or low, for one kind of processing or another or none at all, for one virtue or another, usually requires control of where the photoelectrons shall collect and where the holes shall collect that they leave—on the surface of the crystal, inside, in one place, or many places.

If this sounds something like the task of the creators of those tiny modern electronic devices, it is. That bunch have been inserting their strange atoms by diffusion. Lately they have been placing them more precisely by implanting them as ions. That's what is now being tried at the Kodak Research Laboratories. We can't see it becoming a practical production technique for us very soon, but we are learning a lot.



AgBr crystals, micromini electronic devices

Kodak

Photographically basic

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200,000 Europeans have driven the Opel Manta over 2 billion miles.

Now Buick introduces the Manta to America.

September, 1970. The Opel Manta was introduced to Europe. Since then, over 200,000 Europeans have bought it and driven it more than 2 billion miles over European roads. In real-life conditions.

Day-in, day-out.

Now Buick brings the Manta to America. A proven, reliable, economy car with rack and pinion steering, power front disc brakes, 1.9 liter engine and a long list of standard equipment.

Plus a little something extra.

Luxury.

Which is a little something you don't usually find in economy cars.

Test-drive the new Manta in America.

German precision imported by General Motors.
Sold and serviced by 2200 Buick dealers.

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Each Manta luxus interior matches the car's exterior color. This maroon one comes only inside maroon Mantas.

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Premise: Pollution control begins with effective sensing and measurement.

For the job of cleaning up water, Honeywell has some useful tools.

Clean, pure water is a simply-stated goal. Yet achieving it presents complex problems.

One industrial plant may discharge carbolic acid. Another may be the source of cyanide effluents. Or chromium. Or both. Public sewage wastes bear bacteria and other biological pollutants.

While there are treatments for virtually every known water pollutant, no single off-the-shelf cure-all exists. Nor is it likely to be found.

For that reason, the prompt, practical answer lies in prevention. Prevention that begins with the sensing and measurement of specific pollutants at each potential source.

In this area, Honeywell technology has developed certain precise tools: sensors for dissolved oxygen, pH, conductivity and several other parameters affecting water quality. Beyond that, our long-term experience in control equipment enables us to design automated systems which can make water treatment both more effective and more economical.

Meeting today's water quality standards is an important and difficult job. For information concerning our capabilities in this or other aspects of pollution control, please write Mr. Richard Boyle, Director of Environmental Programs, Honeywell, 2701 Fourth Ave. So., Minneapolis, Minn. 55408.

We'd like to help.

Honeywell

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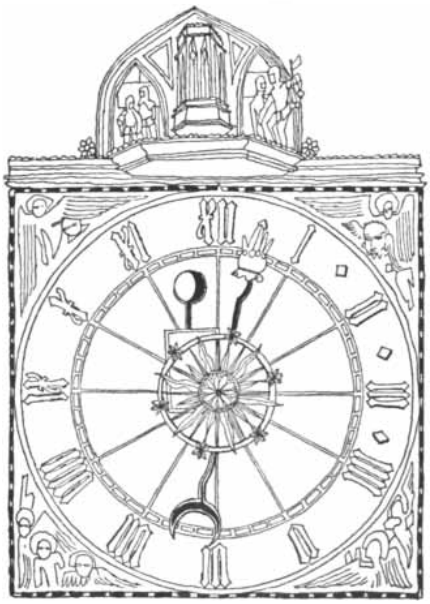


SCIENCE AND THE CITIZEN

The Strong and the Weak

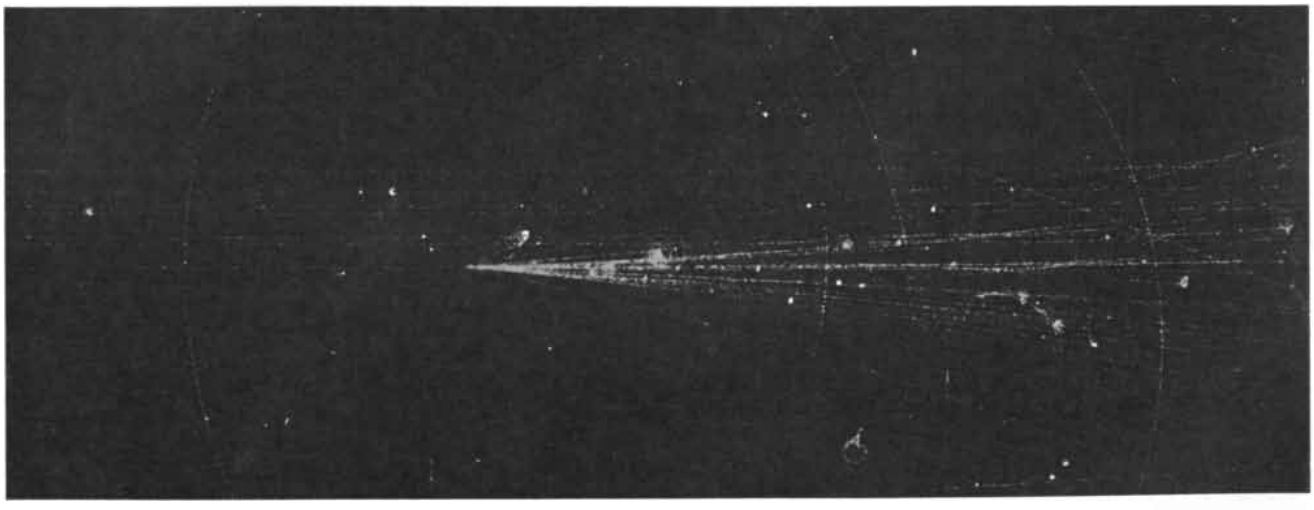
The 16th "Rochester" International Conference on High Energy Physics was recently held at the University of Chicago and at the National Accelerator Laboratory (NAL) in Batavia, Ill., where for several months the world's largest synchrotron has been accelerating protons to energies of 300 billion electron volts (300 GeV). The several hundred physicists in attendance heard, among other things, that the neutral *K* meson sometimes decays into a positive muon and a negative muon after all (previous efforts to find this predicted decay had failed), that the latest results from the NAL machine confirm that the number of particles produced in proton-proton collisions increases in a straight line as a function of energy (refuting earlier cosmic ray results to the contrary) and that promising new theories unifying electromagnetism and the weak interactions seem eminently testable at the energies provided by the NAL machine and by the intersecting storage rings (ISR) recently added to the 28-GeV synchrotron at the European Organization for Nuclear Research (CERN) in Geneva. In the ISR protons circulating in one ring collide with protons circulating in another ring, with the release of energies up to 1,500 GeV; the number of protons involved in such collisions, however, is hundreds or thousands of times smaller than the number available at Batavia, where protons slam into stationary targets.

It is perhaps too soon to say that the controversy over the decay of neutral *K* mesons into positive and negative muons, or mu mesons, is settled. The previous failure to observe such a decay had proved an embarrassment to electromagnetic theory. The elusive decay mode was observed in experiments performed at the Brookhaven National Laboratory by an international group from Columbia University, New York University and CERN.

No one was particularly surprised to hear that the number of particles produced in proton-proton collisions increases steadily as a function of energy. The cosmic ray experiments that had suggested a leveling off with increasing energy had been suspect because of the difficulty of recording enough events at various energies to provide good statistics. With the NAL accelerator now running steadily it should be possible to decide between two classes of models, or theories, describing what happens when a high-energy proton strikes a proton and produces a shower of secondary particles (*see illustration below*). According to the "fireball" model, at least one of the protons becomes highly excited and on deexcitement emits a burst of particles. In the "multiperipheral," or independent-emission, model the particles emerge individually rather than in a burst. Both models can be made to fit the observation that the number of particles emitted per collision increases as a function of energy.

A somewhat more sensitive test of the models is to examine the frequency with which 2, 4, 6, 8, . . . , $2n$ particles ("multiprong events") are created as the energy of the incident proton increases. On the basis of a rather limited number of observations the frequency count tends to favor the multiperipheral model, which predicts that for any given number of prongs the number of events should rise to a broad maximum with increasing energy and then fall again.

Perhaps the most sensitive test of the two models is now in progress. By close examination of bubble-chamber photographs it should be possible to determine whether the particles produced in a specific collision are released in clumps or whether they are spread out. The fireball



A "high-multiplicity" event produced by a 300-billion-electron-volt proton at the National Accelerator Laboratory

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model predicts that the emitted particles should tend to clump; the multiperipheral model predicts that they should tend to be spread out.

To many theoretical physicists the most exciting prospect discussed at the Batavia-Rochester conference was the possibility of testing theories whose aim is to unify the understanding of electromagnetic interactions and weak interactions. The unification would be analogous to that achieved when James Clerk Maxwell reduced electric and magnetic phenomena to a single set of equations. Weak interactions involve forces only a trillionth (10^{-12}) as strong as the electromagnetic force, which in turn is about a hundredth as strong as the nuclear, or strong, force that binds atomic nuclei together. Weak interactions are associated with the radioactive decay of atomic nuclei and all reactions involving the release of neutrinos.

At least three obstacles have blocked the theoretical unification of electromagnetism and weak interactions, and indeed all theories of weak interactions. Unlike the electromagnetic force, which operates through a well-known quantum, or intermediary, the photon, the weak force has no known quantum. A weak-force quantum called the intermediate vector boson, or *W* particle, has been postulated but has not been observed. If the *W* particle exists, it must be very massive, whereas the photon has zero mass. A unifying theory must deal with this huge discrepancy in mass.

The second obstacle to a satisfactory theory is that many calculations involving the weak force quickly lead to infinite results. In electromagnetic theory similar divergences are handled by the process called renormalization. Until recently no one could see how to renormalize the divergences presented by the weak force.

Finally, a unifying theory must deal with the general problem of symmetries and how they are broken in particle physics. For example, the proton and neutron are identical particles so far as the strong force is concerned and should have an identical mass. The symmetry is evidently broken because one of the particles, the proton, carries a positive electric charge and is slightly lighter than the neutron. Since there is as yet no procedure for calculating the mass difference on the basis of existing electromagnetic theory, it remains a problem for a unifying theory.

Several years ago Steven Weinberg of the Massachusetts Institute of Technology outlined a general way in which the divergences of the weak force might be made renormalizable and how symmetries might be broken. Little progress was made in constructing useful theories along these lines, however, until the summer of 1971, when a graduate student at the University of Utrecht, Gerhard 't Hooft, proved that the general class of theories proposed by Weinberg are renormalizable. Subsequently a number of physicists have presented specific models of such theories. Each model predicts new phenomena not predicted by present theories of the weak force. Specifically the models predict the existence either of new "leptons," particles similar to the electron, muon, photon and neutrino, or a new intermediate vector boson. Although it is not clear that the Batavia accelerator or the ISR at CERN are powerful enough to create the predicted particles, Weinberg and others are confident that the new machines should be able to reveal certain effects traceable to the particles.

Family Planning in China

China may become one of the first developing countries to succeed in controlling its population growth before it becomes completely industrialized. This is the major conclusion of a joint report by two Western obstetricians who separately toured the People's Republic for two weeks last March. Anibal Faundes of the Barros Luco Hospital at Santiago in Chile and Tapani Luukkainen of the University of Helsinki in Finland were struck by the lack of any statistical data, either demographic or with regard to family-planning practices, at the national, provincial or district level. They nevertheless felt able to report the "dramatic success" of family-planning programs on the basis of visits to health centers, interviews and examination of local population and birth-control statistics. Their account has been issued as a supplement to *Studies in Family Planning*, a publication of the Population Council, in whose behalf they undertook their visits.

Family planning in China is integrated into maternal-health programs, according to Faundes and Luukkainen, and is therefore carried to the population through a variety of organizations: the commune's hospital, health stations or mobile units in rural areas, and hospitals, factory health centers or "street and lane" health stations in urban communities. As with other health services, a shortage of professionals is compensated for by the use of nurses, midwives and the paramedical "barefoot doctors." Delivery of family-planning services is inevitably more effective in cities than in the countryside, because of both the greater availability of trained health workers in the cities and the greater resistance to contraception and limitation of family size in the rural population.

Family planning is achieved through four kinds of control, the authors report: late marriage, abortion, contraception and sterilization. Of these late marriage, combined with premarital chastity, has the greatest impact. Although the minimum legal age for marriage is 18, Chairman Mao has "asked" that women postpone marriage until the age of 23 and men until 26. At least in urban areas, that request is generally respected; in the villages women usually marry between 20 and 22 and men between 22 and 24. Premarital sex is assumed to be illegal but the authors could not determine the punishment because they were told that "it never happens," apparently because of public opinion and the "total absence of sexual stimulation."

Induced abortion is performed on request, usually in very early pregnancy. Typically, a woman who has missed a menstrual period attends a clinic; if the diagnosis is pregnancy and she does not want the baby, she is immediately referred for abortion. The procedure is almost always done by vacuum aspiration conducted by nurses, midwives or barefoot doctors and the rate of complications is said to be very low.

Contraceptives are provided free of charge, with the pill and the intrauterine device (IUD) being the principal methods. The pill is the most popular, surpassing the IUD by two to one in Shanghai and 10 to one in Canton, for example. The pills, of Chinese formulation and manufacture, are considered extremely effective, with a failure rate of less than one per 100 women per year; the IUD's in current use are apparently less effective. In the past two years extensive clinical trials to develop once-a-month injections or pills have been conducted in many hospitals but both are still in an experimental stage.

Sterilization through tubal ligation is widely undergone, usually by women between 35 and 40 who have had two or three children. Vasectomy is much less popular because of the common belief that the procedure reduces a man's working capacity.

Faundes and Luukkainen were told that the proportion of families practicing contraception varies from 30 to 89 percent depending on location, with the highest percentage in Shanghai and the average in cities around 65 percent. The "ideal family size" is considered to be

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two or three children. In the cities family-planning education is so effective that young couples who have more than three children are said to be regarded as showing disrespect for the Party and society in general.

The sheer size of China's population and the country's importance as a model for developing nations lend great significance to its achievements in family planning. Unfortunately the only demographic data Faundes and Luukkainen could collect were for Peking and Shanghai. The birthrate in Peking was given as 18.8 per 1,000, the mortality rate as 6.4; the rates for Shanghai were 12.1 and 5.2 per 1,000. That would make the annual rate of natural increase 1.24 percent in Peking and .69 percent in Shanghai. (Comparable recent rates were 1.1 percent in the U.S., 2.6 in Taiwan and an estimated 2.1 in India.) Recent estimates of China's population have ranged from about 730 million to 850 million, but last summer a total population figure of 697 million was published in a Chinese pocket atlas. The population growth rates and the success in family planning reported by Faundes and Luukkainen—if they are representative of the country as a whole—would tend to confirm that relatively low figure.

Plumes in the Mantle

According to the prevailing geological theory known as plate tectonics, the earth's lithosphere, or rocky outer shell, consists of a mosaic of rigid plates that are in constant motion with respect to one another. New crustal material, in the form of solidified volcanic magma, is generated from the earth's mantle principally at the boundaries of these plates, both at the mid-ocean ridges, where the plates diverge, and at the subduction zones, where they converge, with one plate diving under the leading edge of its neighbor (see "Plate Tectonics," by John F. Dewey; SCIENTIFIC AMERICAN, May). How, then, does one explain the existence of certain volcanic features that lie well within the borders of the stable plates, or cratons, and are clearly independent of the plate boundaries?

A new hypothetical model that attributes such features to the passage of the plates over narrow, stationary "hot spots," or "plumes," of upwelling mantle material that pierce the overlying crust has recently been gaining support. In the plume model, as it is formulated by W. Jason Morgan of Princeton University, most of the upwardly convecting plume material impinges on the bottom side of the lithosphere and spreads out radially. The combination of several such plumes exerting viscous forces on the underside of the lithosphere could therefore be the mechanism that initiates rifting at the mid-ocean ridges and drives the spreading of the crustal plates.

In support of this model Morgan has cited the geometric symmetry of four Pacific Ocean volcanic chains, including the Hawaiian Islands, that could have resulted from the passage of the Pacific plate over four stationary plumes. Now three of Morgan's Princeton colleagues, R. A. Duncan, N. Petersen and R. B. Hargraves, have examined the geological history of two roughly contemporaneous volcanic chains in the European plate and have found additional support for the validity of the stationary-plume model.

Writing in *Nature,* Duncan, Petersen and Hargraves point out that "the passage of a lithospheric plate over mantle plumes should leave surface scars in the form of igneous activity. If the plumes are stationary within the mantle (asthenosphere), the pattern of these scars, on oceanic or continental crust, would be a record of the absolute motion of the plate relative to the asthenosphere. Therefore if cratonic igneous centres are plume scars, they should demonstrate a temporal sequence and a systematic geometry. Furthermore, if polar wander curves are the result of lithospheric plate motion only, and the Earth's magnetic field is and has been a centered, axially symmetric dipole field, then the magnetic polar wander curve for a particular plate should likewise be compatible with its plume trace." If the last test is not met, they add, "then either the assumptions implicit in it are invalid or true polar wander has occurred."

Of the two European volcanic formations studied by the Princeton geologists, one (termed the Thulean plume) traverses both oceanic and continental crust; it consists of three distinct geographic segments, one extending from Iceland to the Faeroe Islands north of Scotland, the second extending from the offshore Scottish island of Skye to the Mourne Mountains in Northern Ireland and the third extending from the Faeroes to Skye. The other volcanic chain (the Eifel plume) is entirely confined within the continent; it extends from the Eifel Mountains in western Germany across Czechoslovakia to Upper Silesia in Poland.

When the traces of the Eifel plume and Iceland-Faeroes segment of the Thulean plume were compared, Duncan, Petersen and Hargraves found that they could derive a common rotation pole "that simulates well both the geometry of these two contemporaneous segments, and their apparent plate motion velocity." A second rotation pole, located perpendicular to this trend, was required to account for the remaining two segments of the Thulean plume scar. The resulting pole positions, however, in both cases were "distinctly removed" from the pole positions indicated by paleomagnetic data from the same sites. After "correcting" the observed paleomagnetic pole positions for the inferred continental drift, the three believe the difference that remains represents "true polar wandering, applicable in principle to the whole Earth."

Although the Princeton group points out that the stationary-plume hypothesis "remains a working one, with many complex and uncertain features," they conclude that "if continental manifestations of plumes can be identified, and conform to the model, then in conjunction with paleomagnetics, it will be possible to unravel plate motions and distinguish true polar wander in times prior to the oldest existing ocean floor."

Razor's Edge

The problem of dealing with the issue of insanity as a defense in criminal cases has proved troublesome for U.S. courts because it is at the interface of medicine, law and ethics. The courts have agreed that a defendant should receive treatment rather than punishment if he was so deranged as not to be responsible for a criminal act, but it has traditionally been difficult for juries to decide whether or not a particular state of mind rendered the defendant incapable of recognizing the criminality of a particular act. Now, in the case of *U.S.* v. *Brawner,* the U.S. Court of Appeals for the District of Columbia has attempted to clarify the matter by adopting as a standard a rule set forth in the Model Penal Code of the American Law Institute. The rule states: "A person is not responsible for criminal conduct if at the time of such conduct as a result of mental disease or defect he lacks substantial capacity to appreciate the wrongfulness of his conduct or to conform his conduct to the requirements of the law."

For many years the courts followed the M'Naghten rule, laid down in a British case in 1843, stating that a defendant should not be held responsible for a criminal act if he was "labouring under such a defect of reason, from disease of the mind, as not to know the na-

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ture and quality of the act." In time the rule came to seem narrow and antiquated, and the District of Columbia court (among others) undertook to improve on it. In *Durham* v. *U.S.* (1954) the court held that "an accused is not criminally responsible if his unlawful act was the product of mental disease or mental defect." In *McDonald* v. *U.S.* (1962) the court defined a mental disease or defect as "any abnormal condition of the mind which substantially affects mental or emotional processes and substantially impairs behavior controls."

In the Brawner case the court abandons the Durham rule while retaining the McDonald definition of mental abnormality. Judge Harold Leventhal, in an opinion representing eight of the nine members of the court, wrote: "A principal reason for our decision to depart from the Durham rule is the undesirable characteristic, surviving even the McDonald modification, of undue dominance by the experts giving testimony. ... The difficulty is rooted in the circumstance that there is no generally accepted understanding, either in the jury or the community it represents, of the concept requiring that the crime be the 'product' of the mental disease."

In a separate opinion Chief Judge David L. Bazelon (who wrote the court's opinion in the Durham case) expressed concern that the change would prove to be "primarily one of form rather than of substance." Acknowledging the failure of the Durham rule, he argued that the new rule will still tend to give expert witnesses the dominant role in cases of insanity defense. "Instead of asking the jury whether the act was caused by the impairment," he wrote, "our new test asks the jury to wrestle with such unfamiliar, if not incomprehensible, concepts as the capacity to appreciate the wrongfulness of one's action, and the capacity to conform one's conduct to the requirements of law." It is the jury's function, he said, to decide on the blameworthiness of the defendant's action as measured by prevailing standards of the community. "In my opinion, an instruction that tells the jurors candidly what their function is, is the instruction most likely to encourage the jurors to resist encroachments on that function."

Turned On

It is widely accepted that hormonal conditions during pregnancy and birth trigger maternal behavior in mammals; nevertheless, until recently it has been difficult to induce maternal behavior in laboratory animals by the injection of hormones. A novel technique for transfusing blood between rats, in this case between a female that has just given birth and a virgin female rat, has been successful in inducing maternal behavior in the virgins. Only blood from mothers that had just given birth induced maternal behavior; blood transfused 24 hours before and after birth was ineffective.

The new method for cross-transfusing blood between freely moving rats was devised by Joseph Terkel and Jay S. Rosenblatt of the Institute of Animal Behavior at Rutgers University. The method involves the continuous transfusion of blood through implanted heart catheters. A connecting disk and post are sutured to the nape of the experimental animal's neck, and a tube extends from the post to a swivel arrangement above the animal's cage. After the rat has become habituated to the apparatus, a heart catheter is implanted through the right jugular vein. The catheter, which extends into the upper chamber of the heart, is connected to the tube through the post. A tube from a similarly prepared second animal also is attached to the swivel. A peristaltic pump shunts blood first in one direction and then in the other. After about three hours nearly 50 percent of the blood circulating in each animal has come from the other animal.

Terkel and Rosenblatt conducted cross-transfusion experiments with four different groups of rats. In the first group blood was transferred between a virgin rat and a mother rat 30 minutes after she had given birth. At the start of the blood exchange five rat pups were placed in the virgin rat's cage. Maternal behavior (licking the pups, retrieving them and allowing them to suckle) was recorded. Normally virgin females will avoid contact with pups for several days, after which they will exhibit maternal behavior. Virgin recipients of blood from females that had just given birth began to exhibit maternal behavior in about 14 hours. The other transfused groups consisted of a virgin rat and a pregnant rat 24 hours before parturition, a virgin rat and a mother rat 24 hours after parturition and two virgin rats. Only an occasional female in these groups exhibited any maternal behavior.

"Cross-transfusion results," Terkel and Rosenblatt write in *Journal of Comparative and Physiological Psychology*, "suggest that it is not the entire sequence of hormonal changes of pregnancy which triggers maternal behavior but rather a particular combination of hormones (or a single hormone, perhaps) that in turn may be the product of the changing hormonal picture of preparturition and early postparturition."

Twilit Desert

Additional knowledge about the cloudy planet Venus has been gathered by the Russian space probe *Venus 8*, which made a soft landing on the planet in July. One of the debates about Venus was whether or not its cloud cover was so thick that sunlight would not be able to penetrate to the surface on the daytime side. *Venus 8* was designed primarily to investigate the levels of illumination at various heights above the planet's surface. It carried a photometer that was sensitive to wide variations in luminosity and gave readings as the probe parachuted through the atmosphere for nearly an hour before landing. The photometer showed that sunlight is greatly attenuated by the atmosphere, but there is a definite difference in illumination between the nighttime side and the daytime side, and that some sunlight does manage to penetrate to the surface on the daytime side.

Although one day on Venus is four earth months long, the average temperature and pressure of the atmosphere does not vary much between night and day. These findings confirmed the data sent back by the earlier probe *Venus 7*, which landed in December, 1970. *Venus 8*, which landed on the planet's illuminated side, recorded the daytime temperature as 470 ± 8 degrees Celsius, and the pressure as 90 ± 1.5 atmospheres. (One atmosphere is the pressure of the earth's atmosphere at sea level, about 14.7 pounds per square inch.) *Venus 7*, which landed on the planet's dark side, recorded the nighttime temperature as 475 ± 20 degrees C. and the pressure as 90 ± 15 atmospheres.

Venus' atmosphere is composed of some 97 percent carbon dioxide. There is not more than 2 percent nitrogen, less than .1 percent oxygen and perhaps 1 percent water vapor close to the cloud layer. Some 20 to 30 miles above the surface the probe detected tiny amounts of ammonia: of the order of .01 percent to .1 percent. Zonal, or latitudinal, winds blow in the direction of the planet's rotation on its axis. Their speeds decline from a recorded 160 feet per second at an altitude of 28 miles to six feet per second at between six and seven miles.

After the probe had landed it continued to return data for another 50 minutes (twice as long as *Venus 7* did in 1970). It analyzed some surface soil with a gamma-ray spectrometer. The

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surface layer appeared to be loose and had a density of somewhat less than 1.5 grams per cubic centimeter. The analysis suggests that the surface of Venus resembles granitic rocks on the earth. The spectrometer revealed that the surface contained 4 percent potassium, .002 percent uranium and .00065 percent thorium. The rocks seem similar to terrestrial rocks that have been heavily modified by various factors after emerging in molten form.

Sweet and Sour

Sugar is sweet and most people find sweetness attractive; sugar is generally accepted as a desirable food or food additive, quite innocuous except for the fact that too much of it may promote obesity or dental caries. For some years John Yudkin of Queen Elizabeth College at the University of London has proposed a hypothesis that sugar may, on the contrary, be dangerous: that its ingestion in the large quantities now characteristic in affluent Western societies is nutritionally harmful and may actually cause disease. He has summarized his argument and evidence in a recent article in *Nature*.

Yudkin points out that the average per capita intake of sugar (sucrose) in Western countries is now more than 100 pounds per year, constituting perhaps 15 or 20 percent of the energy value of the diet (in Britain, for example, a higher percentage than is provided by bread and flour, by meat, poultry and fish or by milk, cheese and eggs). Sucrose calories are uniquely "empty calories," barren of nutrients, he observes, so that "we should be more concerned about the displacement of nutritious foods by sugar" than about nutritionally harmful food-processing methods.

In addition to reviewing evidence connecting sucrose with such disorders as obesity, caries, dyspepsia, gout and maturity-onset diabetes, Yudkin considers heart disease in particular. Animal studies associate sucrose with an increase in blood triglyceride and sometimes cholesterol, and with accelerated maturation of the adrenal glands. In young men a high-sucrose, low-starch diet increases the triglyceride and cholesterol level and in some cases also the level of the hormone insulin; the rise in insulin is sometimes accompanied by an increased level of corticosteroids, which are secreted by the adrenal cortex. Increased levels of insulin and of triglycerides and cholesterol have often been associated with atherosclerotic heart disease; the hard questions have to do with cause and effect. Yudkin suggests that the changes observed in atherosclerotic disease "are likely to be the results of interrelated hormonal changes, induced by sucrose and other agents."

The diseases he connects with sucrose ingestion may appear to be disparate in nature, Yudkin concedes. Yet a relation is accepted among obesity, diabetes and coronary disease and also among gout, peptic ulcer and coronary disease. "Each of these diseases has several causes, and if dietary sucrose is one of them," just such a slight relation among them all would be expected. Yudkin concludes that what most seriously calls into question the assumption that sucrose is innocuous is its profound effect on the secretion of certain hormones, notably insulin and the corticosteroids.

White Overnight

The statement "His hair turned white overnight" expresses a durable belief of folklore. Indeed, history records several examples of the phenomenon, allegedly at times of severe stress. Sir Thomas More is said to have turned white when, after long imprisonment, he was at last sentenced to death. The same is said of Marie Antoinette following her capture while attempting to flee France, and of the British general Charles George ("Chinese") Gordon during the siege of Khartoum. In addition to such anecdotes contemporary medical observations include authenticated instances of premature whitening. What accounts for it?

Addressing the question in the *Bulletin of the New York Academy of Medicine*, J. E. Jelinek finds little evidence in support of the view that such changes can occur overnight. He notes, however, the existence of a not uncommon form of baldness: alopecia areata. The condition selectively destroys pigmented hair but leaves unpigmented hair largely unaffected. Moreover, after an attack the new hair that appears in the bald areas is usually unpigmented.

Jelinek suggests that Marie Antoinette's white hair may be attributable not to alopecia areata but to the unavailability of hair dyes during her imprisonment. The anecdote about Gordon, however, may represent an authentic attack of the disease. Before Khartoum was besieged Gordon's beard and hair were flecked with gray. If a person with such a mixture of pigmented and unpigmented hair should lose the pigmented hair over a period of days or weeks, Jelinek points out, he would indeed turn white.

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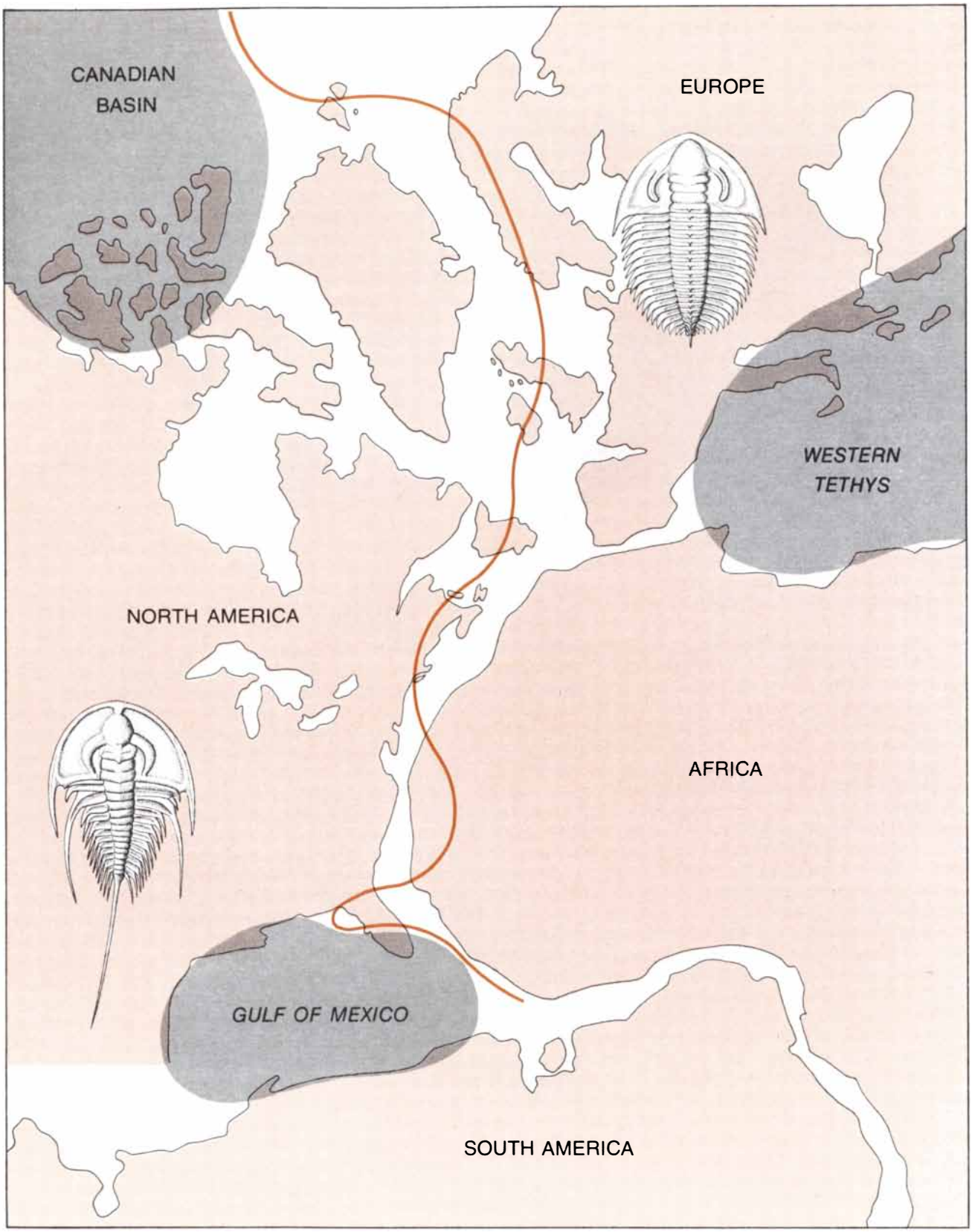

DISAPPEARING ATLANTIC of some 400 million years ago may have been reduced to two comparatively minor bodies of water: the Canadian basin and the Gulf of Mexico. The broad colored line divides regions that are connected today, such as the Scandinavian peninsula, the British Isles and parts of eastern North America. It marks the boundary between faunal realms that were distinctly different in Cambrian and early Ordovician times. A fossil typical of each realm is illustrated. The American form is the trilobite *Paedeumias transitans;* the European form is the trilobite *Holmia kjerulfi.* The difference between the two realms grew progressively less, and by the middle of the Paleozoic era it had vanished. Convergence of the two faunas suggests that what had once been a wide, deep proto-Atlantic was swallowed up along zones of subduction as American and European continental plates came together.

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Continental Drift and the Fossil Record

Similarities between the fossils found in widely separated areas led to the first theories of continental drift. Today's advocates of plate-tectonic theory are also supported by the fossil record

by A. Hallam

In the past 10 years geologists have been widely converted to plate tectonics, a concept that implies the lateral migration of the continents. If Alfred Wegener, who put forward the hypothesis of continental drift around the turn of the century, were alive today, he might be wryly amused. The workers who revitalized his conception paid comparatively little attention to the evidence in its favor provided by fossils. Yet by Wegener's own account he began to take the idea of drifting continents seriously only after learning of the fossil evidence for a former land connection between Brazil and Africa. The fossil record, rather than the much noted physical "fit" between the opposing coastlines, was what inspired him.

The fossil record is no less important to students of continental drift today. The similarities and differences between fossils in various parts of the world from Cambrian times onward are now helping paleontologists both to support the drift concept and to provide a reasonably precise timetable for a number of the key events before and after the breakup of the ancestral continent of Pangaea.

In Wegener's day there was nothing particularly novel about the idea that the various continents had been connected in various ways off and on in the distant past. Biologists and paleontologists in the 19th century and in the early 20th readily invoked such land connections to explain the strong resemblances between plants and animals on different continents. It was generally agreed that links had existed between Australia and other regions bordering the Indian Ocean until early in the Jurassic period, some 180 million years ago. The same was held to be true of a link between Africa and Brazil until early in the Cretaceous period, some 140 million years ago, and a link between Madagascar and India up to the start of the Cenozoic era, only 65 million years ago.

At the same time the orthodox explanation of these connections was that the position of the continents was fixed but that "land bridges" had spanned the considerable distances of open ocean between them. In the orthodox view these extensive bridges had later sunk without a trace [*see upper illustration on page 59*]. Wegener dismissed such explanations in trenchant terms. The earth's crust, he pointed out, is composed of rocks that are far less dense than the material of the earth's interior. If the floors of the oceans were paved with vast sunken bridges composed of the same thickness of light crustal material as the continental areas that lie above sea level, then gravity measurements made at sea should reveal that fact. The gravity measurements indicate the exact opposite: the underlying rock of the ocean floor is much denser than the crustal material of the continents.

The essential improbability of sunken land bridges can also be stated in terms of isostatic balance. If the low-density crustal rocks of the vanished bridges had indeed been somehow forced downward into the denser sea bottom, the bridges would tend to rise again. None of the hypothetical land bridges, however, has reemerged. This makes it necessary to assume the existence of some colossal unspecified force that continues to hold the bridges submerged. The existence of such a force seems improbable in the extreme. Unless one chose to dismiss the fossil evidence out of hand, Wegener concluded, the only feasible means of explaining intercontinental plant and animal resemblances was by the drifting of the continents themselves.

It is odd that neither paleontologists nor geophysicists paid much heed to Wegener's cogent argument. The paleontologists were almost unanimous in rejecting the notion, perhaps because they did not fully appreciate the force of Wegener's geophysical proposals. The main effect of his hypothesis on this group was that quite narrow land bridges became more popular than the embarrassingly broad avenues that had been favored at the turn of the century [*see lower illustration on page 59*]. Of course even when the bridges were pared down in this fashion, serious isostatic problems remained. As for the geophysicists, they largely ignored the considerable body of fossil evidence for continental drift that Wegener had assembled. Perhaps they failed to appreciate its significance or perhaps they mistrusted data of a merely qualitative kind and were suspicious of the seemingly subjective character of taxonomic assessments.

The Zoogeography of the Past

In recent years there has been a major resurgence of interest in the zoogeography of the past. This is no doubt due in part to the prospect that fossil evidence will enable paleontologists to test independently the conclusions that have been reached on purely geological and geophysical grounds about plate tectonics. Here I shall describe how some of this evidence, in particular the remains of higher animals on land and of simpler bottom-dwelling marine organisms offshore, can shed light on the making and breaking of connections between continents in the past and can help to determine how long some of these continental linkages and separations endured.

Two principal factors control the geo-

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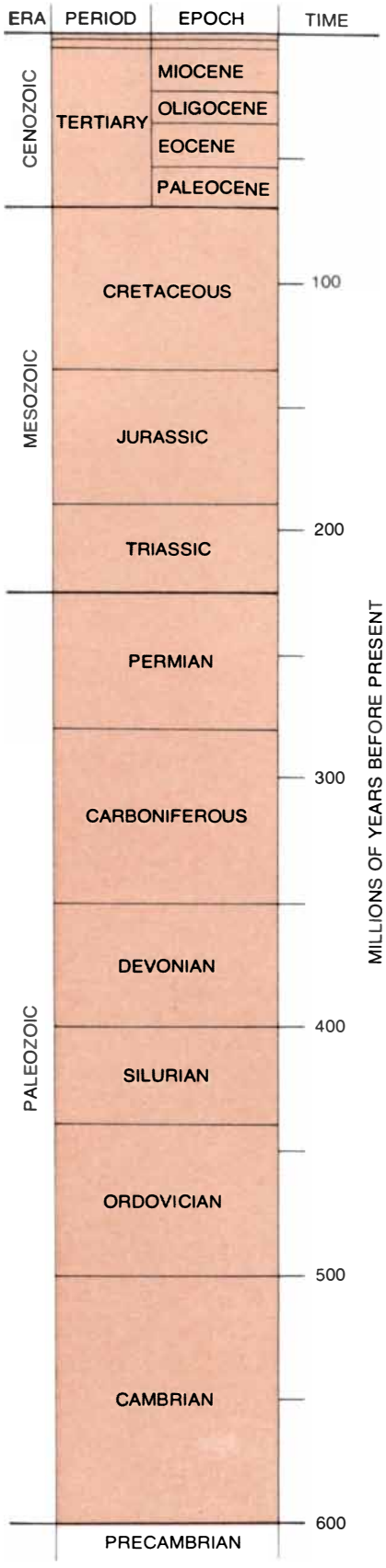

THREE SUCCESSIVE ERAS occupy the 600-million-year span seen in this geological time scale. Patterns of distribution found in the fossil record of each era throw light on plate-tectonic theory of continental drift.

graphical distribution of land animals. They are on the one hand the climate and on the other various water barriers and in particular wide stretches of sea. The effectiveness of climate as a barrier is nicely illustrated by the fact that the animals that live near the poles are far less diverse than those that live in the Tropics. Polar ice, however, is not a permanent feature of the planet. In times of a more equable world climate such as prevailed during the Mesozoic era far and away the most significant deterrents to movement must have been ocean barriers.

An animal need not be exclusively terrestrial to be confined by an ocean barrier. For example, a large number of fishes cannot survive except in fresh water. Amphibians are also severely circumscribed by the sea, although frogs are better able to colonize islands by swimming across the sea than newts or salamanders. As for the probability that reptiles or mammals might successfully move across the sea by accidental rafting, the chances are obviously best for the small and the rapidly reproducing. By the same token, however, the small animals are the very ones that would first die of starvation if the rafting were prolonged. Hence even fairly narrow marine straits can be highly effective barriers to terrestrial animals.

The paleontologist George Gaylord Simpson has made a useful distinction between three kinds of dispersal route. The first, which he calls "corridors," are land connections that allow free migration of animals in both directions. The second, called "filter bridges," combine a land connection with some additional factor, such as climate, in a way that bars some prospective migrants. As an example, it seems doubtful that warm-weather-loving animals crossed the Bering Strait bridge between Asia and North America during the Pleistocene. The passage was open only when the sea level was low during the colder phases of that glacial epoch.

Simpson's third category, "sweepstakes routes," takes its name from the small proportion of winners compared with losers. The rare winners are those that survive chance rafting and succeed in colonizing isolated areas. Unlike corridors (or even filter bridges), which favor the eventual homogeneity of the faunas at both ends of the passage, sweepstakes routes lead to the development of populations that are low in diversity and ecologically unbalanced. The reason is that, in addition to the high mortality rate, chance rafting can only be possible for a very small fraction of any continental fauna. One result of this double selectivity is that islands are often a refuge for a comparatively primitive group of animals. The tuataras of New Zealand, the sole surviving representatives of one major order of reptiles, are one example; the lemurs of Madagascar are another.

The three routes Simpson defines are the ones that are available to land animals in general and to the higher vertebrates in particular. It is obvious, however, that the same kinds of connection would also influence the dispersal of marine organisms such as bottom-dwelling invertebrates. Of course, the effects would be exactly reversed. For example, the establishment of a corridor between two landmasses would simultaneously raise a barrier between two segments of a previously homogeneous marine fauna. The disappearance of a land connection, in turn, would result in the establishment of a corridor as far as marine organisms were concerned. Analogous to the filter bridge for land animals would be the marine "filter barrier." Here a bottom-dweller on one side of an ocean basin might migrate freely to the other side as long as it could drift in tropical waters, but it would be unable to survive the rigors of such a journey in the cooler waters of the temperate zones.

Isolation and Homogenization

Bearing these considerations in mind, what does evolutionary theory predict with respect to continental drift? Clearly when a formerly unified landmass splits up, the result is genetic isolation (and hence morphological divergence) among the separated segments of a formerly homogeneous land fauna. Conversely, the suturing of two continental areas is followed by the homogenization of the corresponding faunas as there is cross-migration. The process will quite probably be accompanied by the extinction of any less well-adapted groups that may now face stronger competition.

In land areas that are unconnected two factors, parallel evolution and convergence, may produce animal species that develop a similar morphology because they occupy identical ecological niches. A well-known instance is provided by the ant bear of South America, the aardvark of Africa and the cosmopolitan pangolin. Forces of this kind are unlikely, however, to affect entire faunas.

So much for the land animals. What are the effects of continental drift on the invertebrates that inhabit the shal-

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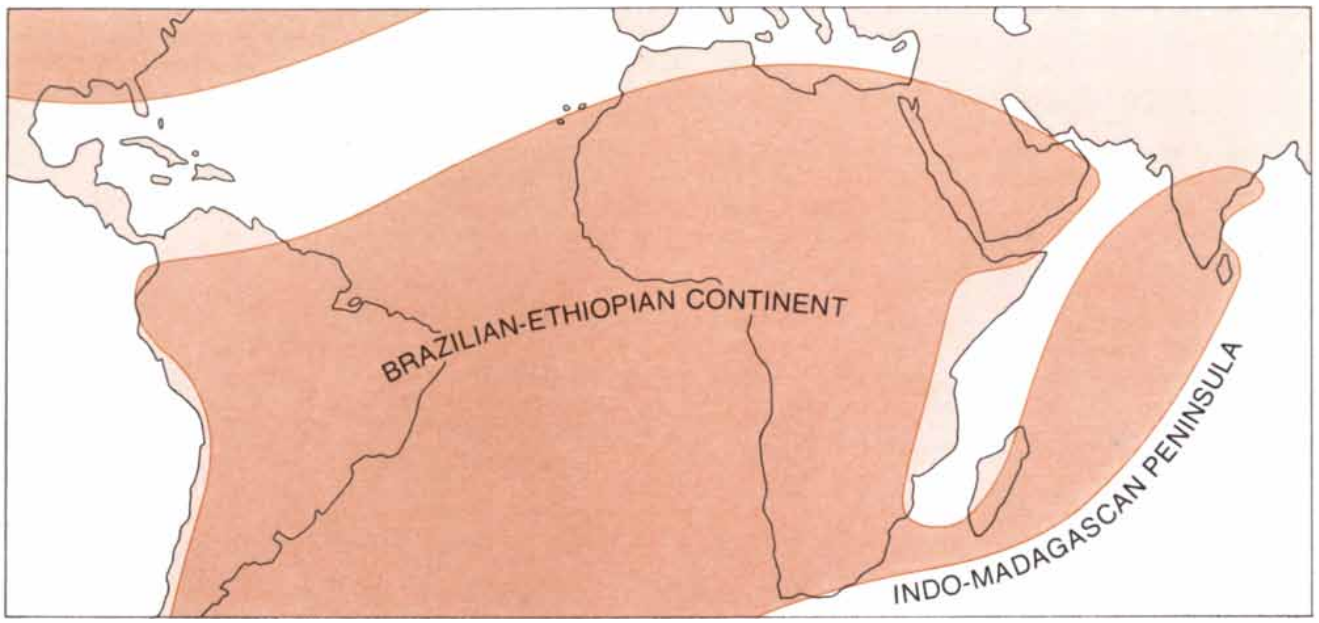
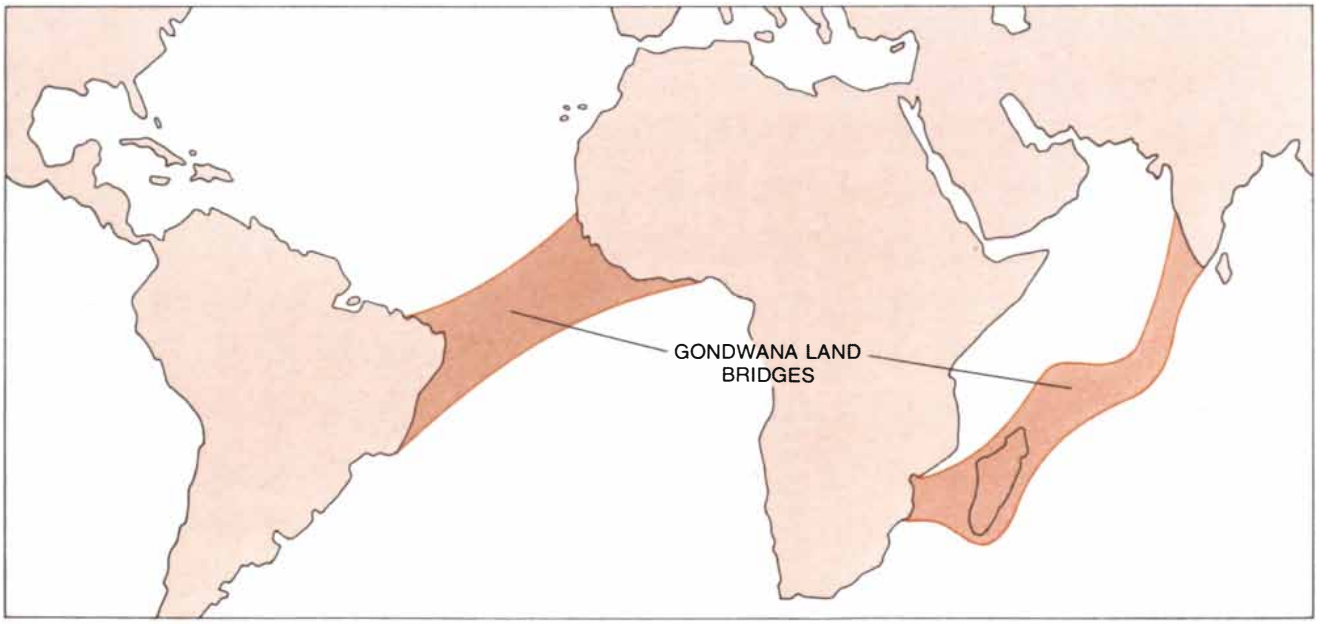
low ocean floor? It is obvious that a stretch of land that separates two oceans acts as a barrier to marine migration. It is less well appreciated that a wide stretch of deep ocean may be almost as effective as a land barrier in preserving the genetic isolation of the marine shelf dwellers on opposite shores. This isolation is due to the fact that such animals disperse at only one time in their life cycle: when they are newly hatched larvae that join the plankton community at the ocean surface or close to it. A bottom dweller's larval stage is normally not long enough to enable the animal to survive a slow ocean crossing.

This matter was quantified some time ago by the Danish biologist Gunnar Thorson. He studied the larval stages of no fewer than 200 species of marine invertebrates, and he concluded that only 5 percent could survive in the plankton for more than three months. That length of time is too short to allow transoceanic colonization except by an occasional "transport miracle." More recently Thorson has been criticized for confining his attention to organisms that inhabit cool temperate waters. New data gathered by towing fine nets through the plankton indicate that a significant number of larvae of tropical species can survive an Atlantic crossing in either direction; they drift with the equatorial surface current one way and with the subsurface countercurrent the other way. It is also true



GRANDIOSE BRIDGE-BUILDING was the custom late in the 19th century when biologists and paleontologists sought to explain the strong similarities between the fossil records of different continents. This Mesozoic bridge between South America and Africa, proposed in 1887, is nearly as big as the two continents it links. It was thought to have sunk without a trace early in the Cretaceous.



MORE MODEST BRIDGES were proposed in the 20th century as geophysical studies found no evidence in support of vast drowned intercontinental connections. This pared-down link between Brazil and West Africa and another (supposedly in existence until the end of Cretaceous times) between East Africa and India represent an effort to satisfy those who were critical of the broader bridges.

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that some mollusks and some corals are found everywhere in the Tropics, a fact that gives added support to the notion that transoceanic migration is possible for long-lived larvae. At the same time it is possible that organisms with prolonged larval stages represent a late evolutionary development that has taken place only since the present Atlantic and Indian oceans began to open up.

Be this as it may, it is evident that, although Thorson's conclusions must be somewhat amended, an ocean barrier is effective in restricting the migration of a majority of the shelf-dwelling marine invertebrates. Moreover, the capacity for migration being in direct proportion to the length of the larval stage, it follows that the wider the deep-ocean barrier is, the more the faunas of the opposing shelves should differ. That is true today. There are fewer species in common among the faunas on opposite sides of the Pacific than there are on opposite sides of the Atlantic. Therefore among marine fossil faunas the degrees of similarity or difference between two coastal assemblages should allow an estimate of the amount of deep-ocean separation between the two coasts.

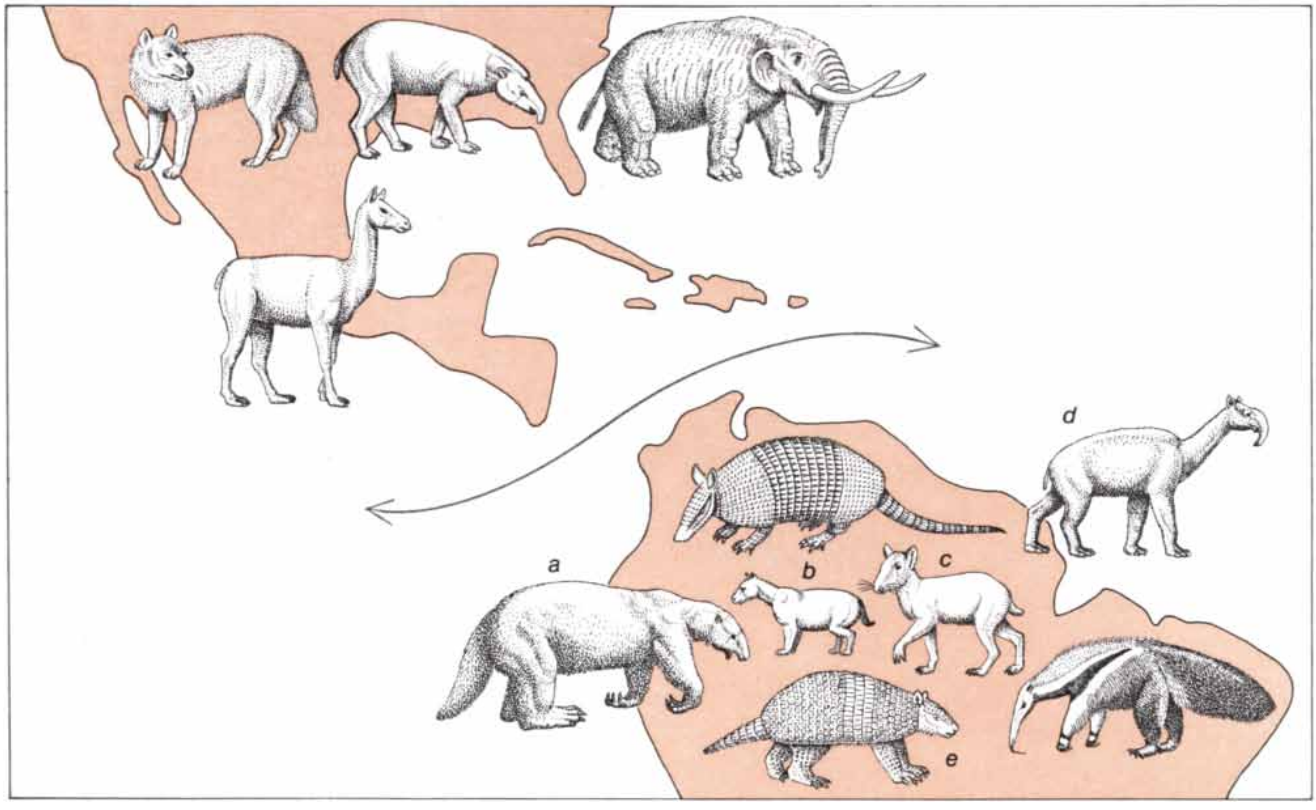
Given the present state of knowledge, it would be futile to seek any absolute measure of similarity between fossil faunas. If, however, one adopts a dynamic approach and deals with changes in the degree of resemblance during successive intervals of geologic time, a fair amount of progress can be made. Such an approach has several advantages. For one, animals belonging to widely separated phyla can be grouped together. For another, the specific factors that control a particular species' migration potential need not be precisely understood. Further, one can use the work of many different taxonomists, without regard to whether they are "lumpers" or "splitters" in their method of classification, as long as the work is self-consistent. Best of all, the approach takes fully into account the factor that is all-important to the geologist: the factor of time.

The Distribution of Fossils

There are four principal patterns revealed by the distribution of fossils. They are closely interrelated and I shall define them in order, accompanying each definition with one or more examples. All the examples will concern the making or breaking of land or sea connections, but not all will be the result of continental drift.

The first pattern is "convergence." The term describes an increase, as time passes, in the degree of resemblance between faunas of different regions. An example unrelated to continental drift is provided by the history of South America during the Cenozoic era, beginning some 65 million years ago. Throughout most of the era South America had a highly distinctive land fauna [*see illustration below*]. The fossil mammals from Cenozoic formations in Argentina were among the most spectacular finds of Darwin's voyage aboard H.M.S. *Beagle*. The strongly endemic nature of this fauna, comparable in this respect to the fauna of Australia today, is clear evidence that the continent was isolated for many millions of years.

At about the end of the Pliocene epoch, two million or so years ago, a drastic change took place. A land connection—the Isthmus of Panama—was established between North and South America and many New World animals



DIVERGENCE OF MAMMALS in the New World occurred during a period of millions of years when North and South America were unconnected. Mammals then unknown in the south included mastodons, tapirs, primitive camels and various carnivores. The mammals of the south included many that are now extinct. Illustrated here are (*a*) *Mylodon*, a giant sloth, (*b*) *Paedotherium*, a notoungulate, (*c*) *Prodolichotis*, a rodent, (*d*) *Macrauchenia*, an ungulate, and (*e*) *Plaina*, an early relative of the more successful armadillo.

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that had been unable to move south now crossed the bridge. Among them were the mastodon, the tapir, primitive camels and a number of carnivores. Simultaneously many of the indigenous South American faunas became extinct; the losers included all but two genera of the many primitive marsupials that had been sheltered there and were evidently incapable of competing with the better-adapted migrants from North America. The traffic was not, however, entirely one-way. Armadillos soon extended their range northward throughout Central America and into the southern U.S. [*see illustration below*].

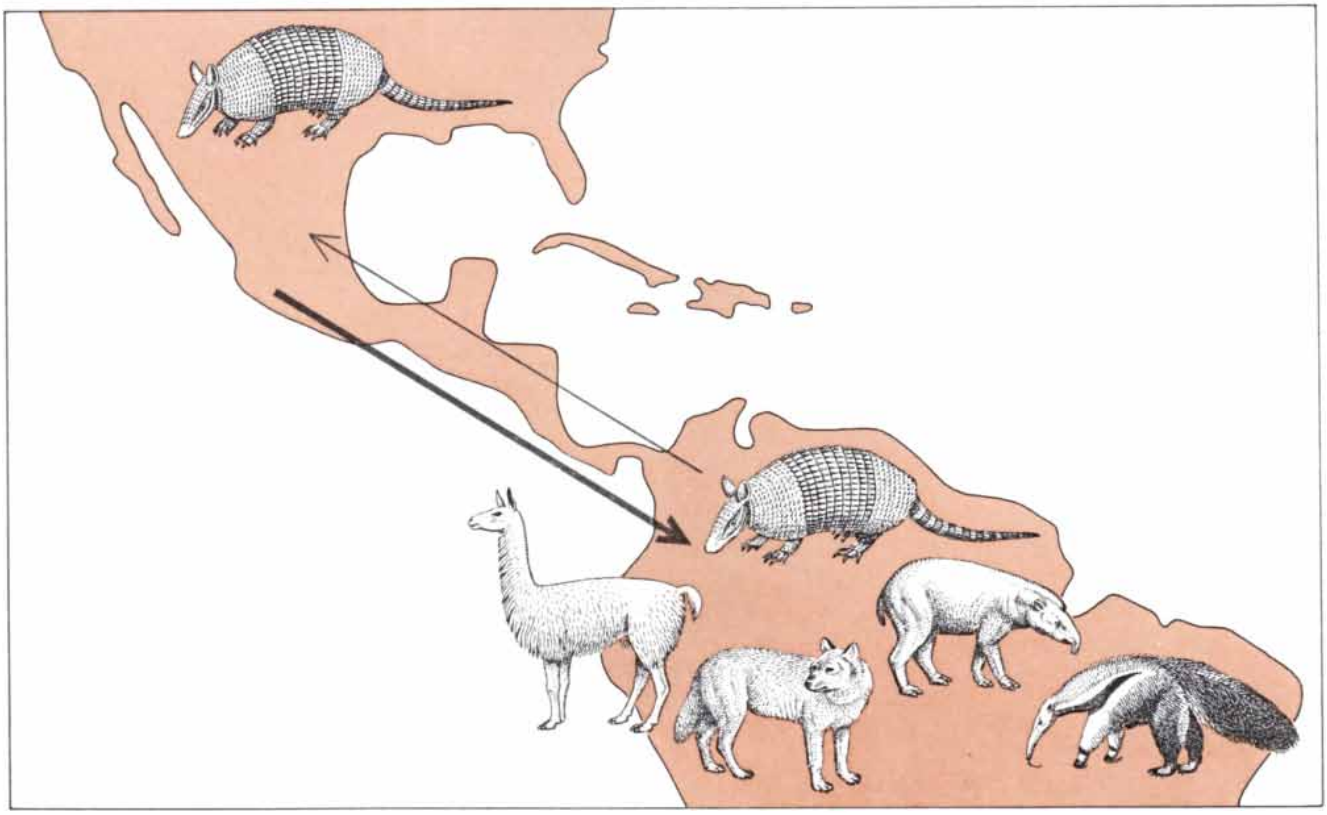
Simpson has estimated that before North America and South America were united perhaps 29 families of mammals lived in the area south of the Isthmus of Panama and perhaps 27 entirely different families of mammals lived to the north. After the union the faunas of both continents had 22 families of mammals in common. This is a particularly dramatic example of convergence, even though the establishment of the Panama bridge seems to have owed nothing to continental drift.

The mammalian fauna of Africa during the Cenozoic era provides another example of convergence. Up to some 25 million years ago the African fauna had a strong endemic element. The animals ancestral to the living elephants, the manatees and the hyrax were found only there. This suggests that the continent had been isolated for a substantial period.

Early in the Miocene epoch a number of mammals from Eurasia entered Africa by means of one or more land connections. The migration led to the reduction and even the extinction of some of the indigenous African fauna. At the same time the ancestral elephants crossed over to Eurasia and had soon spread around the world. Less than 25 million years later mastodons were waiting at the emerging Isthmus of Panama to enter the last major continental area in the world still barred to the proboscoids. The Miocene bridge-building that allowed a substantial degree of convergence between the faunas of Africa and Eurasia can be attributed to continental drift, specifically a northward movement of the Africa-Arabia plate.

A third example of convergence takes us all the way back to the Cambrian and early Ordovician periods, some 500 to 600 million years ago. The most spectacular marine organisms of the Cambrian, the early arthropods known as trilobites, turn out to be sharply separated into two distinct faunas; the line that divides the two faunal provinces runs through eastern North America and through the British Isles and Scandinavia [*see illustration on page 56*]. Over the next 75 million years or so, during late Ordovician and Silurian times, the two trilobite faunas tend to lose their regional distinctiveness. So do a number of other early marine invertebrates: corals, brachiopods, graptolites and conodonts. So do two groups of early freshwater fishes: primitive jawless ostracoderms belonging to the orders Anaspida and Thelodonti. Freshwater fishes are, of course, prisoners of the continental streams they inhabit. By late Silurian or early Devonian times, some 400 million years ago, only one faunal province existed in the North Atlantic region.

The paleontologist A. W. Grabau noted the difference between the trilobites of adjacent areas many years ago, and he suggested that the sharp delineation might be attributable to the former



CONVERGENCE OF MAMMALS began about the end of the Pliocene epoch, after a land bridge was established between North and South America. One mammal native to South America, the armadillo, migrated northward. So many mammals formerly unknown south of Panama moved to South America, however, that the two continents soon came to have 22 families of mammals in common. At the same time many South American mammals were unable to compete with the immigrants from the north and became extinct.

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existence of a deep-ocean barrier. More recently J. Tuzo Wilson of the University of Toronto followed up Grabau's suggestion and proposed that the border between the two faunal provinces marked the closure of a proto-Atlantic ocean that was eliminated by continental drift in Paleozoic times. Since then John F. Dewey of the State University of New York at Albany has developed this concept with considerable success in terms of plate tectonics and subduction: the process in which the leading edge of a drifting plate is destroyed by plunging under another plate [see "Plate Tectonics," by John F. Dewey; SCIENTIFIC AMERICAN, May].

Dewey's view, which is based primarily on geological grounds, envisions the loss of an ancient segment of ocean down one or more zones of subduction as an American and a European plate drifted together. Compression and subsequent uplift in the region of subduction formed the Caledonian mountain belt in northwestern Europe and the "old" Appalachian Mountains in eastern North America. The record of faunal convergence in the interval between Cambrian and Devonian times evidently reflects the steady narrowing of the proto-Atlantic, a process that continued for tens of millions of years until most of the ancient ocean was swallowed up. Here we have an example of the fossil record supporting a reconstruction of a drift episode that has been independently inferred from geological data.

The Case of the Urals

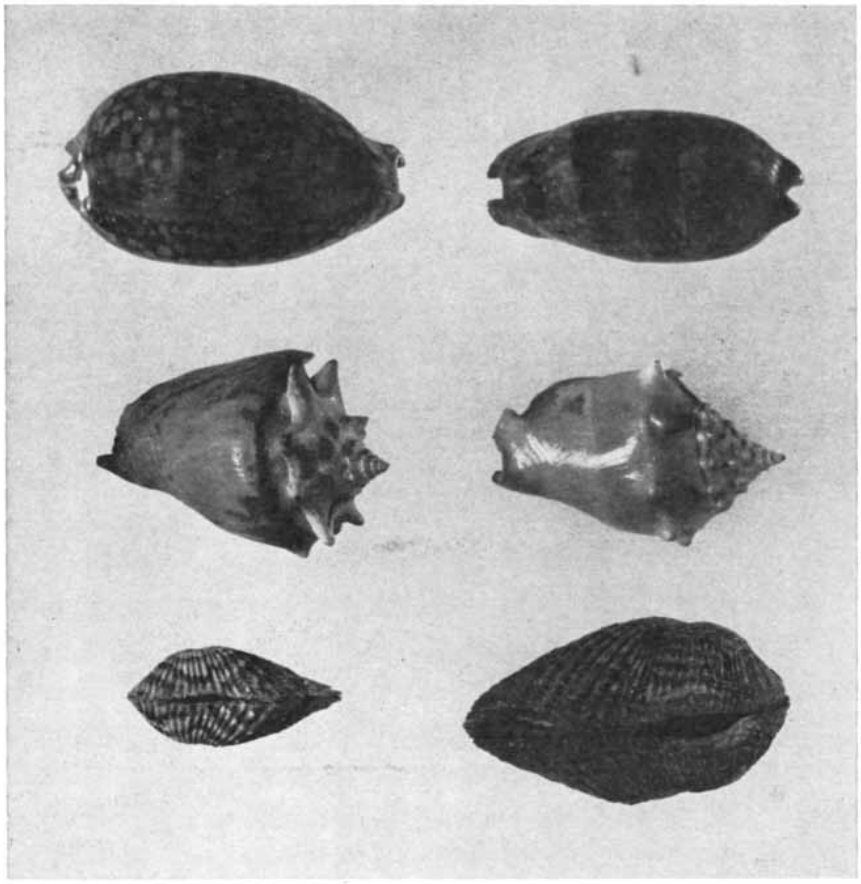
The Caledonian belt is not the only ancient mountain range that hints of a collision between two drifting plates. The Urals, the mountains that separate the European and Asiatic parts of the U.S.S.R., have also been interpreted as a collision feature on geological grounds. Let us see whether the fossil record supports this interpretation.

In Devonian times an order of jawless freshwater fishes, cousins to the orders that once flourished on opposite sides of the proto-Atlantic, inhabited the streams of the region that is now the European and Asiatic flanks of the Urals. These fishes are the Heterostraci. Specimens of the order from fossil formations on the European side of the Urals clearly belong to a faunal province that is distinct from the province on the Asiatic slope. It follows that, at least during the 50 million years of Devonian times, a marine barrier separated the two landmasses that now meet in the Urals.

There is negative evidence to suggest that the same barrier persisted during the succeeding interval: the Carboniferous period. Fossil deposits of Carboniferous age in the European U.S.S.R. contain the remains of amphibians and reptiles. In spite of more than a century of prospecting, however, no Carboniferous amphibians or reptiles have been found in the Asiatic U.S.S.R. Yet 50 million years later, at the beginning of the Mesozoic era, the amphibians and reptiles of Asia closely resemble those found elsewhere in the world. Evidently by that time land connections between the two regions were firmly established.

Does this array of fossil evidence, which seems very much like the evidence for a proto-Atlantic, show that the Urals are indeed the products of continental drift? Not necessarily. A further example will show why. Early in the Cenozoic era the mammals of Europe comprised a fauna that was different in many respects from the mammalian fauna of Asia. This was not, however, because two continental plates had drifted apart. Instead the regions were separated at that time by the intrusion of a long arm of shallow sea. As far as land animals are concerned, a shallow sea is quite as effective a barrier as a true deep-ocean basin. How do we know that the separation of the two regions in Paleozoic times was not a similar shallow sea?

Examination of another fossil group, the bottom-dwelling marine invertebrates, should enable us to resolve this question. If a deep-ocean basin separated the European and Asiatic parts of the U.S.S.R. in Paleozoic times, then the wider that ocean was, the more divergent the invertebrate fossils on opposite sides of the Urals should be. Unfortunately, when we apply this test, the existing data prove to be somewhat indecisive. Still, the weight of evidence seems to suggest that the Paleozoic marine gap between Europe and Asia was not very large. This fossil finding suggests that, if continental drift formed the



THREE PAIRS OF MOLLUSKS, each pair belonging to the same genus but to different species, exemplify the divergence that marine animals undergo when a barrier divides a once uniform fauna. The cowries (*top*) are of the genus *Cypraea;* the Caribbean species, *C. zebra* (*left*), has diverged from the Pacific species, *C. cervinetta* (*right*). The same is true of a second gastropod pair (*middle*), both of the genus *Strombus,* and the bivalve pair (*bottom*), both of the genus *Arca*. Divergence began when the Isthmus of Panama arose.

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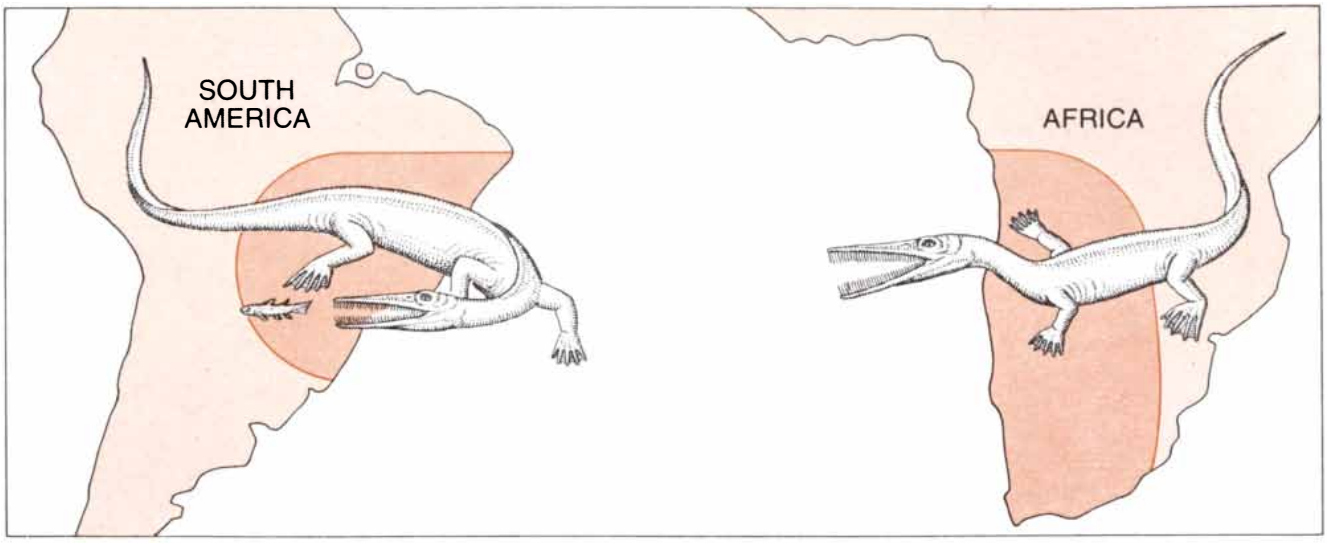

FOSSILS OF MESOSAURUS, a late Paleozoic reptile seen in a restoration here, are found on both sides of the South Atlantic and nowhere else in the world. If *Mesosaurus* was able to swim well enough to cross the ocean, it should have diffused far more widely. Since it did not, this example of "disjunct endemism" suggests that South America and Africa must have been joined at that time.

Urals, the ocean that disappeared as a consequence was a narrow one.

The Pattern of Divergence

We can now consider the second principal pattern of fossil distribution. This is "divergence," which is simply the reverse of convergence. To illustrate the pattern I shall use three examples drawn from the Cenozoic fossil record and one from the Mesozoic. The first is the late Cenozoic rise of the Isthmus of Panama that, as we have seen, allowed the convergence of the land faunas of North America and South America. Simultaneously the rise cut in two a marine region that until then had been inhabited by a homogeneous population of bottom-dwelling invertebrates. The consequence of this genetic isolation was divergence; during the Pleistocene epoch a number of "twin" species, the descendants of identical but isolated genera of marine invertebrates, have evolved independently on opposite sides of the isthmus.

The second example concerns the invertebrate faunas of the Tethys seaway, an ancient span of ocean that in early Cenozoic times reached all the way from the Caribbean, by way of the Mediterranean basin, to the western shores of Indonesia. Throughout this vast region in early Cenozoic times the invertebrate faunas were markedly homogeneous. Beginning about 25 million years ago, however, during the Miocene period, the homogeneity of the Tethys faunas was abruptly disturbed. Thereafter the marine invertebrates of the Indian Ocean differed sharply from those of the Mediterranean. And whereas the faunas of the Mediterranean continued in general to resemble the faunas of the Atlantic, there are indications that some groups, in particular bottom-dwelling foraminifera, also began to show divergence.

The land animals of the Cenozoic era provide the third example. During that era the fossil faunas of the various continents, the mammals in particular, differ in many respects. The most obvious differences are evident in Australia, South America and Africa—the continents of the Southern Hemisphere. During the preceding Mesozoic era, in contrast to this Cenozoic pattern of divergence, the land-dwelling animals (most of them reptiles) were quite homogeneous irrespective of their continued residence. The Cenozoic pattern of divergence is the inevitable consequence of the breakup of Pangaea in late Mesozoic times.

Two groups of late Mesozoic marine invertebrates yield a fourth example of divergence. They flourished during the Cretaceous period, when the breakup of Pangaea was well under way. When one compares certain species of bivalves and foraminifera from fossil strata of the lower Cretaceous in the Caribbean with similar organisms in the Mediterranean region, the two faunas prove to be very much alike. By late Cretaceous times, however, new genera of bivalves and foraminifera have appeared that are unique to one or the other of the formerly homogeneous regions.

This late Cretaceous divergence conforms with the inference, drawn from geological and geophysical data, that the final period of the Mesozoic era witnessed a progressive enlargement of the deep-ocean separation between the Mediterranean and the Caribbean. To the north of the Tropics in the newborn Atlantic a sea-shelf connection between the Old World and the New persisted, but there is little doubt that the diverging marine faunas (including the rudists, a peculiar group of reef-building bivalves) were unable to migrate in any but warm waters and were thus inhibited from crossing from one side of the Atlantic to the other through the cool shelf sea.

The Pattern of Complementarity

I term the third of the patterns of fossil distribution "complementarity" because the faunas in adjacent areas of shore and ocean shelf react to alterations of the environment in a complementary way. For example, when a land connection forms, the newly united land faunas tend to converge and the newly divided marine faunas tend to diverge, whereas the breaking of a land connection gives rise to the opposite effect. The pattern of complementarity is significant because it provides a cross-check on interpretations of the fossil record that depend exclusively on either the marine faunas or the terrestrial ones.

One additional example will suffice to define complementarity. As we have already noted, there is evidence from the Miocene of divergence among the

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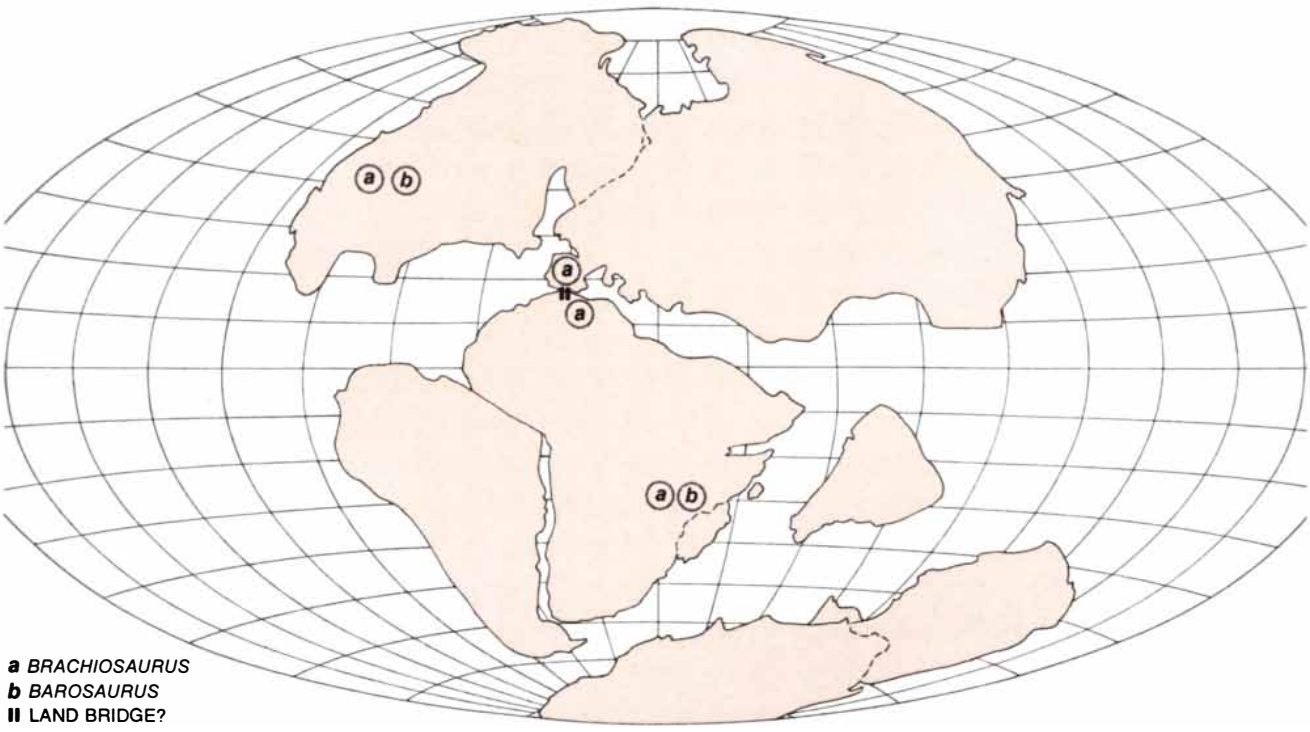
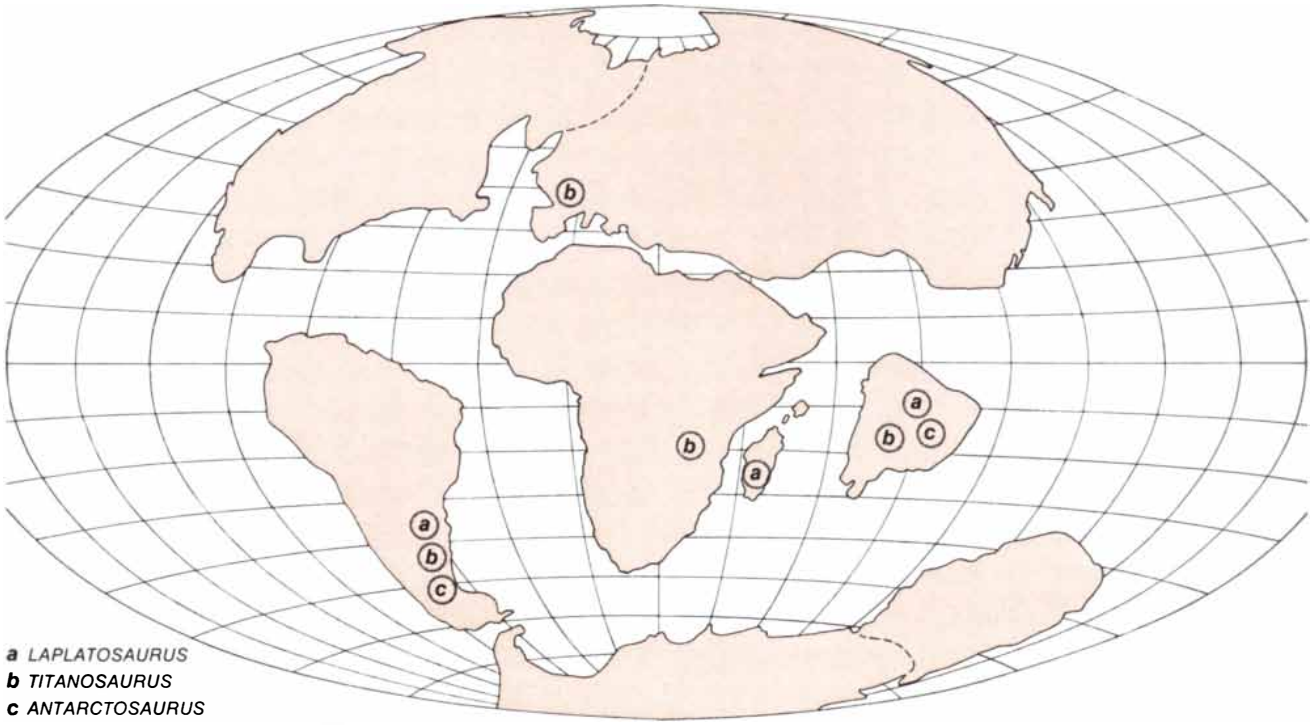


FOSSIL-RICH STRATA that contain the remains of two genera of late Jurassic dinosaurs are located in western North America and in East Africa respectively. Fossils of one genus (*a*) are also found in Portugal and Algeria. At that time the ancient world continent, Pangaea, had broken apart; its components are shown here at the positions calculated by Robert S. Dietz and John C. Holden of the National Oceanic and Atmospheric Administration. Unless a land bridge existed in the late Jurassic where North Africa and Spain nearly touch, the presence of identical fossils on separate continents is another example of disjunct endemism. But where the bridge should be there are oceanic rocks of Jurassic age instead, making the existence of a land connection at that time improbable.



SIMILAR DILEMMA is posed by the disjunct endemism of three genera of late Cretaceous dinosaurs. All three genera are present in fossil formations in South America and in India. One genus (*b*) is also present in both Europe and Africa and another (*a*) is also found in Madagascar. The map shows the various continents in the positions calculated for the late Cretaceous by Dietz and Holden. By that time, students of continental drift generally agree, India had moved well away from the Africa-Arabia plate, continuing a trend that supposedly first isolated the drifting subcontinent some 100 million years earlier. Unless the dinosaur fossil identifications are mistaken, however, the land connection between India and South America could scarcely have been severed at so early a date.

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marine invertebrates along the length of the Tethys seaway on the one hand and of convergence among the land mammals of Africa and Eurasia on the other. It appears that this pattern of complementarity in the Miocene fossil record signals the withdrawal of the Tethys seaway from the region of the Near East and Middle East. From the viewpoint of plate tectonics the withdrawal of the Tethys must have been a consequence of the Africa-Arabia plate impinging on Eurasia. The fossil evidence is thus in accord with the geological evidence of compressive, generally north-south earth movements and mountain uplift in southern Spain, Turkey and Iran in Miocene times.

There is also geological evidence of compressive tectonic activity in the Near East and Middle East in late Cretaceous times, some 50 million years earlier. This episode could not, however, have eliminated the Tethys seaway; the fossil record shows no matching record of complementarity in the late Cretaceous. When the story of the faunal migrations between Europe and Africa is finally known in detail, it will surely prove to be a complex narrative. It will probably not call, however, for any fundamental modification of the general picture I have presented here.

Disjunct Endemism

We come now to the fourth and last of the fossil-distribution patterns, which I call "disjunct endemism." The term describes the following situation. A group of fossil organisms is limited in its geographical distribution but nonetheless appears in two or more parts of the world that are now separated by major geographical barriers such as zones of deep ocean. The classic case in point is *Mesosaurus*, a small, snaggle-toothed reptile that lived in late Paleozoic times, some 270 million years ago. Strata that contain fossils of *Mesosaurus* are found only in Brazil and in South Africa [*see illustration on page 63*]. This animal, measuring some 18 inches from snout to tip of tail, was evidently aquatic. It could hardly have been able to swim very far, however, without having diffused into many parts of the world other than Brazil and South Africa. The application of Occam's razor suggests that in late Paleozoic times Brazil and South Africa were contiguous; this bit of fossil evidence in favor of continental drift was first noted many years ago.

In at least two instances that involve the ruling reptiles of the Mesozoic era, the dinosaurs, the fossil evidence seems

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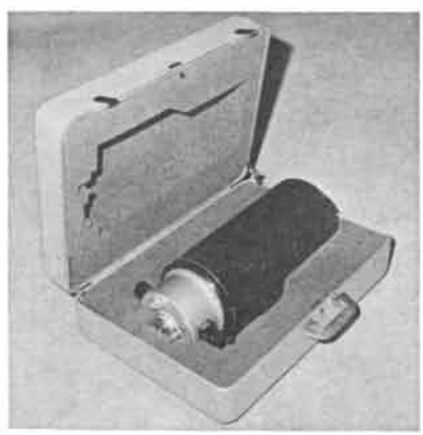

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to require sharp revisions of the drift timetable. The dinosaurs involved are five genera of sauropods, the line that gave rise to such museum favorites as *Brontosaurus* and *Diplodocus*. Two of the genera flourished in late Jurassic times and three in the late Cretaceous, some 70 million years afterward.

The Jurassic dinosaur genera are *Brachiosaurus*, the biggest of all the sauropods, and *Barosaurus*. The remains of dinosaurs of both genera are found in the Morrison Formation of the western U.S. and in the Tendaguru fossil beds of Tanzania; *Brachiosaurus* fossils have also been found in Portugal and in Algeria. These huge herbivores seem to have occupied an ecological niche comparable to an elephant's. Although they might possibly have negotiated swamps, they would have had trouble swimming across a wide river, let alone an ocean. Their presence in both Africa and North America thus points to the existence of a land connection between these areas in late Jurassic times. The necessity for this connection in turn imposes a constraint on the timing of the oceanic separation of the northern and southern halves of Pangaea.

Now, one popular reconstruction of the continental array in Jurassic times, prepared by Robert S. Dietz and John C. Holden of the National Oceanic and Atmospheric Administration, shows a possible place of crossing between Eurasia (which was then linked to North America) and Africa. That is where Spain and North Africa nearly touch; a Jurassic land bridge here would solve the problem of the seemingly disjunct endemism of the two sauropods [*see top illustration on page 64*]. The existence of marine deposits of Jurassic age in the parts of Spain and North Africa that might have been joined, however, seems to rule out any such land bridge.

Another way to be rid of this supposed example of disjunct endemism is to attack the biological classifications involved. One could assert that the African species of these two dinosaur genera are actually quite different from the North American species and attribute this divergence to a break in the land connection between the two regions. By and large, however, the dinosaurs are a group that has been excessively split by taxonomists. An admitted resemblance even at the genus level is likely to signify a close genetic affinity if not an actual ability to interbreed. On balance, then, close similarities between the late Jurassic dinosaur faunas of the Tendaguru beds and of the Morrison Formation pose a problem for the continental-drift timetable that has not yet been satisfactorily resolved.

The disjunct endemism of the three late Cretaceous sauropods—*Titanosaurus, Laplatosaurus* and *Antarctosaurus*—presents an even more clear-cut contradiction between the fossil record and the accepted timetable for continental drift. These three dinosaurs are known from fossil formations both in South America and in India. Yet the Indian subcontinent had supposedly become isolated by surrounding ocean some 100 million years before late Cretaceous times, toward the close of the Triassic [*see bottom illustration on page 64*]. Unless the fossil identifications are in error, such an early date for the severance of India from the rest of Gondwanaland is clearly inadmissible. Several similar arguments from the fossil record, which I need not give in detail, can be used to support the persistence of land connections (if only intermittent ones) between the Africa–South America landmass and the Australia-Antarctic landmass until quite late in the Mesozoic period.

I have tried to show here how the fossil record can contribute to plate-tectonic theory by helping to establish a more refined timetable for continental drift. Critics may say that the fossil data are often imprecise and are in addition subject to ambiguous interpretation. That is undoubtedly true in some instances. Moreover, we must beware of oversimplification and of overinterpretation of patchy evidence. We should also acknowledge that endemism cannot be explained in every instance on the basis of continental movements. Nonetheless, the general level of agreement between paleontology and the other earth sciences is sufficiently high to warrant some confidence in our fossil-based conclusions.

As time passes and the reconstruction of past plate movements becomes more precise, I believe interest in several biological questions that arise from the new view of earth history will increase. For one thing, we shall be in a better position to learn more about the rates of evolution among isolated organisms. For another, we shall be able to make findings about the relative ease of migration and colonization under different geographical circumstances. The disjunct distribution of many living animals—for example the lungfishes, the marsupials and the giant flightless birds—will be better understood. Perhaps most intriguing of all, we may acquire new insights into why many groups of plants and animals have become extinct.

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The Social Behavior of Army Ants

The complex and permanent social organization of these insects is maintained by interactions among a great many individuals. Each individual, however, can alter its behavior only slightly

by Howard R. Topoff

Every living organism must at some time interact with other members of its species. As a result some degree of social behavior is the rule in the animal kingdom. The late T. C. Schneirla, for many years a curator in the department of animal behavior of the American Museum of Natural History, was greatly interested in the evolution and development of social behavior in species of animals representing many levels of evolutionary history. One of the groups of animals he selected for study was the army ants. These ants were already famous for their awesome marches in masses of hundreds of thousands of individuals. Their notoriety had given rise to an abundance of military metaphors, exemplified by the following description by A. Hyatt Verrill, a naturalist and explorer of animal life in South America: "In all the world, the army ants of the tropics are the most remarkable in many ways. Utterly blind, yet they move in vast armies across the land, overcoming every obstacle other than fire and water, maintaining perfect formation, moving with military precision and like a real army having their scouts, their engineering corps and their fighting soldiers."

In 1932 Schneirla proceeded to study army ants more objectively, and he discovered by close and long-continued observation of their habits that colonies of army ants show a degree of social organization every bit as impressive as the apocryphal stories of the early naturalists [see "The Army Ant," by T. C. Schneirla and Gerard Piel; SCIENTIFIC AMERICAN, June, 1948]. How were the ants' activities organized and coordinated? Schneirla's studies gave rise to various hypotheses, and the nature of the social bond in these insects continues to intrigue investigators of animal behavior. During the past 10 years my colleagues and I have been continuing these investigations in an attempt to better understand the complex mechanisms that organize the remarkable social behavior of the army ants.

MARAUDING COLUMN of army ants forms the diagonal ribbon in the photograph on the opposite page. These are ants of the genus *Dorylus*, native to Africa and famous for colonies that may number as many as 20 million ants. The photograph was made by William H. Gotwald, Jr., of Utica College.

The army ants comprise one of the subfamilies of ants known as Dorylinae (so named from the Greek word meaning spear, because of their potent sting). There are some 150 species of army ants in the Western Hemisphere, most of them in Latin America, and about 100 other known species in Africa, Asia, Indo-Malaysia and Australia. The majority of species inhabit tropical regions, but many have adapted to temperate climates; some 20 species are found in the southern and mid-central U.S.

Practically all army ants are notable for four characteristics. The first is that they typically have very large colonies. Even small colonies, such as those of the Asian genus *Aenictus,* consist of at least 100,000 individuals. *Eciton burchelli* of Central and South America has colony sizes approaching a million individuals. In certain species of the African genus *Dorylus* colonies have been estimated to run to more than 20 million individuals. The second characteristic is the ants' periodic shifting of nesting sites. These colony movements, or emigrations, involve the entire colony: workers, brood and queen. At the end of each emigration the army ants settle down only in temporary bivouacs.

The third characteristic is that the army ants are almost exclusively carnivorous. They feed on other arthropods, particularly insects, and some species have been observed to eat small vertebrates such as lizards and snakes. The raiding parties of certain species are so huge that wherever they live the ants rank as major predators in the ecological community. Edward Step, an observer of insect life, described the army ants' forays in these terms: "They march in such enormous numbers that everything which desires not to be eaten has to fly before them; from the cockroach to the mouse to the huge python, the elephant, the gorilla and the warlike native man, the story is the same." This is a gross exaggeration, but it is a well-authenticated fact that the ants' food consumption is tremendous; the workers of a colony of *Eciton burchelli,* for example, may bring in more than 100,000 other arthropods a day to feed the nest.

The last characteristic that typifies the behavior of doryline ants is their tight cohesiveness. Unlike many species of ants from other subfamilies, army ants do not forage for food individually. Instead all raiding and emigrations to new bivouacs are conducted by groups of individuals that closely follow a chemical trail deposited continuously by all the ants as they run along the ground.

To find an explanation of the social behavior of these animals we must look into their physiology and their means of communication, which, since they are essentially blind, is based mainly on chemical and tactual stimuli. Let us first examine the army ants' life-style. We shall consider specifically three species that are well known because they con-

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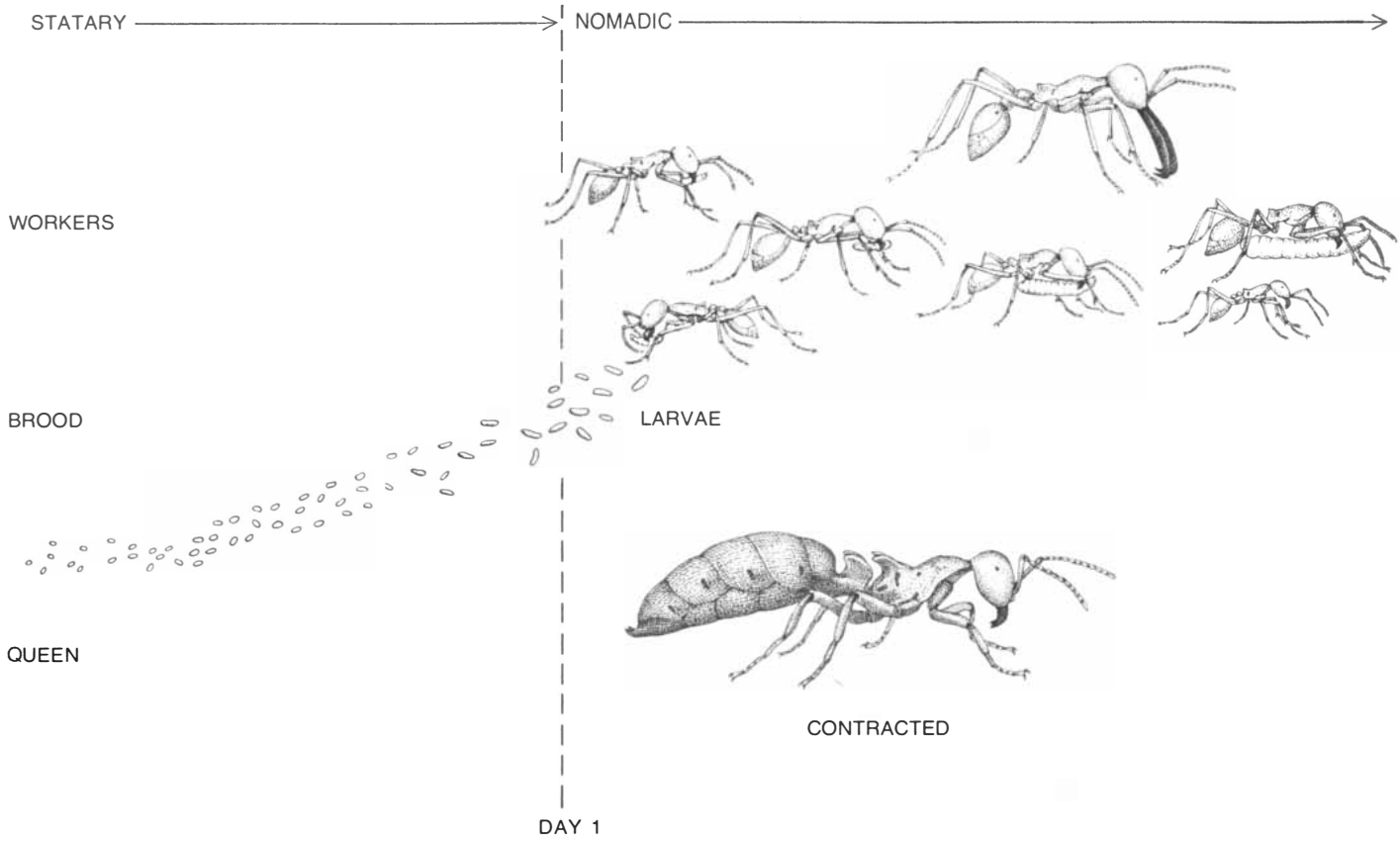

ALTERNATING PHASES in the behavior of army ants of the New World tropical genus *Eciton* are illustrated here, beginning with Day 1 of a nomadic phase (*left*). For 14 to 17 days after a new generation of workers emerges from the pupal stage a colony of army ants sends out large parties of raiders for food every day. Every night the colony shifts to a new bivouac, carrying the larvae that will become the next generation of workers. During the nomadic phase the queen's abdomen remains contracted. The phase

duct their activities principally aboveground: *Eciton hamatum* and *Eciton burchelli* of Central and South America and *Neivamyrmex nigrescens,* which ranges into temperate climates and is found in the U.S. The three species are closely related evolutionarily and are much alike in their life cycle and behavior.

Colonies of army ants typically consist of a single queen, a brood of developing young and a large population of adult workers. The queen is the colony's sole agent of reproduction, and she is responsible to a great extent for the colony's cohesion. The queen secretes certain substances that are attractive to the workers and therefore hold the colony together. More important, the chemical secretions of the queen actually enhance the survival of the workers (as has been shown by Julian F. Watkins II of Baylor University and Carl W. Rettenmeyer of the University of Connecticut). At regular intervals (about every five weeks) the queen's large abdomen swells with fatty tissue and eggs, and she may lay well over 100,000 eggs in the course of a week. The eggs then give rise to four successive stages of development: embryo, larva, pupa and adult, which on emergence from the pupal stage is lightly pigmented and readily recognizable as a "callow," or young worker. The workers are all female but sterile, with underdeveloped ovaries.

In species of *Eciton* and *Neivamyrmex* the workers developing from a given batch of eggs vary in size and structure, a condition known as polymorphism. The developmental basis for polymorphism is not clear, although two possibilities exist. The first is that the developmental pathways leading to adult workers that differ in size and structure are determined by the amount and kind of food eaten by the larvae immediately after they hatch from the egg. This mode of development exists in honeybees. The second possibility is that the eggs laid by the queen are so different biochemically that the subsequent development of the larvae is unaltered by the quantity or quality of food consumed. (In some genera, such as *Aenictus,* the adults are not polymorphic.) Whatever the differentiating mechanisms may be, the adult ants that differ in size and structure also exhibit contrasting patterns of behavior, with the result that there is a division of labor in the colony. Small workers (as little as three millimeters in length) spend most of their time in the nest feeding the larval broods; intermediate-sized workers constitute most of the population, going out on raids as well as doing other jobs. The largest workers (more than 14 millimeters in species of *Eciton*) have a huge head and long, powerful jaws. These individuals are what Verrill called soldiers; they carry no food but customarily run along the flanks of the raiding and emigration columns. An excited "soldier" is a formidable animal: it rears up on its hind legs, vibrates its antennae and rhythmically opens and closes its jaws. The tips of the mandibles are extremely sharp and are curved backward; if the ant bites a human being, they penetrate the skin and are difficult to remove.

In the colony's behavioral cycle there is a "nomadic" phase during which a large proportion of the adult workers go out on daily raids and collect food. In both species of *Eciton* the raids begin at dawn. The ants pour out of the bivouac and form several columns, each column later dividing into a network of

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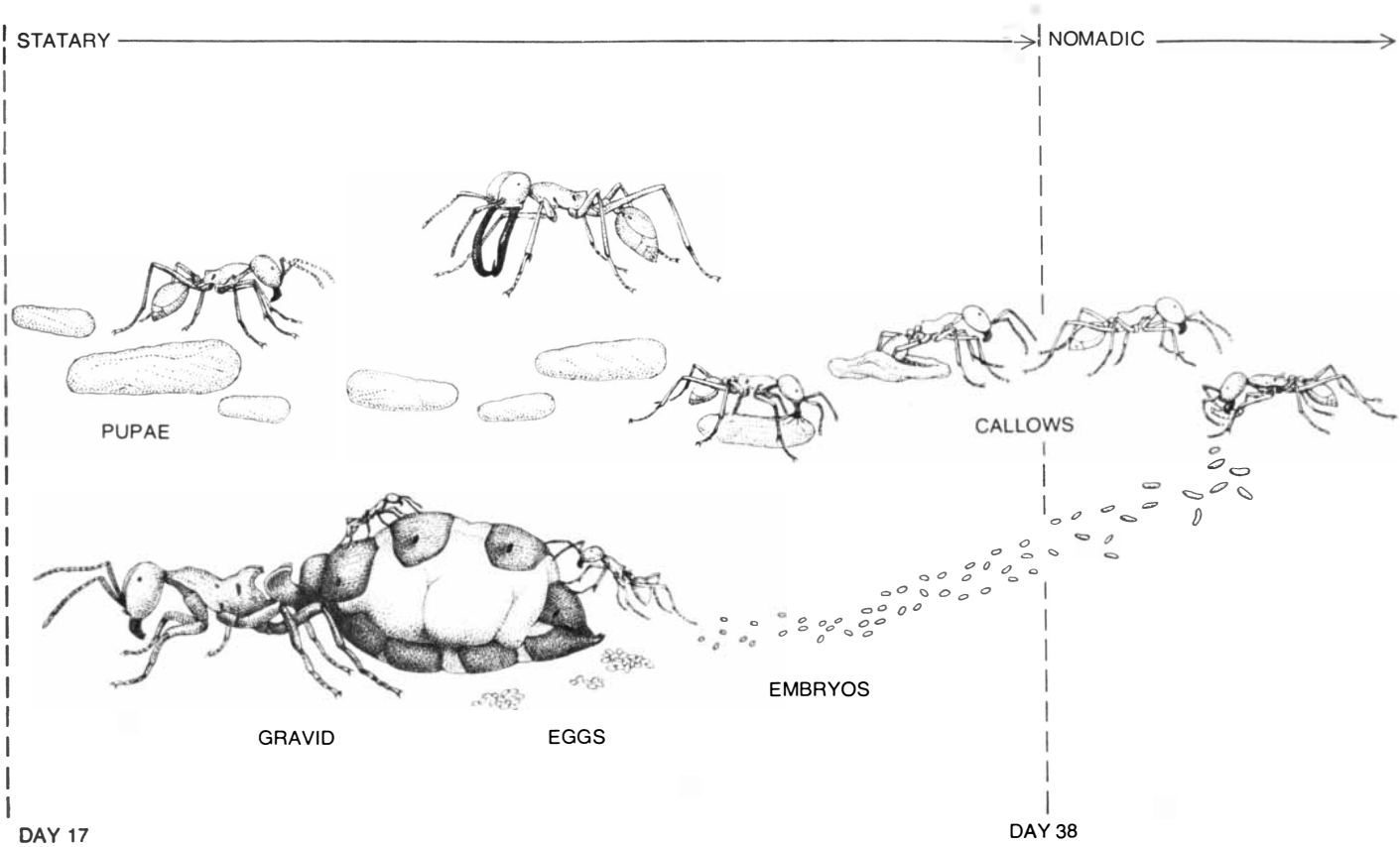

ends when the colony's larvae enter the pupal stage. The statary, or resting, phase then begins (*center*). The colony ceases to move nightly and the daily raiding parties are smaller. The statary phase continues for some 21 days. During the first week the queen's abdomen enlarges rapidly. During the second week she may produce as many as 100,000 eggs. By the end of the third week, as a new generation of worker ants completes the pupal stage, the queen's eggs hatch into larvae. This initiates a new nomadic phase (*right*).

branches. In running along these trails the ants seem not to depend much on vision. Species of *Eciton* and *Neivamyrmex* have vestigial eyes consisting of only a single facet; they can detect changes in the intensity of light but almost certainly cannot reproduce an image of an object. The raiding ants stay together by following a chemical trail laid on the ground by the other workers. Murray S. Blum of the University of Georgia and Watkins have determined that the substance deposited by the army ants originates in the hind intestine, but it is not yet established whether the substance consists of undigested food or a glandular secretion or a combination of both.

By midmorning the raiding columns have overrun an area extending a considerable distance from the nest, often more than 100 meters. At the front of the raiding columns the ants attack insects and other arthropods, biting and stinging the prey, pulling it apart and carrying the softer pieces back to the nest. Thus the column is actually a two-way stream, with some ants advancing and others returning with their prey.

At nightfall the entire colony moves on to a new bivouac, typically emigrating along one of the principal raiding trails of that day. It may take the colony most of the night to complete the move to the new nesting site. This daily routine of massive raids and emigrations from bivouac to bivouac is followed for 14 to 17 days. Then, more or less abruptly, the colony settles down to a much quieter phase. Comparatively few of the workers go out on raids; their forays are much smaller and the colony stops emigrating and remains at the same nesting site. This "statary" phase lasts approximately three weeks. At the end of that time the cycle begins again; the colony resumes rushing out on great daily raids and making nightly emigrations.

The foregoing pattern is typical of the *Eciton* ants' behavior. The cycle in species of *Neivamyrmex* follows a similar pattern but differs in some aspects, depending on differences in the habitat; for example, in an area of high daytime temperature and low humidity the ants conduct both their raiding for food and their emigrations at night instead of during the day.

In 1932 Schneirla set out to learn what factors regulate the cycles of behavior in *Eciton hamatum* and *Eciton burchelli*. At the time there were already two rival hypotheses. One suggested that the cycles of behavior were influenced by physical conditions of the environment, such as temperature, humidity, air pressure or the phases of the moon; the other suggested that the stimulus for emigrations might simply be depletion of the food supply in the area around the bivouac. Schneirla soon showed that both of these conjectures must be incorrect. He found that generally within a given environment some of the colonies were in the nomadic phase and some were in the statary phase; that ruled out environmental conditions as the determinant of whether or not a colony would make nightly emigrations. Schneirla disposed of the second hypothesis by observing that a colony of army ants would sometimes move into a nesting site that had just been vacated by another colony, and the newcomers would remain at this site even for a three-week statary period—clear evidence that the food supply around the bivouac had not been exhausted.

The actual regulator of the ants' nomadic and statary behavior, as Schneir-

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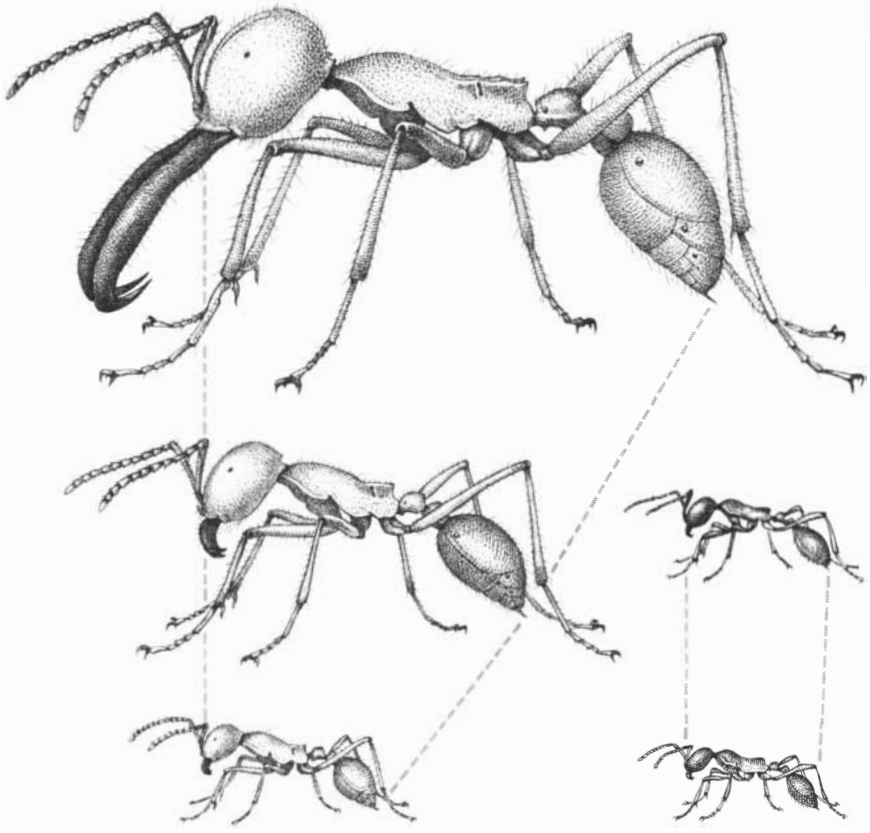
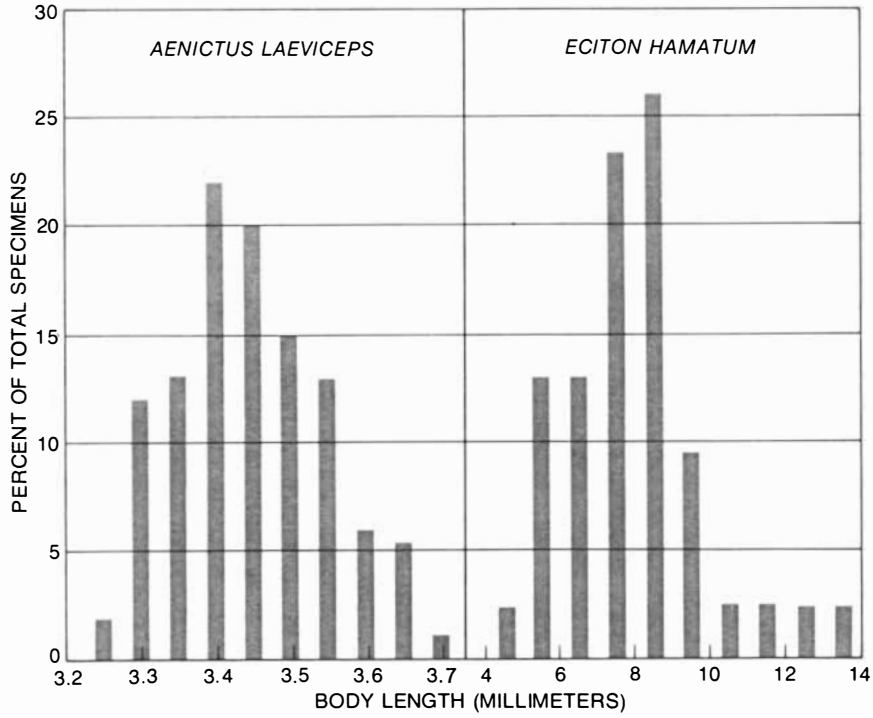


WORKERS OF DIFFERENT SIZES are common in some army ant species and virtually absent in others. Illustrated here are workers of the species *Eciton burchelli* (*left*) and of the Philippine species *Aenictus gracilis* (*right*), enlarged some seven diameters. Workers that differ in size also differ in patterns of behavior. The smallest *Eciton burchelli* workers do little more than feed and maintain larvae; the largest are the "soldiers" of the colony.



RANGES OF SIZE within two species of army ants are compared in this graph. In *Aenictus laeviceps* the body of the largest worker is scarcely half a millimeter longer than that of the smallest one. In *Eciton hamatum*, however, the body-length difference is nine millimeters.

la eventually demonstrated, was not some external influence but the breeding cycle within the colony. He noted that the nomadic phase always coincided with the period when a larval brood was developing in the colony, and that the statary phase began when the larvae started to spin cocoons and went into the pupal stage of development.

When army ants emerge from the pupal cocoons as young workers, the nest is suddenly stirred to a high level of activity. The important stimuli for this excitation are probably substances secreted by these young callows; the older workers respond to the callows by stroking and licking them and by dropping pieces of food on them. This intense social stimulation, which originates with the interactions between the callows and the older workers, is subsequently transmitted throughout the bivouac by communication among the older adults. The result of this high level of mutual stimulation is that the nomadic phase of massive daily raids and emigrations from one bivouac site to another begins. As the callows mature, their chemical excitatory effects wear off but nomadic activities continue in the colony. These activities are maintained by comparable chemical and tactual stimulation imparted to the adult ants by a brood of developing larvae, which by this time have hatched from eggs laid by the queen during the previous statary phase. When the larvae have completed their development and progressed to the cocoon-wrapped pupal stage, the intensity of the mutual stimulation between them and the adult ants decreases abruptly. At this time the colony again lapses into the statary condition, which continues until the pupal brood once again emerges as callow workers.

Although the precise nature of the chemical interactions between adult workers and the brood is not yet known, the evidence supporting Schneirla's hypothesis is strong. For example, when he removed a larval brood from a colony during the nomadic phase, the colony stopped emigrating and the intensity of its daily raids diminished. By the same token, when he split a colony into two parts, only one of which contained the larval brood, the workers in the portion with the larvae continued to show considerable activity whereas those in the broodless portion became less active.

Schneirla's hypothesis predicts that the large differences in behavior exhibited by colonies of army ants during the nomadic and statary phases must result

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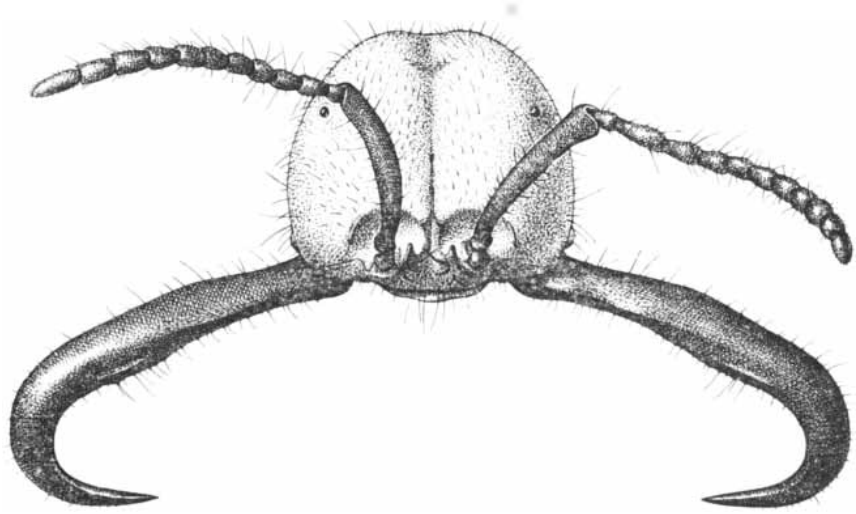
from corresponding differences in the physiological condition and behavior of each individual ant during the two phases. At the present time we are a long way from understanding the changes that take place in each ant's endocrine secretory activity, metabolic processes and sensitivity to physical and chemical stimuli. Nevertheless, several experiments have given us considerable insight into the kinds of factors involved.

Many of my own studies have been focused on the underground-nesting, nocturnal army ant species *Neivamyrmex nigrescens,* which I have observed in the field and in laboratory experiments at the Southwestern Research Station of the American Museum of Natural History in Arizona. I noticed that during the nomadic phase the ants not only spent most of the night raiding outside the nest but also frequently set out on their raids late in the afternoon when there was still considerable light on the ground. During the statary phase, in contrast, a smaller number of ants carried out weak and short raids, and they rarely emerged from the nest before dark. How could one account for this apparently slight but significant difference in behavior? One clue comes from studies of the relation between physiology and behavior in other species of animals. As an example, J. Goldsmid of Rhodes University in South Africa described a series of interesting behavioral changes in larvae of the blue tick *Boophilus decoloratus.* For a few days after hatching these larvae are strongly repelled by light and strongly attracted to one another by their common chemical secretions; the mutual attraction is so strong that the larvae come together even in an area under bright light. A week after the larvae have hatched, however, their behavior changes dramatically; they stop responding to one anothers' chemical secretions and do not withdraw from the light.

I was struck by the thought that the ticks' pattern of changing behavior might fit in with my observations of the army ants during the two behavioral phases. Suppose that during the statary phase the workers' negative response to light increases and at the same time their positive response to one another (as well as to the queen and brood) increases. This could account for the fact that during the colony's statary phase workers spend a greater amount of time inside the nest and the raids do not begin until dark. Conversely, if one supposes that during the nomadic phase the ants are less attracted to other individuals in the nest and less repelled by light, that might explain why most of them readily leave the nest for raiding and why they are not so deterred from starting their raids in daylight.



LARGE HEAD AND HUGE JAWS are characteristic of the soldiers in the genus *Eciton*. Once the sharp jaws have pierced an object their hooked tips make them difficult to remove.

I designed a series of experiments to test whether or not these ants did indeed shift in their responses to light and to stimuli from other ants during the nomadic and statary phases. The experiments consisted in collecting ants in the field and placing them in an arena in the laboratory where they were able to enter into dimly lighted or brightly lighted areas. In order to minimize handling and artificial excitation of the ants I constructed a cylindrical cartridge in which they were picked up by suction. Without further disturbance of the insects the cartridge was then placed in the center of the arena, where through slits in the base of the cartridge the ants could move into dimly lighted quadrants or into quadrants where the light was 100 times more intense. To monitor the ants' movements we photographed their positions at five-second intervals for two minutes.

The results of this experiment showed that ants taken from colonies during the nomadic phase indeed behaved very differently from those taken from the colony during the statary phase. The nomadic ants traveled about indiscriminately in the bright and dim chambers of the arena, and they ran rapidly in columns with the individuals well spaced out. In contrast, ants in the statary-phase condition either entered into one of the dim areas immediately after the start of the test or else they tended to associate into tight clusters near the edge of the brightly lighted central cartridge (as the newly hatched tick larvae did in Goldsmid's experiment). When these experiments were repeated with all the experimental areas kept totally dark, the results were just about the same. The record of the ants' movements (filmed by infrared photography) showed that the nomadic ants ran about freely and the statary ants again clustered tightly near the edge of the central cartridge. This supported the conclusion that the ants' attraction to one another changes significantly from the nomadic phase to the statary phase. Although the behavior of the ants in the field and in the laboratory still suggests that they also respond differently to light during the two phases, in the experimental tests their increased attraction to one another during the statary phase overrides their increased negative response to light.

Obviously these experiments are only a beginning in exploration of the interactions that take place among the individuals in an army ant colony during changes in the social behavior of the colony as a whole. Furthermore, we are still a long way from understanding the biological bases of these differences. For instance, does the excitatory stimulation that the adult workers receive from the callows and the larval brood influence their behavior through neural mechanisms alone, or does it also affect the secretory activity of their endocrine glands? Because every adult army ant continuously alternates from the nomadic phase to the statary phase and back again, these ants are excellent species for future studies of the relation between changes in physiological proc-

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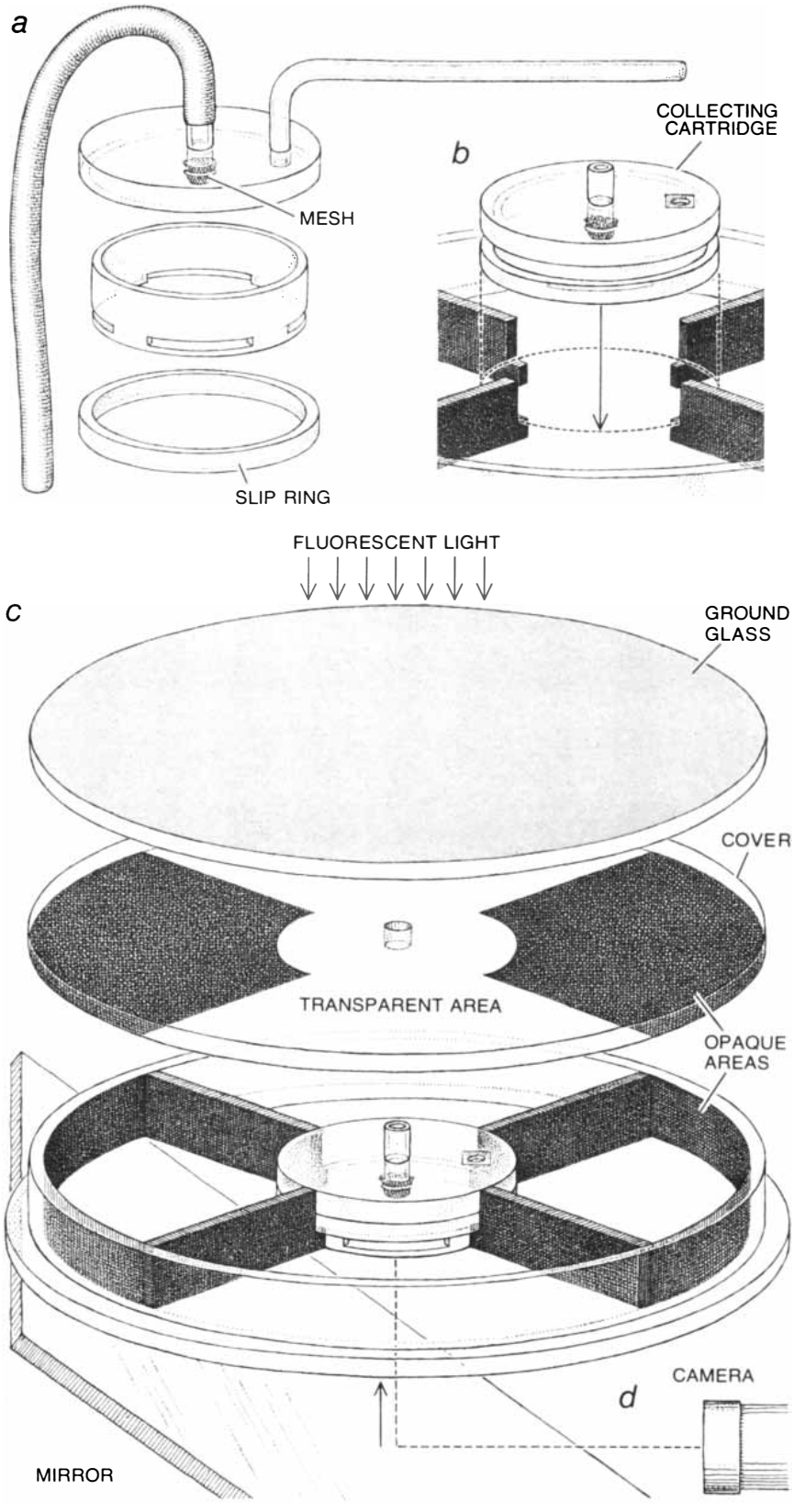

PLEXIGLASS ARENA (*c*) was constructed to study activity patterns of army ants in the nomadic and statary phases. *Neivamyrmex nigrescens*, a widely distributed New World species, was selected for the study. Ants from nomadic and statary colonies were drawn by suction, some 50 at a time, into collection cartridges (*a*). They then remained undisturbed until each cartridge was placed in the center of the arena; this raised the ring seal of the cartridge so that the ants were free to explore the arena (*b*). At first, to assess the ants' response to light, two of the arena quadrants were kept shaded while the other two and the central cartridge were lighted 100 times more brightly. Photographs made at five-second intervals (*d*) recorded changes in the ants' positions (*see illustrations on opposite page*).

esses and corresponding changes in behavior.

I want to turn now to another interesting question we have been investigating. In primate societies, particularly those of humans, it is well known that newborn individuals do not become fully participating members of the society until they have matured and gained much experience within the family group, with their peers and with other members of the society. Many people believe animals such as insects emerge from the pupal stage of development with an immediate capacity to behave exactly like mature individuals. That is simply not so. With experimental procedures I devised in collaboration with Katherine Lawson, a graduate student at the City University of New York, we compared the behavior of callows and fully mature ants of the genus *Eciton* at the Smithsonian Institution's research station on Barro Colorado Island in the Panama Canal Zone.

The behavior of the callow members of a colony exhibits a puzzling inconsistency. During the first few days after the callows have emerged from their cocoons they do not join the mature adults in predatory raids. Furthermore, if a group of callows is taken from the nest and placed in the midst of a raiding column, they move only sluggishly and in a somewhat disoriented fashion, so that they interfere with the two-way traffic of the rapidly running mature ants in the columns. Yet surprisingly the callows have no hesitancy about going along with the entire colony in the emigration to a new bivouac after the day's raid.

Was the callows' failure to participate in raiding due to an inability to follow the trail deposited by the raiding ants? During the day's raid hundreds of thousands of foraging ants continually run from the bivouac to the raiding areas and then back again. As a result at the end of the raid the strength of the trail may be considerably higher than it is during the early hours of morning. That is a reasonable assumption on the basis of experiments conducted by Richard Torgerson of Wartburg College and Roger D. Akre of Washington State University, who demonstrated that the chemical trails of *Eciton* persist on the ground in the field for at least a week. Perhaps by the time a colony of army ants emigrates the trail is so strong that even the callows are able to follow it. To test this hypothesis we measured the comparative ability of callows and ma-

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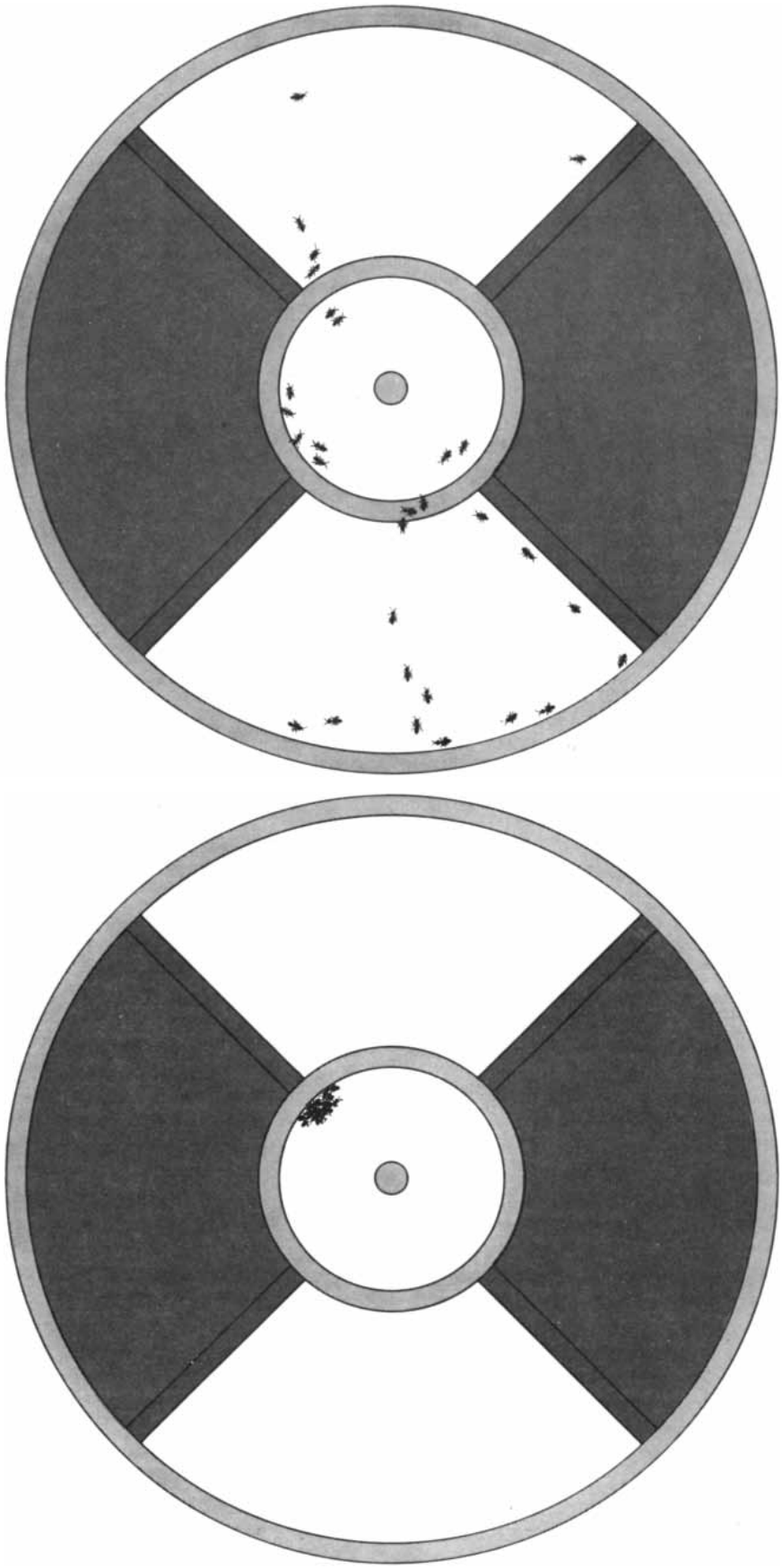
ture adult ants to follow the trail substance of their colony.

To obtain the substance for the purposes of the experiment we washed ants from a colony in ether as a solvent. This procedure gave us an extremely potent solution of the substance that could be diluted to any desired strength by adding pure ether. An artificial trail was now deposited on a disk of chromatography paper that was rotated on a phonograph turntable as the solution flowed onto it from a microburette suspended above it. Within seconds after the circular trail had been deposited the solvent evaporated, leaving behind an invisible residue of the trail substance. The paper disk with the circular trail was removed from the turntable and placed on a template. The template had a black circle drawn on it that coincided exactly with the location of the invisible chemical trail on the disk of paper above it. Because the template circle was visible through the chromatography paper we could easily determine whether or not a test ant was indeed following the trail. Each ant was admitted to the circular trail through a tunnel, and its ability to detect and follow the trail was observed.

First we examined the ants' speed of running over the trail. As we had expected, callows taken from their colony soon after their emergence from the pupal cocoon were considerably slower than mature ants in following the trail. With each day of development in the nest the callows improved in speed on our test, and week-old callows were able to follow the chemical trail almost as rapidly as fully mature workers.

We then compared callows and mature adults on the basic ability to follow the trail, apart from the question of speed. Since the observations in the field and our speed tests had indicated that maturity was an important factor, we expected that the proportion of callows able to follow the trail without error would be considerably smaller than the proportion of adult workers able to do so. To our complete surprise it turned out that statistically the callows scored just about as high as the adults in the fundamental ability to follow the chemical trail of their colony. Evidently the callows were fully capable of recognizing the trail substance and their slowness must have been due to physical immaturity.

Thus we are still left with the question: Why do the young callows stay in the nest instead of going out on raids



BEHAVIOR OF ANTS in the arena depended on the phase of the colony. When workers came from a colony in the early stage of a nomadic phase, they ran throughout the arena, spending equal time in light and dark areas (*top*). Statary workers usually went to one or both of the dark areas. In many tests, however, they remained in the cartridge (*bottom*).

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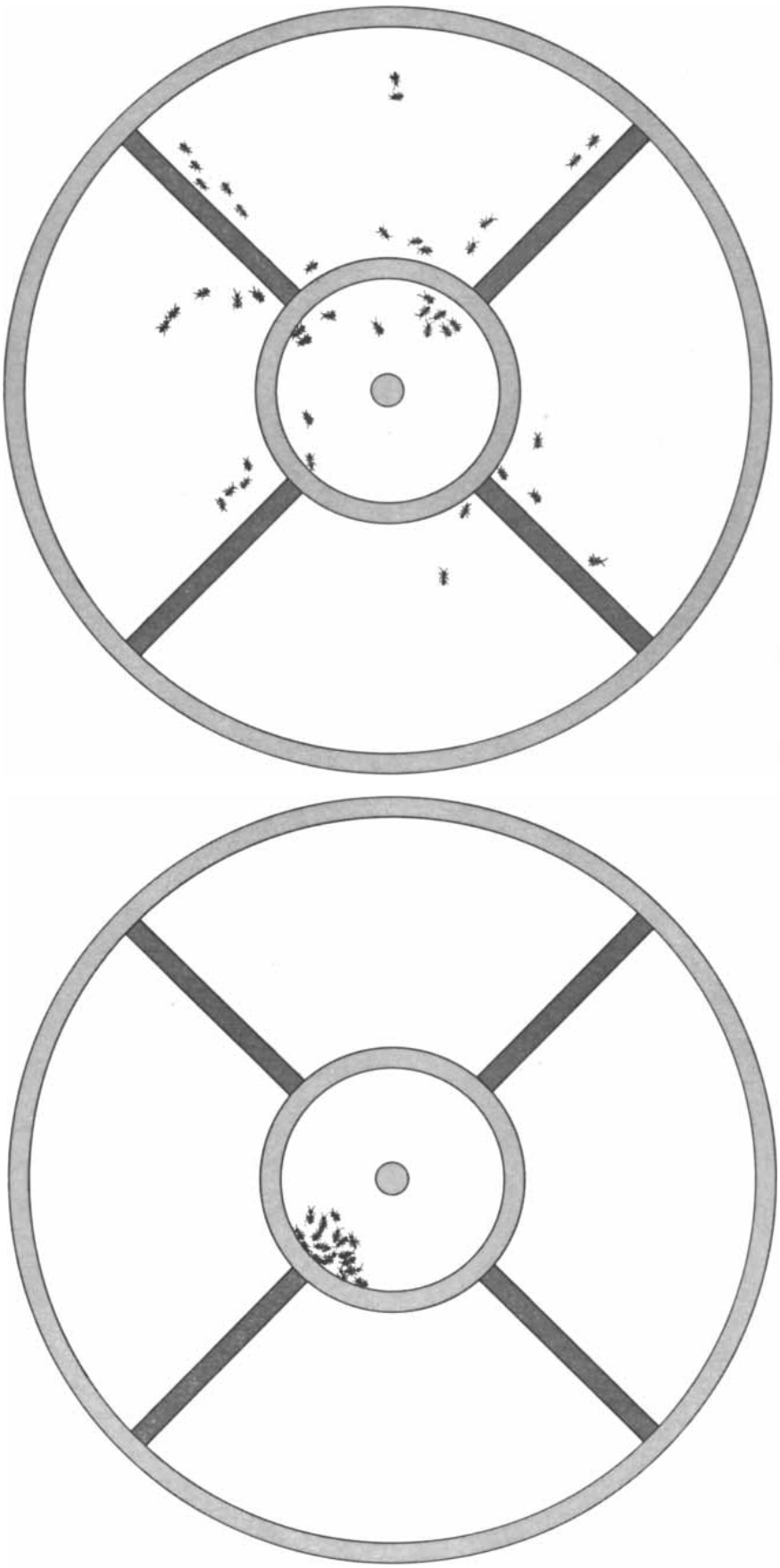

UNDER INFRARED ILLUMINATION the ants continued to behave as they had when they were exposed to visible light. Workers in the early nomadic phase ran rapidly through all the chambers of the arena (*top*) but statary workers often stayed in the cartridge (*bottom*).

with other workers? There are several hypotheses to be considered. First, it has been noticed that much of the callows' time in the first few days is spent in intensive feeding on the nest's food supply. It is possible that this preoccupation with feeding could serve to keep them in the nest during the day. A second hypothesis, and one we plan to test, is that young callows are strongly attracted, probably more so than mature adults are, to stimuli of physical contact and chemical secretions that originate with other members of the colony. The intensity of both of these forms of stimulation is greatest inside the nest. A callow ant leaving the nest will experience a sudden reduction in the intensity of both classes of stimuli. Outside the nest the amount of tactual stimulation decreases as the adult ants fan out along the trail. In the outside air and on the narrow trails the colony's odors are also vastly diluted. As the mature adult workers depart on their massive daily raids, the tension of chemical and tactual attraction between the inside of the nest and the outside becomes less one-sided, but the concentration and pull of the inside might still be stronger. The direction of pull would be reversed only when the colony leaves the nest during an emigration to a new site. As the workers, the larval and pupal brood and the queen move out, the departing stimulation might attract the callows out of the nest. The decisive attractive force may be either the quantitative shift of the predominant mass of individuals or the departure of a source of stimulation that is particularly attractive to the callows, such as the queen, the developing brood, the total population of adult workers or the booty (the food supply).

We have recently made an interesting observation in the field that is consistent with the hypothesis that it is social stimuli that are responsible for keeping callow army ants in the nest. A colony of *Neivamyrmex nigrescens* was completing its statary phase in a bivouac located in the bank of a stream. One day there was a heavy rain followed by a flash flood that destroyed most of the colony; only a few hundred workers and fewer than 100 pupae were left. Under these conditions the callows ran along the entire route of the raiding column with the mature adult ants on the first night after their emergence from the pupal stage of development.

In many respects we have hardly scratched the surface in our attempts to understand how the social organiza-

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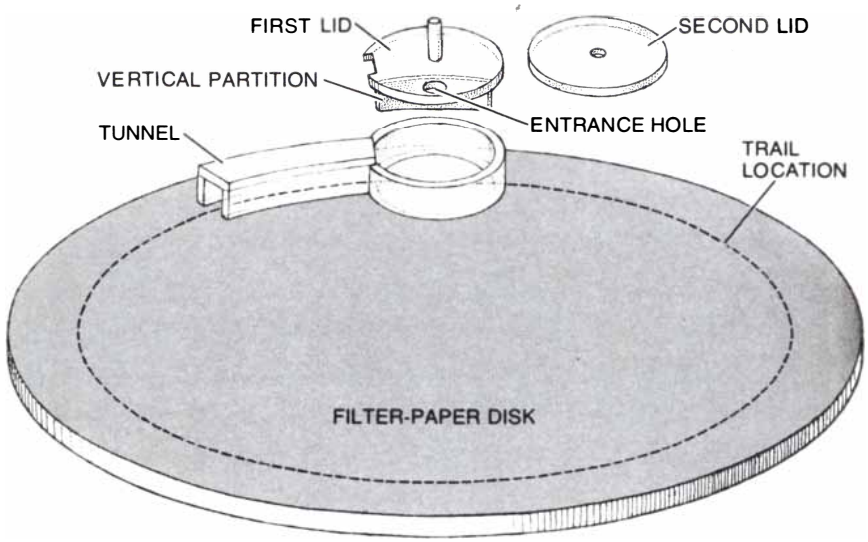
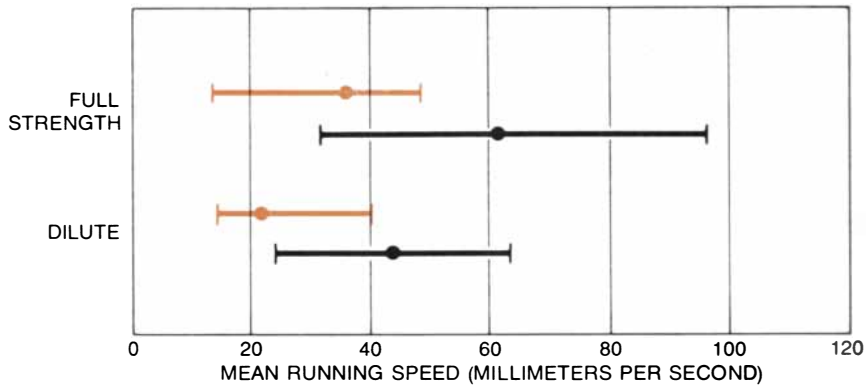
tion of army ants evolved, develops and is maintained by interactions among individuals, each of which has a limited capacity for behavioral adjustment. On the other hand, we have accumulated sufficient knowledge to enable us to compare processes that are important for the social organization of army ants with those that are important for the social organization of species representing other levels of evolutionary history. We know, for instance, that social organizations in all species of animals are maintained by physiological and behavioral interactions among the individuals that enable the group to function as an integrated unit. But each species of animal has an evolutionary and developmental history that is different from all others, and consequently each species has a unique morphology, physiology and behavior. This means that when the comparative animal behaviorist observes similar patterns of social behavior in two species of animals, he cannot automatically conclude that the mechanisms and processes underlying the behavior are the same for both.

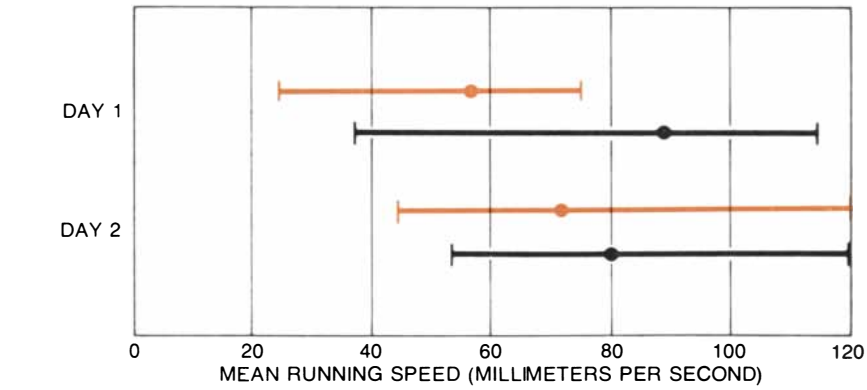
For example, in both ant and human societies individuals exhibit different and specialized behavioral functions, giving rise to a division of labor within the group. But the role that any particular ant plays in its society is influenced directly by its biological organization, whereas human jobs are determined more by economic status, level of education, personal preferences and other cultural factors. Practically every behavior pattern that ants exhibit is based on their responses to a limited number of tactile and chemical stimuli; individuals in human societies interact by means of a much more complex form of communication based primarily on the use of symbolic language. Finally, although the behavior of every adult army ant is influenced by many social experiences it has during its development, the degree to which such developmental factors can modify adult behavior is certainly much smaller in ants than it is in humans. The goal of the comparative animal behaviorist is to study and clarify the bases for social behavior in species representing all levels of invertebrate and vertebrate evolutionary history. Only then shall we be able to judge how unique each species, including man, is. The study of the social behavior of army ants contributes to the attainment of this goal because it gives us a larger view of the diversity of social systems that are to be found within the animal kingdom.



RACECOURSE APPARATUS was used to compare the trail-following performances of newly emerged "callow" workers with older workers. A circular scent trail was deposited on a disk of filter paper (*broken line*). Each ant was then placed in a chamber with a partition that prevented any contact with the trail. When the partition was removed, the ant could run along a short segment of the trail enclosed by a tunnel. On emerging the ant was scored for its ability to complete the circular course and for its mean running speed. By diluting the scent the experimenters were able to simulate both "strong" and "weak" trails.



RUNNING SPEED of callow adults (*color*) of the species *Eciton burchelli* is compared with the speed of mature adults of the same species (*black*). Over a full-strength scent trail (*top bars*) the mature adult speed was better than 60 millimeters per second whereas the callow adult speed was little more than half that. Over a trail only a tenth as strong (*bottom bars*) the performance of both mature and callow ants was poorer but the gap was the same.



CALLOWS' PERFORMANCE improved as they matured. Graph compares the running speeds of callow (*color*) and mature adult (*black*) workers of the species *Eciton hamatum* on two consecutive days. On the first day the difference in mean speeds was some 30 millimeters per second (*top bars*). The next day the difference was less than 10 millimeters per second (*bottom bars*). Tests showed that the callows are virtually mature within seven days.

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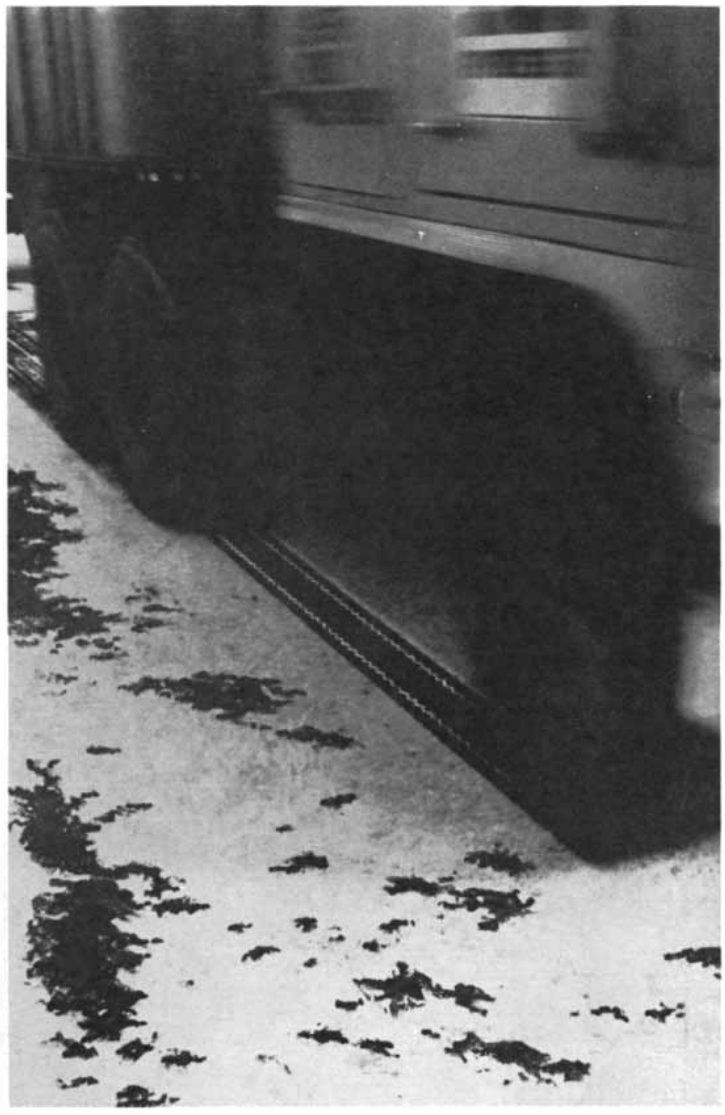

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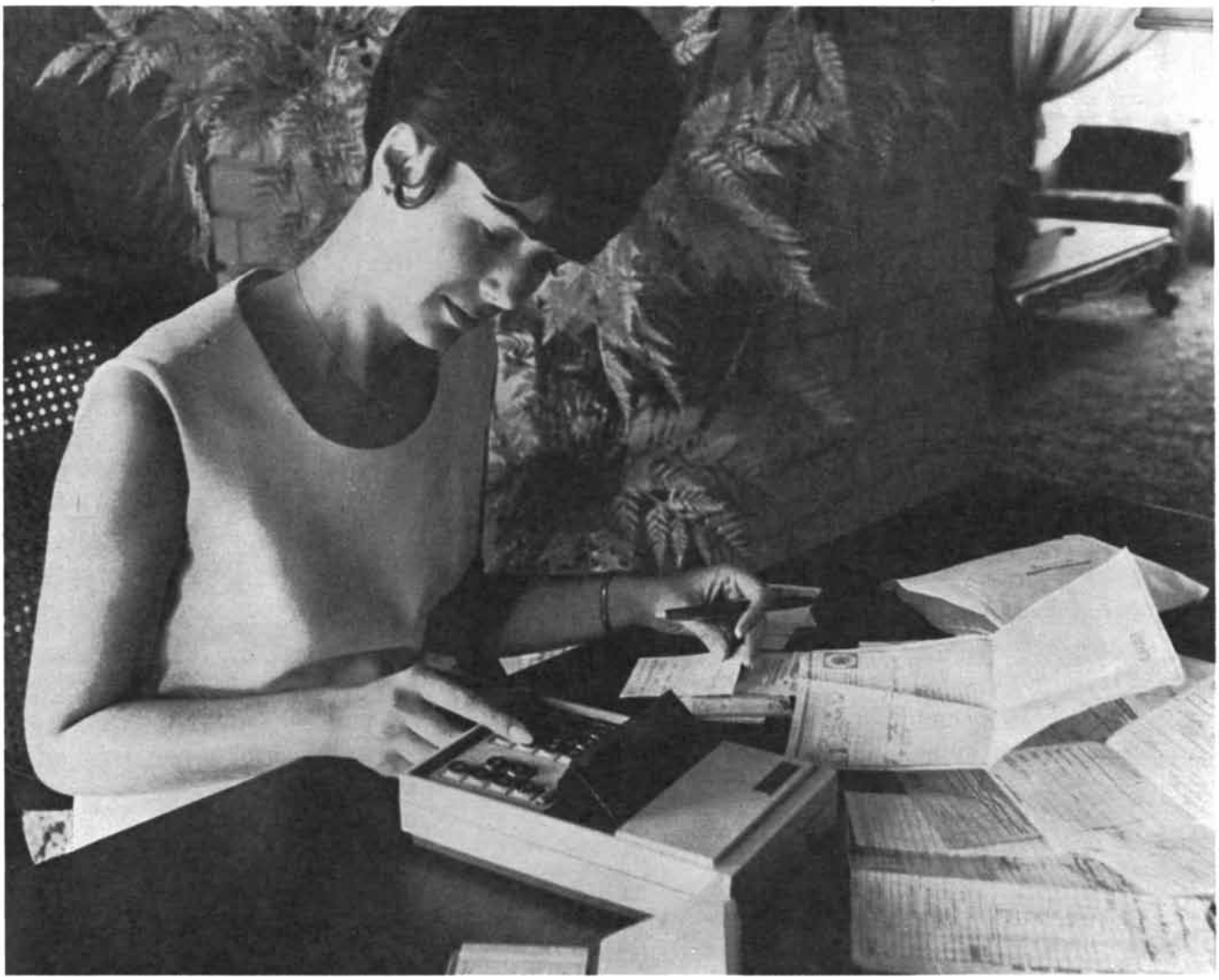

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PICTORIAL PERCEPTION AND CULTURE

Do people of one culture perceive a picture differently from people of another? Experiments in Africa show that such differences exist, and that the perception of pictures calls for some form of learning

by Jan B. Deregowski

A picture is a pattern of lines and shaded areas on a flat surface that depicts some aspect of the real world. The ability to recognize objects in pictures is so common in most cultures that it is often taken for granted that such recognition is universal in man. Although children do not learn to read until they are about six years old, they are able to recognize objects in pictures long before that; indeed, it has been shown that a 19-month-old child is capable of such recognition. If pictorial recognition is universal, do pictures offer us a lingua franca for intercultural communication? There is evidence that they do not: cross-cultural studies have shown that there are persistent differences in the way pictorial information is interpreted by people of various cultures. These differences merit investigation not only because improvement in communication may be achieved by a fuller understanding of them but also because they may provide us with a better insight into the nature of human perceptual mechanisms.

Reports of difficulty in pictorial perception by members of remote, illiterate tribes have periodically been made by missionaries, explorers and anthropologists. Robert Laws, a Scottish missionary active in Nyasaland (now Malawi) at the end of the 19th century, reported: "Take a picture in black and white and the natives cannot see it. You may tell the natives, 'This is a picture of an ox and a dog,' and the people will look at it and look at you and that look says that they consider you a liar. Perhaps you say again, 'Yes, this is a picture of an ox and a dog.' Well, perhaps they will tell you what they think this time. If there are a few boys about, you say: 'This is really a picture of an ox and a dog. Look at the horn of the ox, and there is his tail!' And the boy will say: 'Oh! yes and there is the dog's nose and eyes and ears!' Then the old people will look again and clap their hands and say, 'Oh! yes, it is a dog.' When a man has seen a picture for the first time, his book education has begun."

Mrs. Donald Fraser, who taught health care to Africans in the 1920's, had similar experiences. This is her description of an African woman slowly discovering that a picture she was looking at portrayed a human head in profile: "She discovered in turn the nose, the mouth, the eye, but where was the other eye? I tried by turning my profile to explain why she could only see one eye but she hopped round to my other side to point out that I possessed a second eye which the other lacked."

There were also, however, reports of vivid and instant responses to pictures: "When all the people were quickly seated, the first picture flashed on the sheet was that of an elephant. The wildest excitement immediately prevailed, many of the people jumping up and shouting, fearing the beast must be alive, while those nearest to the sheet sprang up and fled. The chief himself crept stealthily forward and peeped behind the sheet to see if the animal had a body, and when he discovered that the animal's body was only the thickness of the sheet, a great roar broke the stillness of the night."

Thus the evidence gleaned from the insightful but unsystematic observations quoted is ambiguous. The laborious way some of these Africans pieced together a picture suggests that some form of learning is required to recognize pictures. Inability to perceive that a pattern of lines and shaded areas on a flat surface represents a real object would render all pictorial material incomprehensible. All drawings would be perceived as being meaningless, abstract patterns until the viewer had learned to interpret and organize the symbolic elements. On the other hand, one could also argue that pictorial recognition is largely independent of learning, and that even people from cultures where pictorial materials are uncommon will recognize items in pictures, provided that the pictures show familiar objects. It has been shown that an unsophisticated adult African from a remote village is unlikely to choose the wrong toy animal when asked to match the toy to a picture of, say, a lion. Given a photograph of a kangaroo, however, he is likely to choose at random from the array of toys. Yet one can argue that this sample was not as culturally remote as those described above. It is therefore probably safer to assume that utter incomprehension of pictorial material may be observed only in extremely isolated human populations.

Conventions for depicting the spatial arrangement of three-dimensional ob-

PICTORIAL DEPTH PERCEPTION is tested by showing subjects a picture such as the top illustration on the opposite page. A correct interpretation is that the hunter is trying to spear the antelope, which is nearer to him than the elephant. An incorrect interpretation is that the elephant is nearer and is about to be speared. The picture contains two depth cues: overlapping objects and known size of objects. The bottom illustration depicts the man, elephant and antelope in true size ratios when all are the same distance from the observer.

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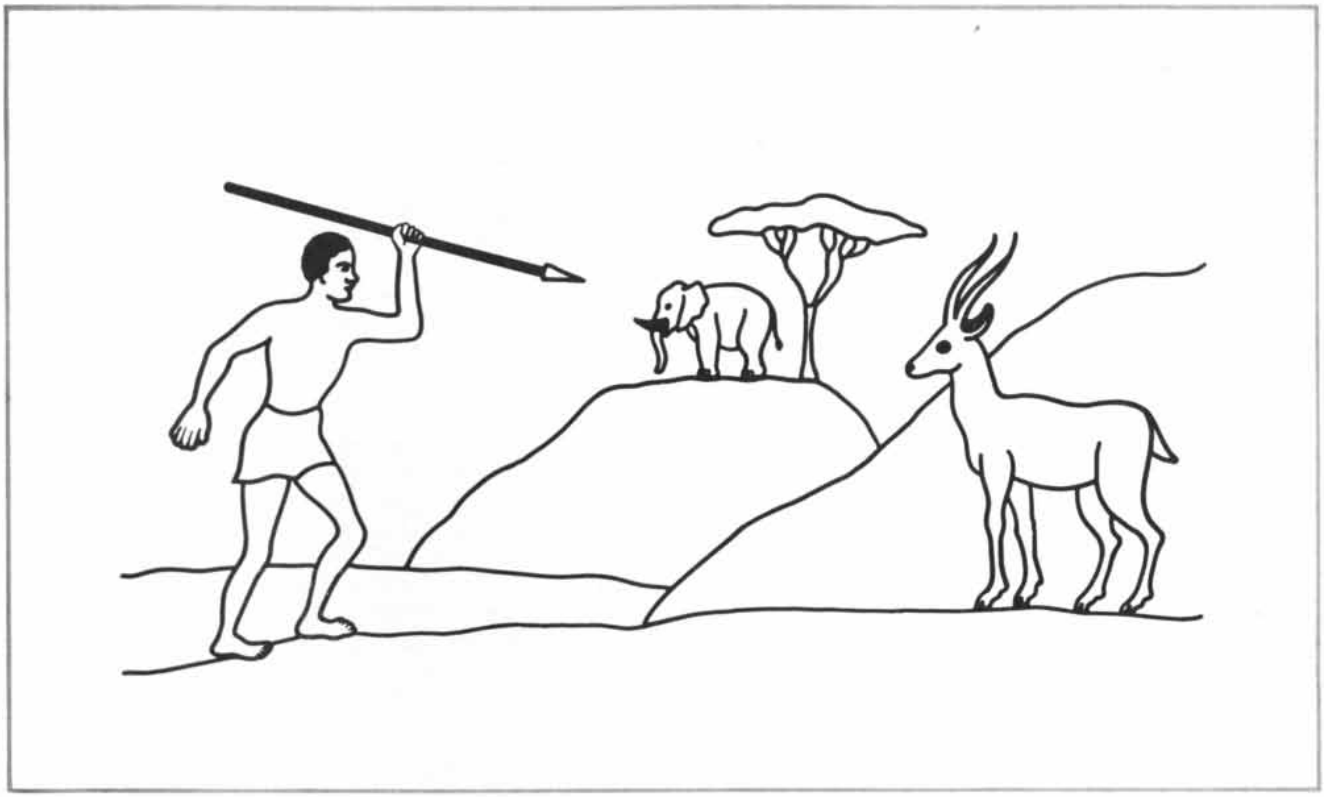

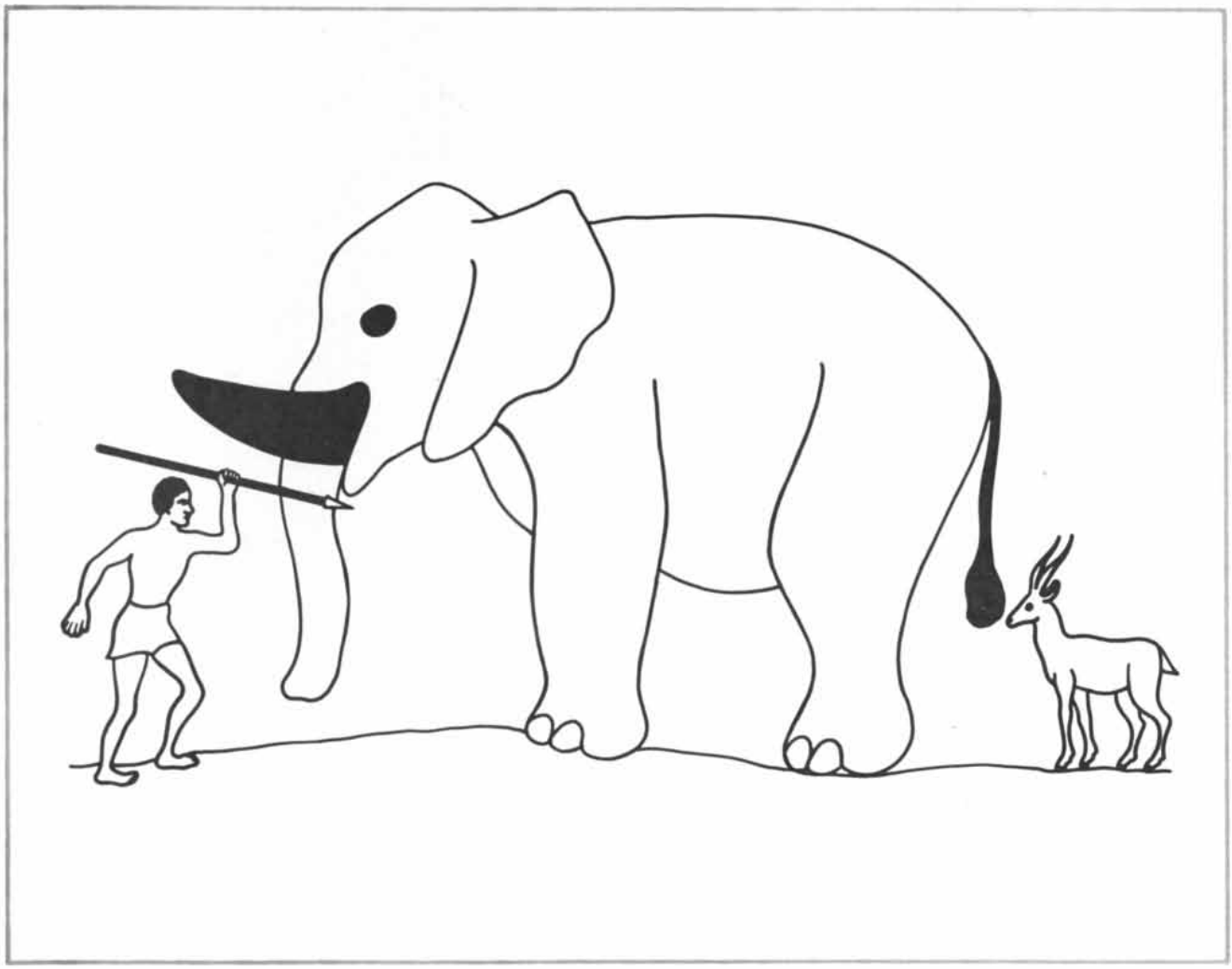

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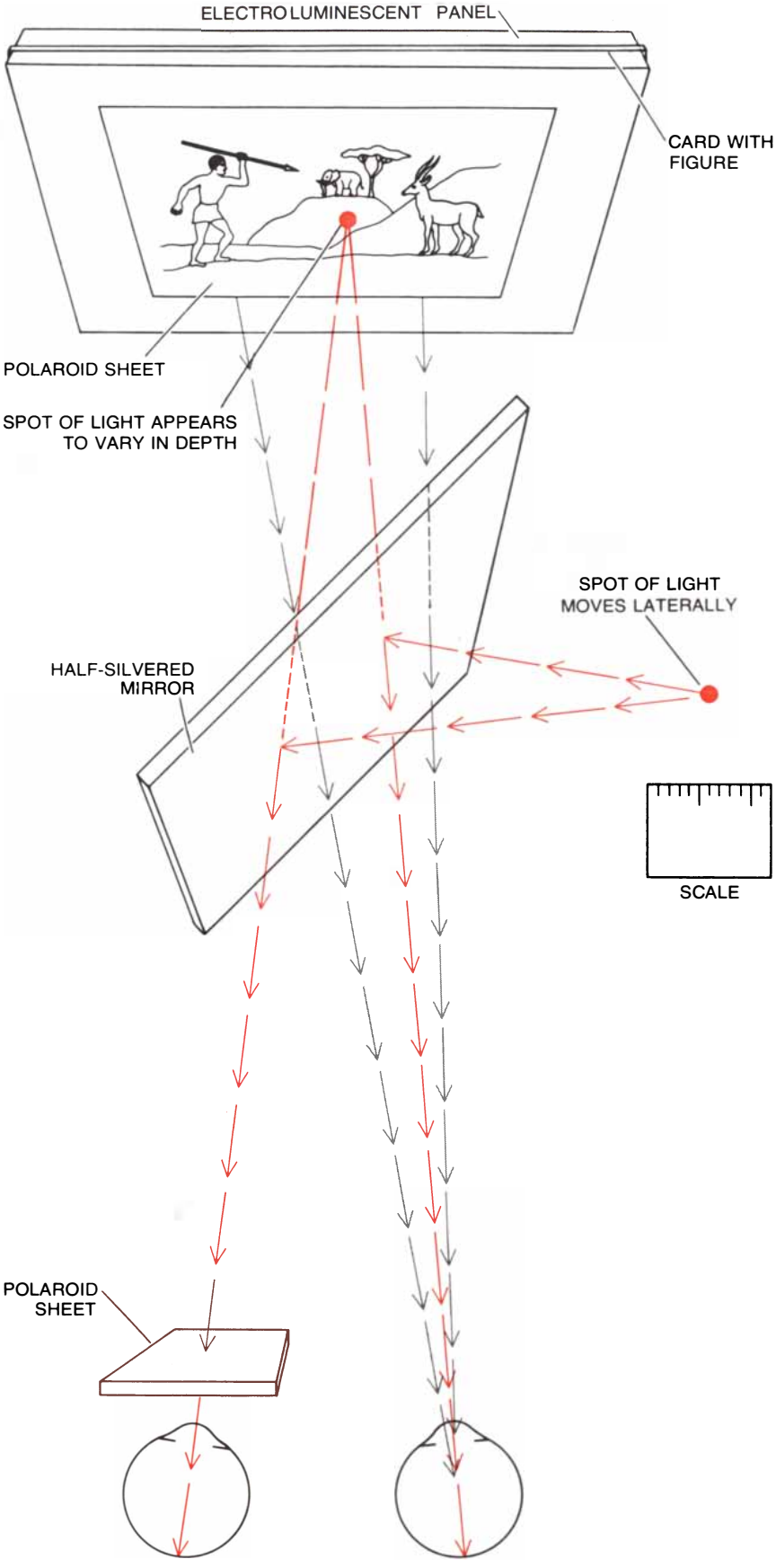

APPARATUS FOR STUDYING PERCEIVED DEPTH enables the subject to adjust a spot of light so that it appears to lie at the same depth as an object in the picture. The light is seen stereoscopically with both eyes but the picture is seen with only one eye. Africans unfamiliar with pictorial depth cues set the light at the same depth on all parts of the picture.

jects in a flat picture can also give rise to difficulties in perception. These conventions give the observer depth cues that tell him the objects are not all the same distance from him. Inability to interpret such cues is bound to lead to misunderstanding of the meaning of the picture as a whole. William Hudson, who was then working at the National Institute for Personnel Research in Johannesburg, stumbled on such a difficulty in testing South African Bantu workers. His discovery led him to construct a pictorial perception test and to carry out much of the pioneering work in cross-cultural studies of perception.

Hudson's test consists of a series of pictures in which there are various combinations of three pictorial depth cues. The first cue is familiar size, which calls for the larger of two known objects to be drawn considerably smaller to indicate that it is farther away. The second cue is overlap, in which portions of nearer objects overlap and obscure portions of objects that are farther away; a hill is partly obscured by another hill that is closer to the viewer. The third cue is perspective, the convergence of lines known to be parallel to suggest distance; lines representing the edges of a road converge in the distance. In all but one of his tests Hudson omitted an entire group of powerful depth cues: density gradients. Density gradients are provided by any elements of uniform size: bricks in a wall or pebbles on a beach. The elements are drawn larger or smaller depending on whether they are nearer to the viewer or farther away from him.

Hudson's test has been applied in many parts of Africa with subjects drawn from a variety of tribal and linguistic groups. The subjects were shown one picture at a time and asked to name all the objects in the picture in order to determine whether or not the elements were correctly recognized. Then they were asked about the relation between the objects. (What is the man doing? What is closer to the man?) If the subject takes note of the depth cues and makes the "correct" interpretations, he is classified as having three-dimensional perception. If the depth cues are not taken into account by the subject, he is said to have two-dimensional perception [*see illustration on preceding page*]. The results from African tribal subjects were unequivocal: both children and adults found it difficult to perceive depth in the pictorial material. The difficulty varied in extent but appeared to persist

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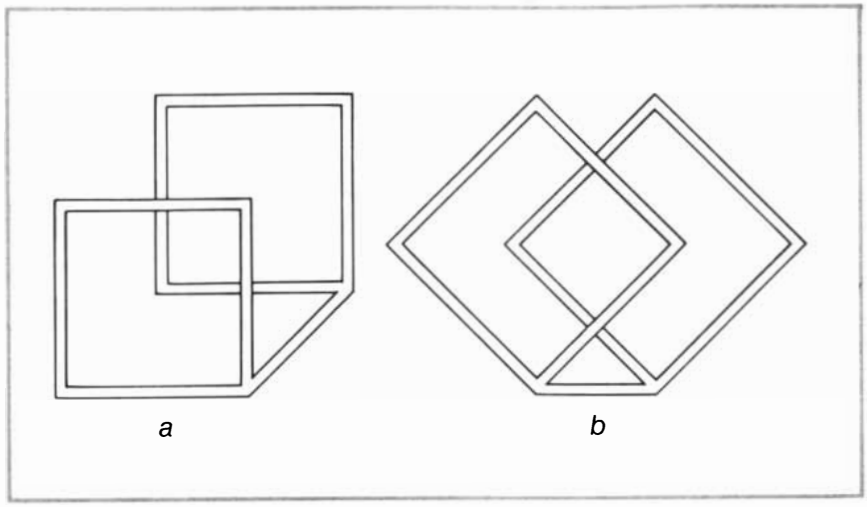
through most educational and social levels.

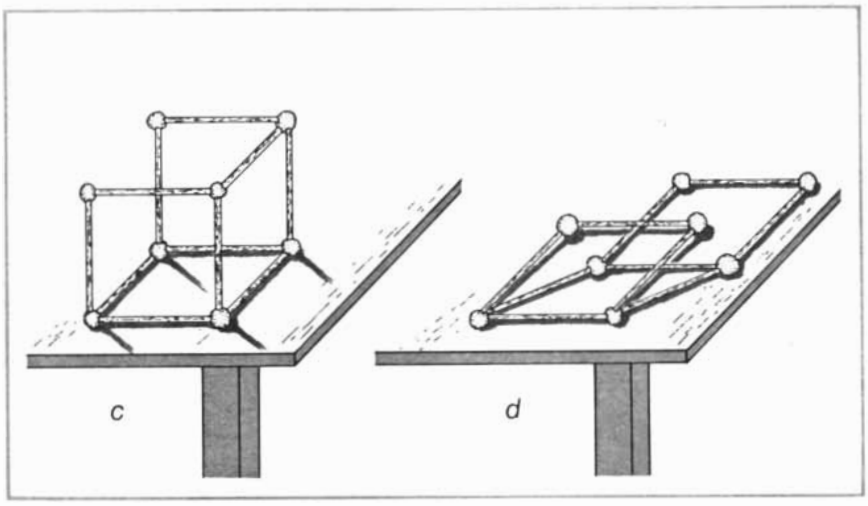
Further experimentation revealed that the phenomenon was not simply the result of the pictorial material used in the test. Subjects were shown a drawing of two squares, one behind the other and connected by a single rod [*see top illustration at right*]. They were also given sticks and modeling clay and asked to build a model of what they saw. If Hudson's test is valid, people designated as two-dimensional perceivers should build flat models when they are shown the drawing, whereas those designated as three-dimensional perceivers should build a cubelike object. When primary-school boys and unskilled workers in Zambia were given Hudson's test and then asked to build models, a few of the subjects who had been classified as three-dimensional responders by the test made flat models. A substantial number of the subjects classified as two-dimensional perceivers built three-dimensional models. Thus Hudson's test, although it is more severe than the construction task, appears to measure the same variable.

The finding was checked in another experiment. A group of Zambian primary-school children were classified into three-dimensional and two-dimensional perceivers on the basis of the model-building test. They were then asked to copy a "two-pronged trident," a tantalizing drawing that confuses many people. The confusion is a direct result of attempting to interpret the drawing as a three-dimensional object [*see top illustration on next page*]. One would expect that those who are confused by the trident would find it difficult to recall and draw. The students actually made copies of two tridents: the ambiguous one and a control figure that had three simple prongs. To view the figure the student had to lift a flap, which actuated a timer that measured how long the flap was held up. The student could view the figure for as long as he wanted to, but he could not copy it while the flap was open. After the flap was closed the student had to wait 10 seconds before he began to draw. The delay was introduced to increase the difficulty of copying the figure. The results confirmed that the students who were three-dimensional perceivers spent more time looking at the ambiguous trident than at the control trident, whereas the two-dimensional perceivers did not differ significantly in the time spent viewing each of the two tridents.

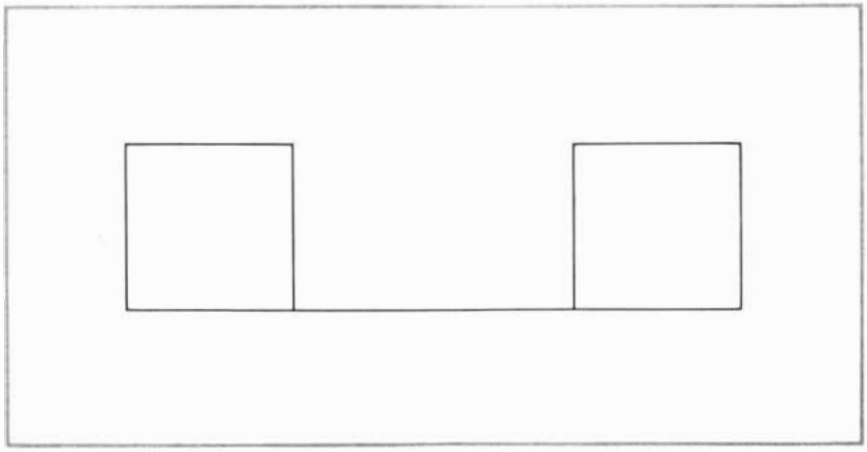
Do people who perceive pictorial



CONSTRUCTION-TASK FIGURES consist of two squares connected by a single rod. Most subjects from Western cultures see the figure *a* as a three-dimensional object, but when the figure is rotated 45 degrees (*right*), they see it as being flat. Africans from a variety of tribes almost always see both figures as being flat, with the two squares in the same plane.



STICK-AND-CLAY MODELS of the figure *a* in the top illustration were made by test subjects. Almost all the three-dimensional perceivers built a three-dimensional object (*left*). Subjects who did not readily perceive depth in pictures tended to build a flat model (*right*).



"SPLIT" DRAWING was preferred by two-dimensional perceivers when shown a model like figure *c* and given a choice between the split drawing and figure *a* in top illustration.

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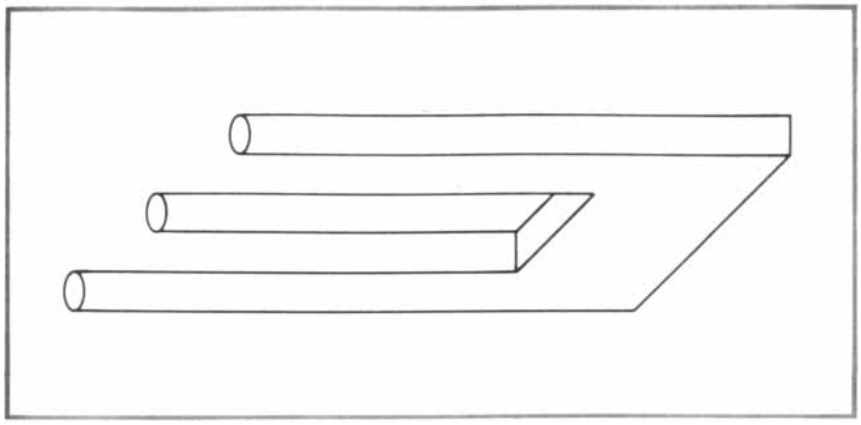
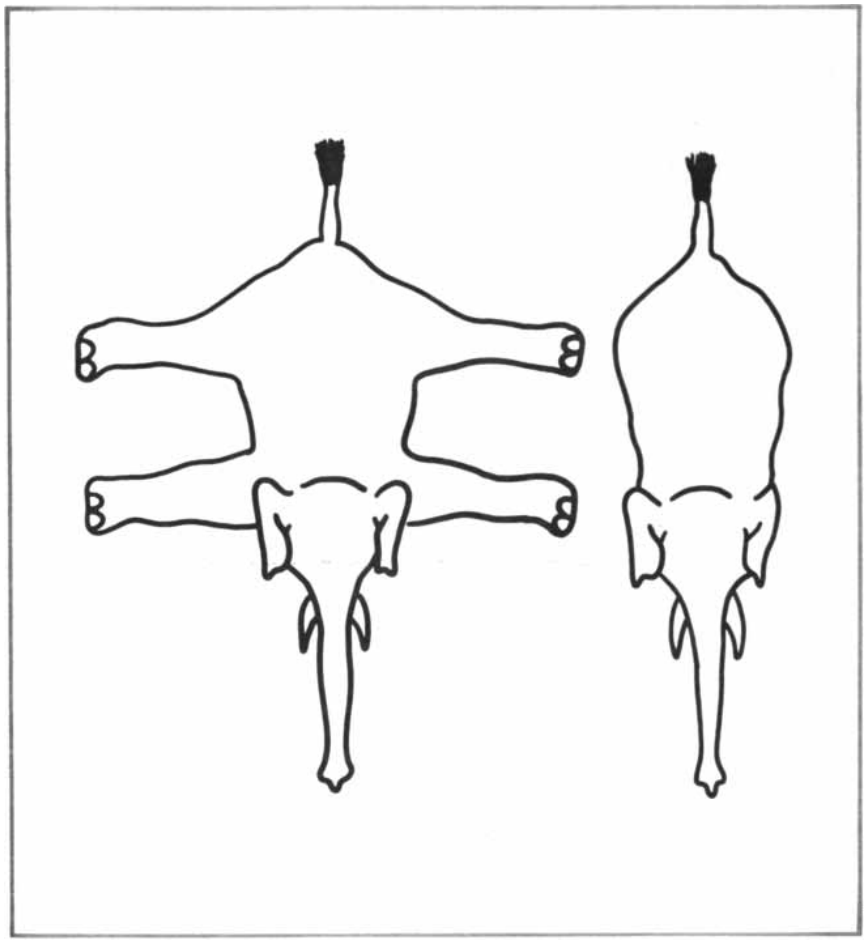


AMBIGUOUS TRIDENT is confusing to observers who attempt to see it as a three-dimensional object. Two-dimensional perceivers see the pattern as being flat and are not confused.

depth really see depth in the picture or are they merely interpreting symbolic depth cues in the same way that we learn to interpret the set of symbols in "horse" to mean a certain quadruped? An ingenious apparatus for studying perceived depth helped us to obtain an answer. This is how the apparatus is described by its designer, Richard L. Gregory of the University of Bristol:

"The figure is presented back-illuminated, to avoid texture, and it is viewed through a sheet of Polaroid. A second sheet of Polaroid is placed over one eye crossed with the first so that no light from the figure reaches this eye. Between the eyes and the figure is a half-silvered mirror through which the figure is seen but which also reflects one or more small light sources mounted on an optical bench. These appear to lie in the figure; indeed, optically they *do* lie in the figure provided the path length of the lights to the eyes is the same as that of the figure to the eyes. But the small light sources are seen with both eyes while the figure is seen with only *one* eye because of the crossed Polaroids. By moving the lights along their optical bench, they may be placed so as to lie at the same distance as any selected part of the figure."



SPLIT-ELEPHANT DRAWING (*left*) was generally preferred by African children and adults to the top-view perspective drawing (*right*). One person, however, did not like the split drawing because he thought the elephant was jumping around in a dangerous manner.

A Hudson-test picture that embodied both familiar-size and overlap depth cues was presented in the apparatus to a group of unskilled African workers, who for the most part do not show perception of pictorial depth in the Hudson test and in the construction test [*see illustration on page 84*]. The test picture showed a hunter and an antelope in the foreground and an elephant in the distance. The subjects set the movable light at the same apparent depth regardless of whether they were asked to place it above the hunter, the antelope or the elephant. In contrast, when three-dimensional perceivers were tested, they set the light farther away from themselves when placing it on the elephant than when setting it on the figures in the foreground. The result shows that they were not simply interpreting symbolic depth cues but were actually seeing depth in the picture.

When only familiar size was used as the depth cue, neither group of subjects placed the movable light farther back for the elephant. The result should not be surprising, since other studies have shown that familiar-size cues alone do not enable people even in Western cultures to see actual depth in a picture, even though they may interpret the picture three-dimensionally.

The fact that depth was seen in the picture only in the presence of overlap cues is of theoretical interest because it had been postulated that a perceptual mechanism for seeing depth cues where none are intended is responsible for certain geometric illusions, for example overestimating the length of the vertical limb of the letter *L*. If the mechanism is the same as the one for the perception of pictorial depth in Hudson's tests, then one would expect a decrease in the perception of geometric illusions in people who have low three-dimensional scores.

Do people who find pictures of the

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perspective type difficult to interpret tend to prefer pictures that depict the essential characteristics of an object even if all those characteristics cannot be seen from a single viewpoint? Here again the first systematic cross-cultural observations were carried out by Hudson. He showed African children and adults pictures of an elephant. One view was like a photograph of an elephant seen from above; the other was a top view of an elephant with its legs unnaturally split to the sides. With only one exception all the subjects preferred the drawing of the split elephant [*see bottom illustration on opposite page*]. The one person who did not prefer the drawing said that it was because the elephant was jumping about dangerously.

Other studies have shown that preference for drawings of the split type is not confined to meaningful pictures but also applies to geometric representations. Unskilled Zambian workers were shown a wire model and were asked to make a drawing of it. Only an insignificant proportion of them drew a figure that had pictorial depth; most drew a flat figure of the split type [*see bottom illustration on page 85*]. They also preferred the split drawing when they were shown the model and were asked to choose between it and a perspective drawing. Then the process was reversed, and the subjects were asked to choose the appropriate wire model after looking at a drawing. Only a few chose the three-dimensional model after looking at the split drawing; instead they chose a flat wire model that resembled the drawing. Paradoxically the split drawing had proved to be less efficient than the less preferred perspective drawing when an actual object had to be identified.

Although preference for drawings of the split type has only recently been studied systematically, indications of such a preference have long been apparent in the artistic styles of certain cultures, for example the Indians of the northwestern coast of North America. Other instances of the split style in art are rock paintings in the caves of the Sahara and primitive art found in Siberia and New Zealand. What art historians often fail to note is that the style is universal. It can be found in the drawings of children in all cultures, even in those cultures where the style is considered manifestly wrong by adults.

Perspective drawings and drawings of the split type are not equally easy to interpret. Even industrial draftsmen with a great deal of experience in interpreting

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engineering drawings, which are essentially of the split type, find it more difficult to assemble simple models from engineering drawings than from perspective drawings.

One theory of the origin of the split style was put forward by the anthropologist Franz Boas. His hypothesis postulated the following sequence of events. Solid sculpture was gradually adapted to the ornamentation of objects such as boxes or bracelets. In order to make a box or a bracelet the artist had to reduce the sculpture to a surface pattern and include an opening in the solid form, so that when the sculptured object was flattened out, it became a picture of the split type. It is possible that this development led to the beginnings of split drawings and that the natural preference of the style ensured its acceptance. There is no historical evidence that this evolution actually took place, however, and it does seem that the hypothesis is unnecessarily complicated.

The anthropologist Claude Lévi-Strauss has proposed a theory in which the split style has social origins. According to him, split representation can be explored as a function of a sociological theory of split personality. This trait is common in "mask cultures," where privileges, emblems and degrees of prestige are displayed by means of elaborate masks. The use of these mask symbols apparently generates a great deal of personality stress. Personalities are torn asunder, and this finds its reflection in split-style art.

Both Boas' and Lévi-Strauss's hypotheses ignore the universality of the phenomenon. If one accepts the existence of a fundamental identity of perceptual processes in all human beings and extrapolates from the data I have described, one is led to postulate the following. In all societies children have an aesthetic preference for drawings of the split type. In most societies this preference is suppressed because the drawings do not convey information about the depicted objects as accurately as perspective drawings do. Therefore aesthetic preference is sacrificed on the altar of efficiency in communication.

Some societies, however, have developed the split drawing to a high artistic level. This development occurs if the drawings are not regarded as a means of communication about objects or if the drawings incorporate cues that compensate for the loss of communication value due to the adoption of the split style. Both of these provisions are found in the art of the Indians of the Pacific Northwest. These pictures were intended to serve primarily as ornaments. They also incorporate symbolic elements that enable the viewer to interpret the artist's intention. Every such code, however, carries the penalty that communication is confined to people familiar with the code. Highly stylized art is not likely to be easily understood outside of its specific culture. Thus whereas the same psychological processes under the influence of different cultural forces may lead to widely different artistic styles, the styles arrived at are not equally efficient in conveying the correct description of objects and evoking the perception of pictorial depth.

STYLIZED BEAR rendered by the Tsimshian Indians on the Pacific coast of British Columbia is an example of split drawing developed to a high artistic level. According to anthropologist Franz Boas, the drawings are ornamental and not intended to convey what an object looks like. The symbolic elements represent specific characteristics of the object.

What are the forces responsible for the lack of perception of pictorial depth in pictures drawn in accordance with the efficacious conventions of the West? At present we can only speculate. Perhaps the basic difficulty lies in the observers' inability to integrate the pictorial elements. They see individual symbols and cues but are incapable of linking all the elements into a consolidated whole. To the purely pragmatic question "Do drawings offer us a universal lingua franca?" a more precise answer is available. The answer is no. There are significant differences in the way pictures can be interpreted. The task of mapping out these differences in various cultures is only beginning.

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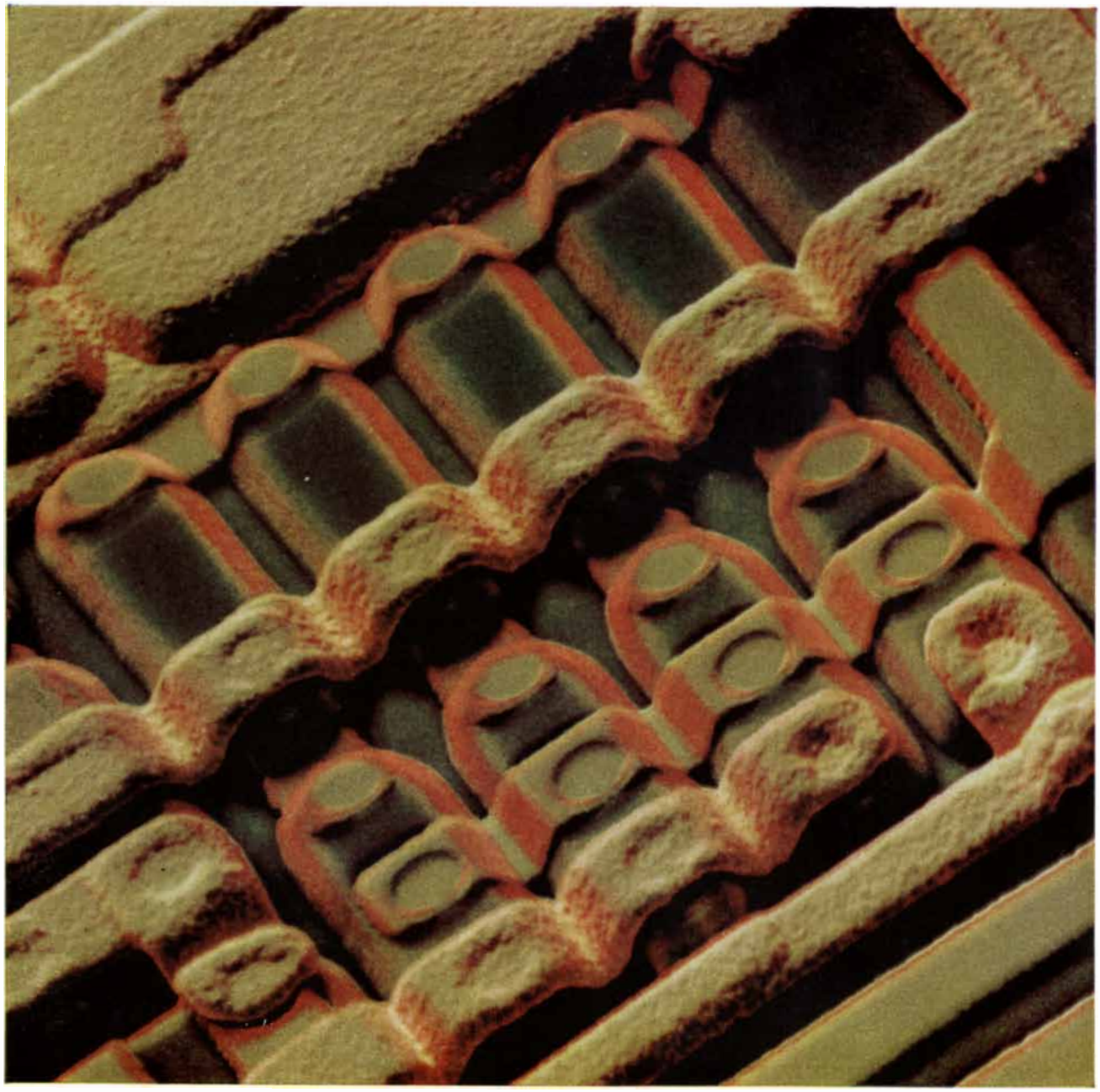

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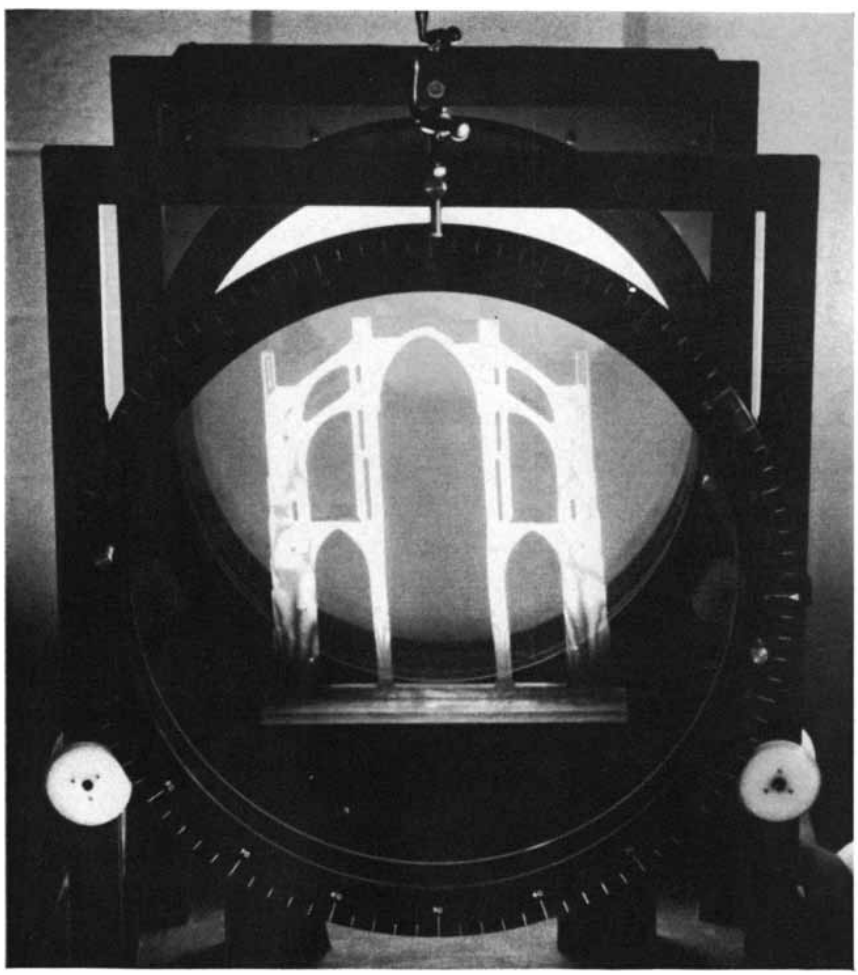
The Structural Analysis of Gothic Cathedrals

Comparison of Chartres and Bourges by optical stress analysis relates the aesthetic achievement to structural imperatives and suggests that later Gothic cathedrals may have been patterned on the wrong building

by Robert Mark

The 12th century was a time of prodigious change in the West. With the end of the First Crusade in 1099 the Mediterranean had again become a European sea; the reopening of trade routes and the creation of a powerful and affluent merchant class began to transform the entire fabric of medieval society. In the resulting context of increased wealth and expanded contact with the East a new form of architecture emerged: the Gothic.

Its primary characteristics were structure and light. Applied decoration was kept subservient to effects produced by the structure's own piers, ribs, vaults and buttresses. Even the achievement of interior "luminosity" was related to structure: it was attained by light admitted through stained glass in enlarged wall openings. By the end of the century this preoccupation with structure had taken visible form. Two immense Gothic cathedrals were under construction, one at Chartres and the other at Bourges. And it was during the first half of the next century, in the Île-de-France region, that Gothic architecture is generally considered to have flowered, with the completion of Chartres in 1221 and then of major portions of the cathedrals of Reims (begun in 1211) and Amiens (begun in 1220).



OPTICAL STRESS ANALYSIS of structure is carried out in a polariscope, in which a plastic model of a section of a cathedral (Amiens in this case) is viewed between polarizing filters (*see illustrations on page 96*). Regions of stress in the plastic produce interference patterns: different colors in white light, and dark and light bands in monochromatic light.

The principal structural features of what came to be called classical High (literally high) Gothic were established at Chartres and refined in the later buildings: thin, quadripartite, pointed ribbed vaults are supported at regular intervals on tall piers; the piers themselves are supported laterally at the level of the clerestory by flying buttresses that lead to pier buttresses, or high exterior towers, usually topped by pinnacles. Intervening load-bearing walls were not required, and so they were largely supplanted by window openings [*see illustration on page 92*]. The height of the central aisle of these cathedrals is striking: the distance from the floor to the bottom of the keystones of the vaults is 118 feet at Chartres, 123 feet at Reims and 137 feet at Amiens. And a peaked wooden roof above the vaults adds as much as 60 feet to the overall height of the building section.

The evolution over a relatively short time interval of new structural systems that made possible this substantially lighter and higher masonry construction

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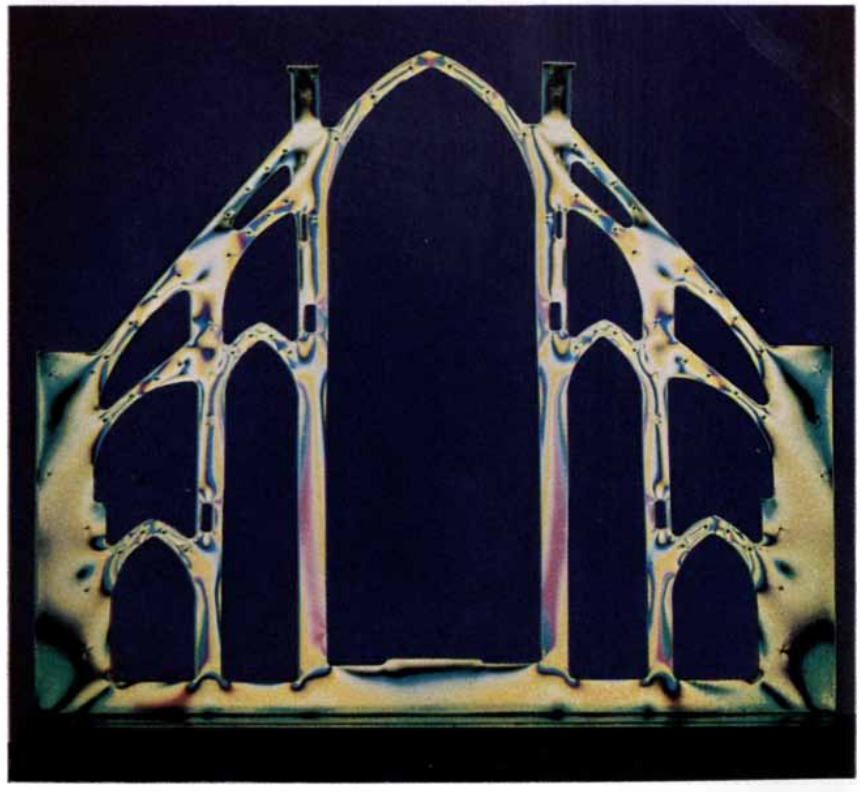
has never been fully explained. The stability of these great structures for some 700 years attests (in spite of a few spectacular failures) to the technical skill of their builders. How was this record of stability achieved? The cathedrals were designed without benefit of any mathematical structural theory; fragmentary evidence indicates, in fact, that the architects of the era worked only with roman numerals, so that they probably were unable even to multiply to calculate simple volumes. It has been suggested that they first built models to aid in planning, but in the absence of any numerical facility, let alone scaling theory, models would not have enabled them to predict the performance of the full-scale structures under load. My own hypothesis is that the design may have been successively modified on the basis of observation of the buildings during the course of construction. Corrections to eliminate the cracking of newly set mortar caused by either high winds or the removal of temporary construction supports could have been the source of structural innovation.

Far from understanding the cathedral builders' approach to the technical problems of design, architectural historians disagree even about the motivation that shaped their approach. For example, the influential 19th-century French restorer of cathedrals, Eugène Viollet-le-Duc, held that "every [Gothic] member was the result of structural necessity." At the other extreme, the contemporary architectural historian John Summerson has written that "reasons for the adoption [of the Gothic pointed arch] have been summarized in terms of statical expediency, but there is plenty of evidence to show that it was a matter of deliberate choice—a matter of taste.... Like almost everything else in Gothic architecture, [the ribbed vault] originated in aesthetic intention." These divergent opinions define a lively controversy that has developed between the "rationalists," who hail the cathedrals as triumphs of technical ingenuity, and the "illusionists," who reject the possibility that such great beauty could be derived from a technological approach.

In 1960 the noted medieval-art historian Paul Frankl, recognizing the difficulty of technical interpretation, urged his colleagues to consult with "the physicist." Modern physics had veered away from the study of applied mechanics, however, leaving it in the hands of research engineers, and in the past decade engineers have acquired

CHARTRES MODEL, stressed by simulated wind loading, is of a section across the nave of the cathedral. The pattern can be interpreted as a contour map of stress intensity; each color represents a different order of interference, which is related to intensity of stress. The stress is zero in black regions of the model and is highest where fringes are closely spaced.



BOURGES MODEL, a section across the choir, was photographed in the polariscope after being stressed by simulated dead-weight loading. Stress-intensity contours are quantified by analyzing the model illuminated by monochromatic light **(*see illustrations on page 97*).**

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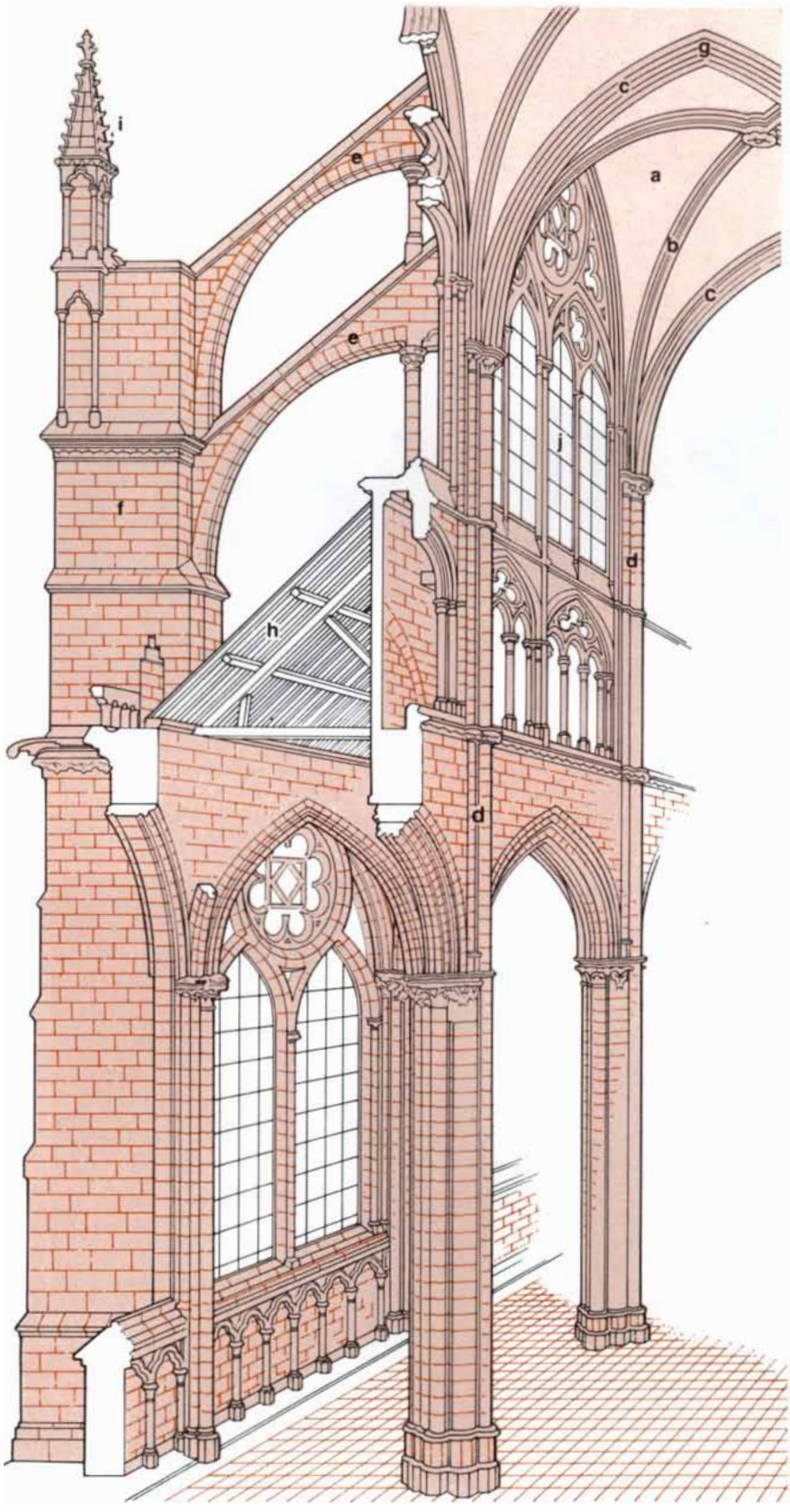

STRUCTURAL CHARACTERISTICS of High Gothic cathedrals are indicated in a drawing of the nave of Amiens Cathedral based on one made by Eugène Viollet-le-Duc. The pointed vaults (*a*) are constructed with a system of diagonal (*b*) and transverse (*c*) ribs on tall piers (*d*). The piers are supported by flying buttresses (*e*) that run to exterior pier buttresses (*f*). Other structural elements are the vault keystone (*g*), the side-aisle roof (*h*) and the pinnacle (*i*). The windowed wall area above the side-aisle roof is the clerestory (*j*).

new experimental and computer-based numerical modeling techniques that make it feasible to analyze the performance of complex structures. It was my students at Princeton University who about six years ago saw that the modern methods of analysis could be brought to bear on unanswered questions about the meaning of Gothic form.

At that time we were conducting research on the behavior of concrete thin-shell roof structures by studying small plastic models with optical stress-analysis techniques that had been developed primarily for studying specialized mechanical components. One goal of our research was to promote the wider application of these techniques for the structural design of complex buildings. We found that the model results could be reliably scaled to predict internal forces and deflections of reinforced concrete structures, even though concrete is an inhomogeneous mixture of materials and is subject to local microcracking. We realized that a masonry structure would also lend itself to this type of analysis provided that it was subjected to only moderate compressive forces. In effect this assumes complete cohesion, which may not actually exist in the full-scale masonry building, but the model does indicate the extent and location of any anomalous regions. If significant tension or compression stresses are found in a model, it can be altered locally, for example slit in tensile regions to represent cracking, and tested again to study the influence of such anomalies. It therefore seemed feasible to use model tests to study the actual structural behavior of the Gothic buildings and possibly also to surmise the intentions of the medieval architects regarding structure.

Our first tentative studies brought us in contact with interested colleagues in the humanities. A number of architectural historians, intrigued by the potential of engineering insights, provided the necessary guidance and criticism. Our early efforts included a study of the distribution of internal forces resulting from high wind and dead-weight loads on a section of the nave of the Amiens cathedral. One specific result was our finding that the pinnacles atop the outer edges of the pier buttresses helped to maintain the integrity of the buttresses by overcoming local tension. This analysis disposed of an illusionist argument that the pinnacles must be purely decorative because gross stability considerations would dictate their location at the inner edges of the buttresses rather than the outer edges. Another study, of the late

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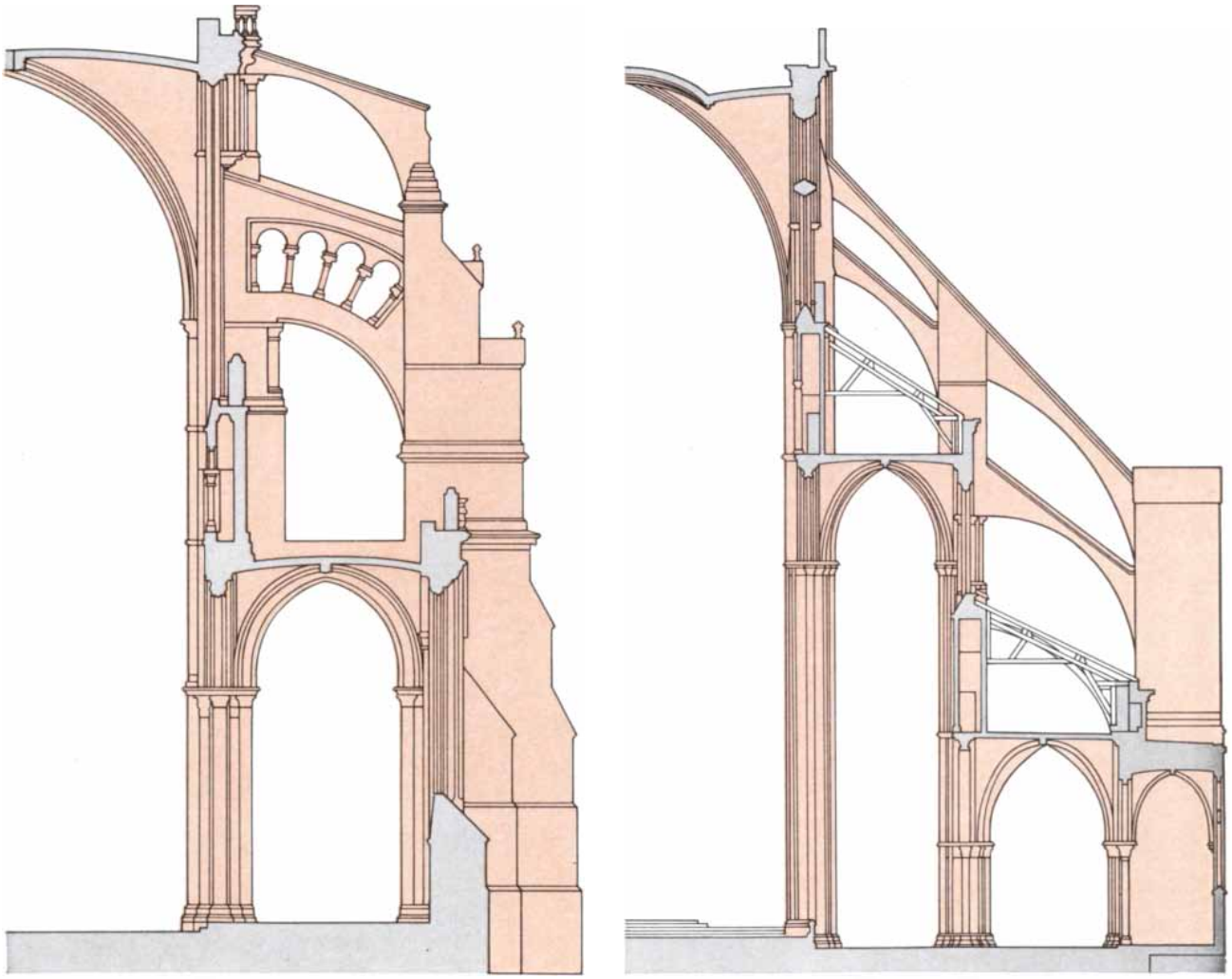
Gothic St. Ouen church in Rouen, indicated how structural ideas had evolved throughout the Gothic period. One particularly satisfying result of this investigation was our prediction that there might be some cracking in a certain region of the nave piers; the cracking was later confirmed by observation.

We have not clearly established whether the Gothic architect was motivated more by structural necessity or by "taste." By showing exactly how the structures perform, however, we have at least indicated how he responded to the actual structural needs, and so a beginning has been made in clarifying many of the questions posed by the historian. Probably the segment of our work that is most revealing about the development of High Gothic structure is a recent study comparing the early High Gothic cathedrals of Chartres and Bourges.

Construction of both buildings began in 1195. At Chartres the work apparently proceeded from west to east, beginning with the nave. At Bourges it proceeded from east to west, and the choir was completed in 1214 although other construction took almost a century to finish. The much more rapid pace of construction at Chartres brought work on the main vessel of the cathedral to a close in 1221. The dimensions of the two buildings are very similar: Bourges is slightly wider and higher and Chartres is longer. Chartres has three aisles and a crossing transept between the nave and the choir; Bourges has five continuous aisles and is without a transept.

Chartres is a very beautiful building, particularly in its details, and from the beginning it received a great deal of attention. After some initial resistance it was accepted as the standard, in effect ending the period of experimentation with Gothic building forms that characterized the 12th century. On the other hand, although Bourges has always been esteemed for its imposing size and beauty, it never attracted a similar architectural following. Even more important to the present study, the profile of its buttressing system was not duplicated in any other High Gothic cathedral. The importance of Chartres is implicit in the emphasis placed on it in the literature on the Gothic cathedral. Bourges, often mentioned as an interesting footnote, has been the subject of only one complete modern study, by Robert Branner of Columbia University. The main reason for the ascendancy of Chartres, according to Branner, is that it was imitable: its design could be reordered to suit almost any site, whereas the Bourges scheme could only be adopted whole. It might also be that Chartres's location, only 50 miles (a one-day journey on horseback) from Paris, allowed it to become far better known, to ecclesiastic patrons as well as to medieval architects, than Bourges,



CHARTRES AND BOURGES sections are compared. The three-aisle layout of the Chartres nave (*left*) became the model for High Gothic cathedrals; the Bourges choir (*right*) has five continuous aisles. Flying buttresses carry the vault and roof loadings more directly to the foundations at Bourges than they do at Chartres. The Bourges section is based on a drawing made by Robert Branner.

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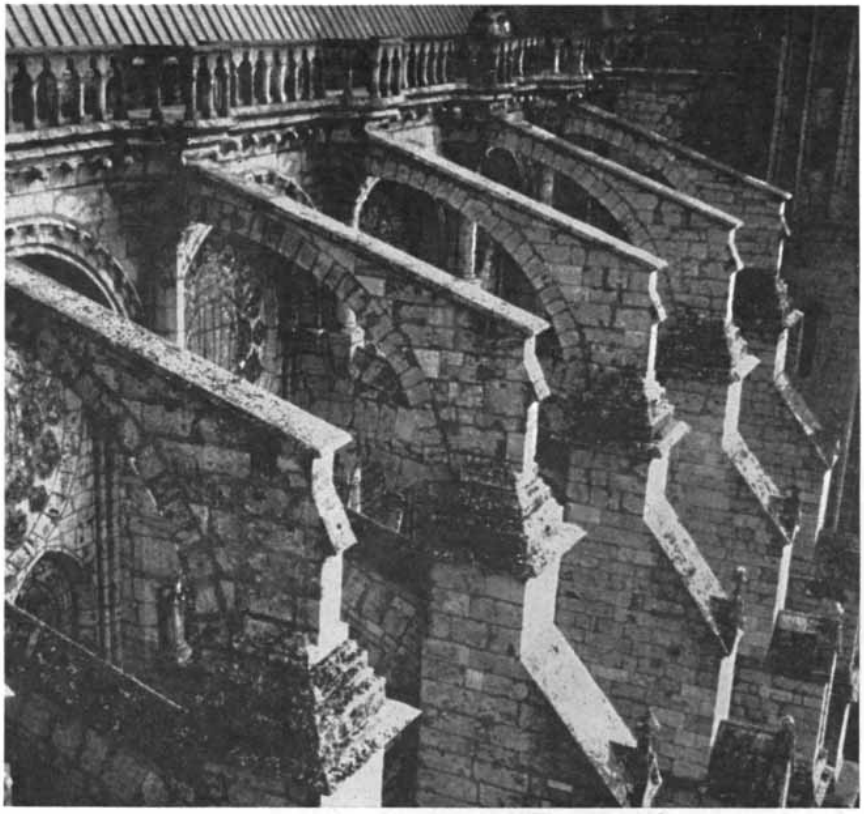
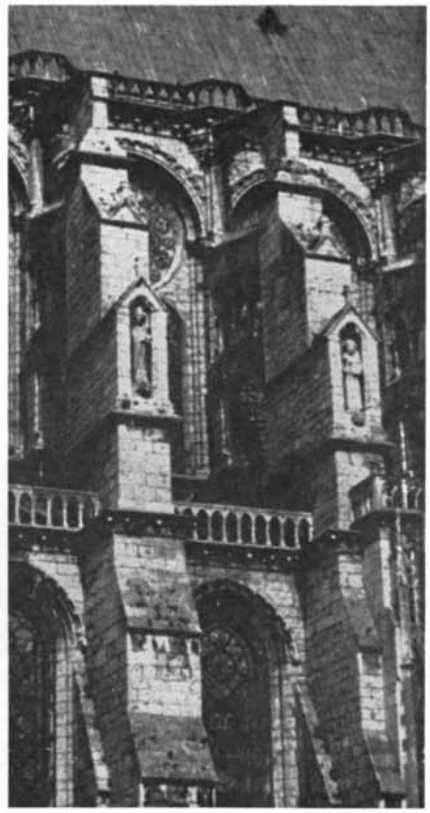
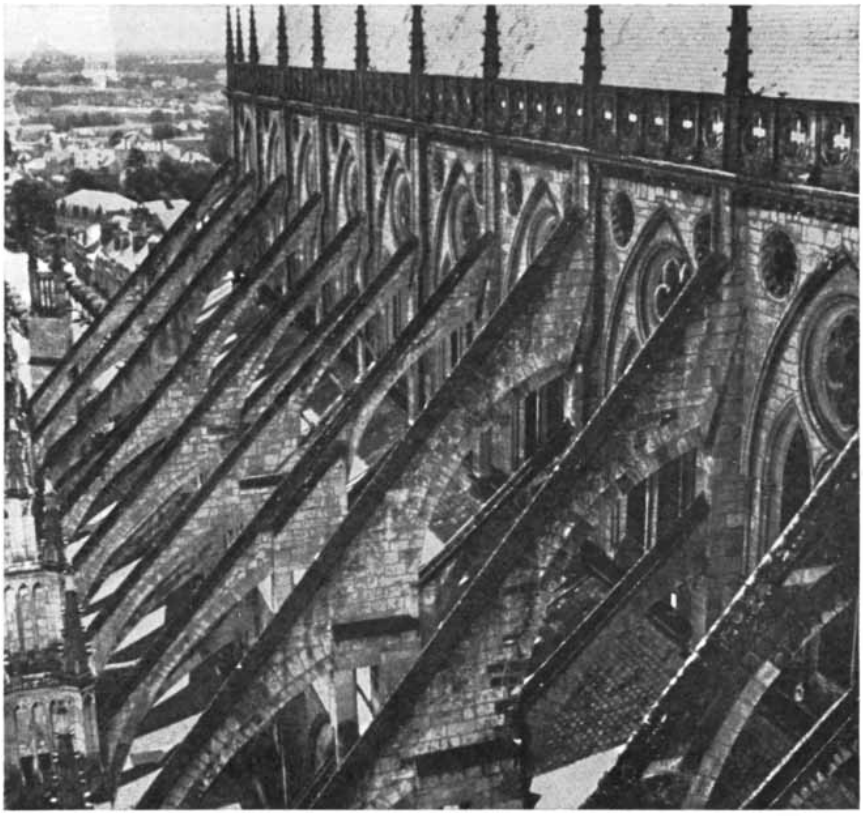




UPPER FLYING BUTTRESSES of Chartres (*left*) are uncharacteristically light and were generally assumed to have been added during the 14th century in order to correct a fault in the original design. The author's analysis indicates that they were probably a part of the original design, however. As seen from the ground (*right*) heavy pier buttresses tend to obscure the flying buttresses.



FLYING BUTTRESSES of Bourges (*left*) were built at different times. Those supporting the choir (*background*) are lighter than those used for the nave, which was constructed later; the nave flying buttresses also come closer to the roof. The piers at the choir are seen to be reinforced, just above their intersection with the flying buttresses, by the parapet: the wall just below the roof (*right*).

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which is more than twice as far from Paris.

At the time the two cathedrals were planned, the exposed flying buttress was a relatively new device. It had been used first in the 1170's at Notre Dame in Paris, but its full significance in allowing a great reduction of clerestory structure was only realized at Chartres and at Bourges. The cross sections of the two buildings reveal that the two masters employed different forms of buttressing [*see illustration on page 93*]. At Chartres the entire system is very heavy except for the light upper fliers; each of the tall pier buttresses, exclusive of its foundation, weighs 1,000 tons. At Bourges, on the other hand, a series of fine, steeply sloped fliers is supported by a low pier buttress weighing only 400 tons.

As with every other feature of Chartres, much has been written of its structure. According to Frankl, "the master who rebuilt the cathedral at Chartres... was the first man to draw the logical consequences from the construction of flying buttresses." In the same vein Otto von Simson wrote that "the flying buttresses of Chartres are the first to have been conceived, not only structurally but also aesthetically, as integral parts of the overall design." Almost all the critics, however, have questioned the role of the light upper fliers at roof level. A 1316 document produced by a group of experts called to examine the fabric of the then century-old cathedral has been generally interpreted as calling for the construction of these additional fliers, but the various opinions as to their function serve only to demonstrate how little is actually understood about the technical behavior of Gothic structure and the medieval architect's conception of structural necessity. Some writers maintain that the fliers are purely decorative; others believe they function as structure, although there is disagreement about how they function.

My colleague Alan Borg reinterpreted the 1316 document and assembled art-historical evidence to indicate that the Chartres upper fliers had been part of the original construction, but the functional reason for their existence still had to be considered. Since medieval roof framing is tied between the piers supporting the roof by stout, pinned cross-members, the only lateral loads on the upper portion of the piers are those due to wind action. The argument that the upper flier was added after 1316 to correct a fault in the original configuration would be substantiated if it could be shown that the upper buttress significantly reduces local tensile stresses in the piers that are caused by wind loading on the high roof. In view of the fact that the strength of the ancient mortar in tension has been estimated to be only 30 pounds per square inch, whereas stone can resist almost 100 times that stress in compression, minimizing or completely eliminating tension in a stone and mortar structure was a critical design requirement.

To examine the pier response we applied engineering analysis methods developed for designing contemporary high-rise buildings and used in our previous cathedral studies. We began by obtaining local meteorological data for the Paris region in order to determine the maximum possible wind velocities over the life of the cathedral and defining from wind-tunnel data the maximum wind-pressure distributions related to the meteorological data, the terrain on

MAIN VAULTING of Bourges rises 120 feet above the floor. Whereas the vaulting of Chartres and almost all other High Gothic cathedrals is quadripartite (*see illustration on page 92*), Bourges's vaulting is sexpartite. Alternate piers meet one vault rib or three ribs.

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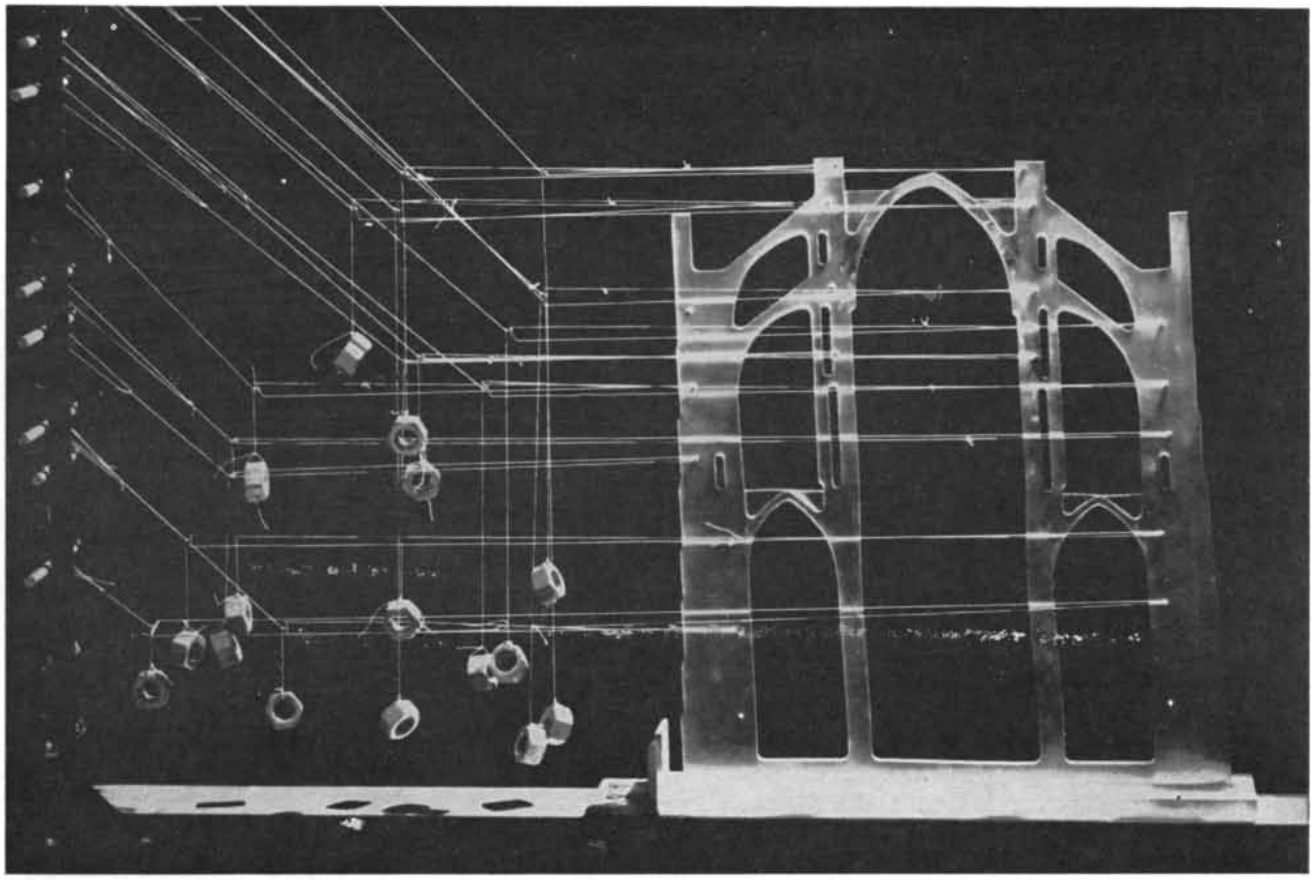
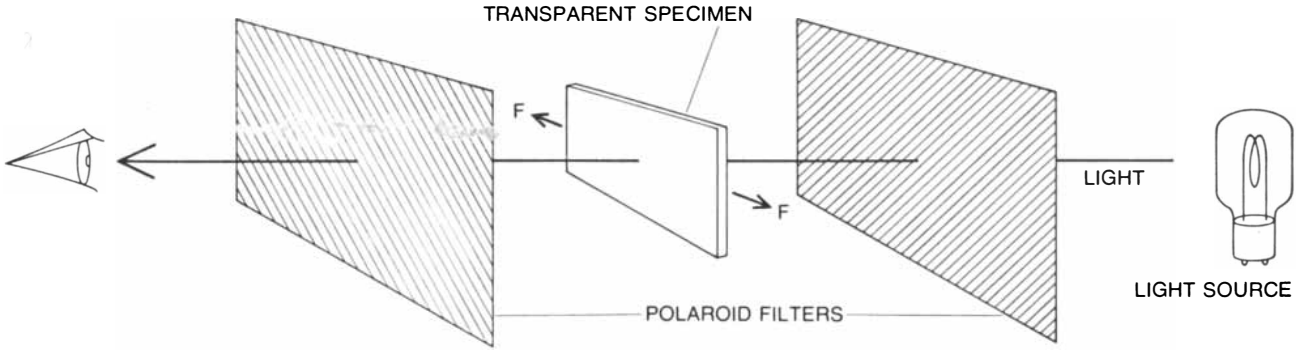


MODEL OF AMIENS is weighted to simulate wind loading against the right side. (Dead-weight loading would be simulated by hanging the weights from the modeled ribs and buttresses.) When the model is heated to 150 degrees Celsius, the plastic becomes rubbery and is deformed; when the heat is reduced, the deformations remain frozen in and the model can be observed in the polariscope.

which the building is sited and the geometry of the building. A 1:180 scale model in epoxy plastic of a typical buttress section of Chartres was fabricated without the upper fliers and tested under loading that represented the actual distribution of wind pressure (and of suction on the lee side). Fortunately the systematically executed French cathedrals are susceptible to simple planar (two-dimensional) analysis, since the nave is generally divided into bays with similar dimensions, the piers, buttresses and transverse arches of the central and side aisles are all in the same plane and the loadings from the bays are entirely directed to these members. We assumed that the massive foundations give complete fixity to the piers and buttresses at ground level, that is, that they do not allow any deflections at the base. Cross sections of the structural members were not fully modeled. (For example, fluted piers are represented by rectangular sections.) The analysis for the full-scale structure therefore contains discrepancies, but they are not significant.

Epoxy plastic undergoes a phase change to a rubbery state when it is heated to about 150 degrees Celsius. Lowering its temperature back to normal locks in any deformations due to loadings that are present during the high-tem-



PHOTOELASTIC PRINCIPLE underlying stress analysis is illustrated. Crossed-axis polarizing filters cut off the light. An unstressed transparent specimen has no effect on the polarization and so the field remains dark, but when forces (F) are applied, the specimen is deformed. As a result the polarization of light leaving the specimen is altered depending on the magnitude of the forces, the material and geometry of the specimen and the wavelength of the light. This altered polarization is seen as an interference pattern.

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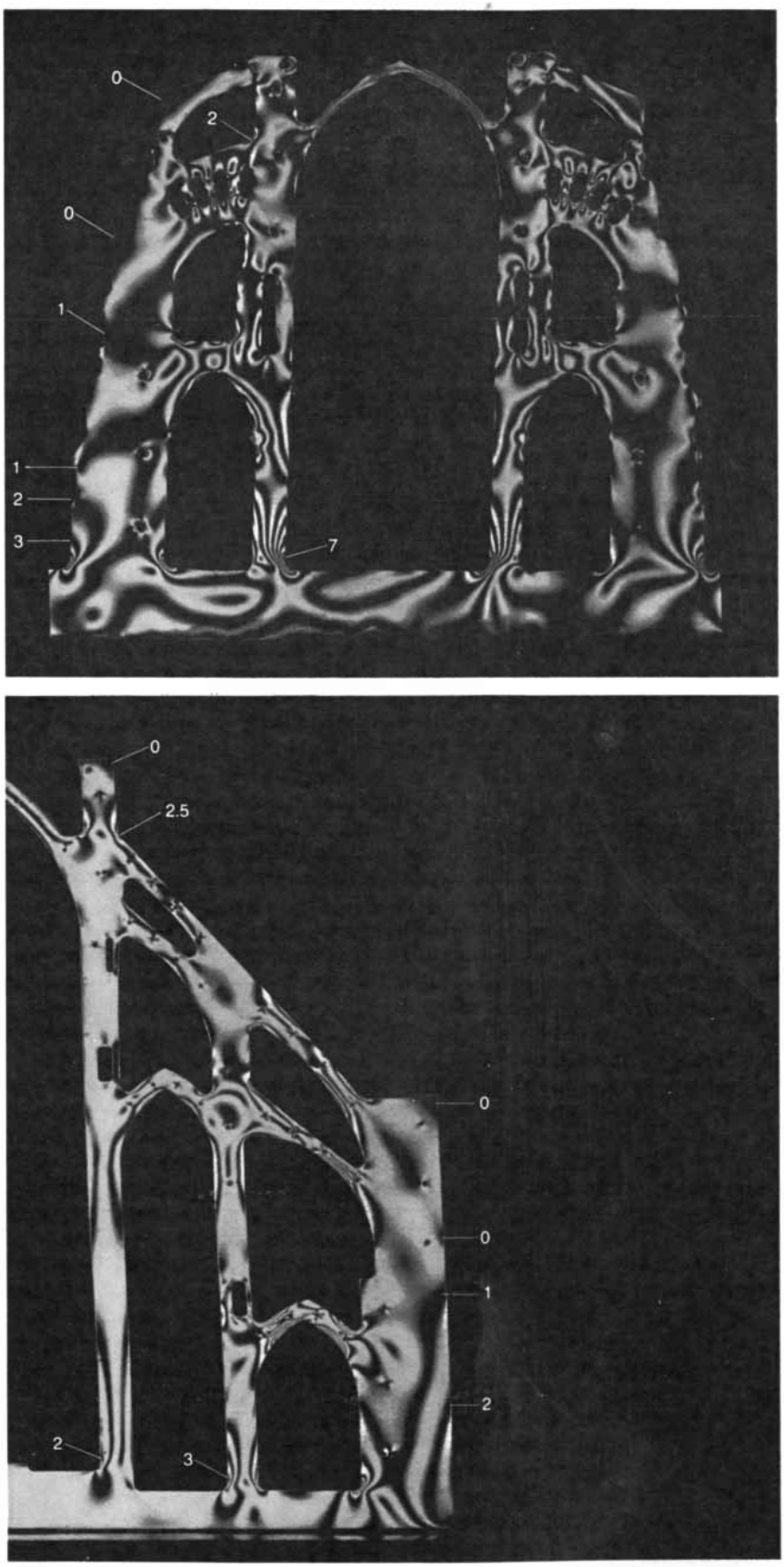
perature phase. This process is called "stress freezing" because the loading can be removed after cooling without disturbing the deformations that occurred at high temperatures, and the model can be examined and photographed conveniently.

The internal force distributions in the deformed model were determined from photoelastic observation, in which the polarized-light interference pattern produced by the model in a polariscope is read as a contour map showing stresses [*see illustrations on page 91 and at right*]. Under white-light illumination each line in the pattern is characterized by a distinctive color indicating a specific order of interference. The intensity of stress at any point is found by multiplying the order of interference by a calibration factor obtained from a specimen of the model material. Scaling laws can then be used to predict full-scale behavior under actual conditions.

Following the first test we annealed the model by heating to restore it to its undeformed condition and then attached the scaled upper fliers with high-temperature epoxy cement and made a second test with the same simulated wind loading. In the final phase of the analysis the stress in the piers caused by the dead-weight loading of the roof and its framing, the weight of the piers above the critical sections and the weight of the heavy longitudinal arches above the clerestory windows were calculated. Combining this dead-weight effect with the stresses arising from the extreme wind forces gave the maximum stresses that could be expected in the structure.

All the compression values in the buttress region were much less than stresses at the pier bases, and they required no further consideration. Low tensile stresses were also indicated at the windward edges of the windward piers just above the main vault-supporting flying buttresses. The onset of this pier tension in the unbuttressed configuration was found to correspond to gusts with a mean velocity at rooftop level of 45 miles per hour, compared with 55 m.p.h. for the buttressed pier. Under the most extreme gust conditions, with mean velocities of 65 m.p.h. near ground level and 85 m.p.h. at the rooftop, there could be a maximum tensile stress of 60 pounds per square inch in the unbuttressed pier and 30 pounds per square inch in the buttressed pier. In other words, a region of local tensile activity is indicated in the upper piers under extreme winds. If there had been no upper flying buttresses, this condition would have been present with somewhat lower wind velocities and the



PHOTOELASTIC PATTERNS in wind-loaded Chartres (*top*) and Bourges (*bottom*) models appear as dark and light lines in monochromatic light. Successive dark lines represent different orders of stress intensity, indicated by numbers; intermediate orders are found by interpolation. By calibration with a known specimen, one can derive quantitative stresses in the model, which are scaled to indicate the behavior of the actual cathedral structure.

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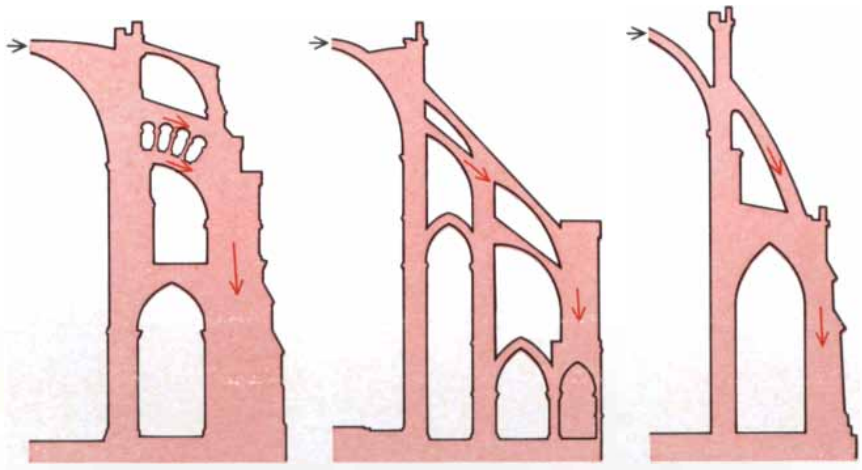

PROGRESSION to lighter and more simplified construction is indicated by a comparison of vault thrusts (*black arrows*) and resulting structural forces (*colored arrows*) in Chartres (*left*), Bourges (*center*) and a hypothetical modern design for a Gothic cathedral: a redesign, by the French critic Julien Guadet in 1902, of the cathedral of St. Ouen (*right*). Guadet substituted steeply inclined arches for the classical buttressing system. Analysis in the author's laboratory showed that the Guadet design is feasible and reduces structural forces.

probability of pier distress would certainly have been greater, but the upper flier does not entirely eliminate the problem; it is too light a structure to have been a deliberate addition intended to rectify an obvious structural flaw.

While it is not possible to draw absolutely firm conclusions from either analyses of the models or art-historical observations, both sources of evidence point to the conclusion that the upper flier was part of the original construction. The analysis has shown that this flier has only small effect on the heavy pier section, and so it becomes difficult to believe that the experts of 1316 would have suggested its addition. By that time the architects had had considerable practical experience with buttressing, and they would hardly have proposed the difficult and expensive addition of extra fliers unless these members were absolutely essential.

The significance of this analysis goes beyond the apparently minor issue of the date and purpose of the upper buttress itself, since our conclusions indicate that the Chartres architect was uncertain about buttressing. Considering the state of the art at the time of construction, that is hardly surprising. Yet an entirely different picture emerges when we examine the contemporaneous Bourges choir, whose light, open buttresses invite comparison with the heavy (in contrast even ponderous) Chartres system.

In planning the model test for Bourges it was necessary to account for its sexpartite vaulting. Unlike the quadripartite vaults of Chartres, which distribute equal loads to all the interior piers, the Bourges vaults transmit alternating high and low loads to correspondingly sized main piers along the interior aisle. A typical "strong" pier section, subjected to the higher vault loads, was modeled in epoxy plastic at a scale of 1:107 and was tested as in the Chartres study, first under dead-weight loading and then under simulated wind loads.

The best meteorological data applicable to Bourges were for Châteauroux, some 35 miles southwest of Bourges, and for a recent 10-year period rather than for 100 years, as at Chartres. The data indicated that Bourges is in a more sheltered area than Chartres. The maximum mean-wind velocity at the elevation of the cathedral roof was taken as being 65 m.p.h. Since wind forces on a building are produced as the square of the wind velocity, this reduction from the 85-m.p.h. velocity at the Chartres roof lowered the calculated maximum total force acting on each cathedral bay from the Chartres value of 110 tons to 60 tons for Bourges.

Under the action of combined dead-weight loading and wind loading, the stress levels throughout the section were found to be quite low. The highest compression stress, at the base of the main piers, was scaled to be 300 pounds per square inch, or about two-thirds of the maximum levels found in several other High Gothic buildings. Part of this reduction is attributable to the lower ambient wind speeds and part to the broader profile of the building section.

Since the Bourges choir does not employ an upper flier at roof level, we were particularly interested in scrutinizing the relatively slender unsupported upper main pier. We found that the vault thrust is entirely carried by the lower of the two flying buttresses that support each pier. The higher one must then have been placed to provide support against roof and parapet wind loading. Why was it not brought up close to the roof as at Chartres, or for that matter as in the seven nave piers of Bourges that were constructed in a later building campaign (after 1232)? The answer can be seen at the choir clerestory if one examines the intersection of the higher flying buttress with the pier. At this point of greatest bending moment the pier is reinforced by the lower part of the parapet to form a stout *T* section [*see bottom illustration on page 94*]. The tests revealed that the onset of tensile stress, which occurs in the windward upper pier, corresponds to gusts with a mean wind velocity at rooftop level of 57 m.p.h.; tension here is less than 10 pounds per square inch under the highest wind condition. The light choir structure of Bourges, then, provides stability to the high roof that is fully comparable to that afforded by the much heavier Chartres buttress configuration. One can speculate that a second Bourges architect, who clearly attempted to maintain the visual pattern of the choir buttresses when he designed the nave, was familiar with Chartres and probably was uneasy over his predecessor's daring. He modified the original design by deepening the flying buttresses and raising the point of abutment of the higher buttress against the pier.

Our analysis also indicated that without its pinnacles the low pier buttress would not be subjected to tension; the existing pinnacles have no structural role, as they do for example on the Amiens pier buttresses. This observation is entirely consistent with the fact that the Bourges pinnacles have been shown to be a 19th-century addition.

Additional light is shed on the achievement of the Bourges architect by a critique of the late Gothic St. Ouen church at Rouen that was published in 1902 by the French architectural authority Julien Guadet. He questioned the unique necessity of the classical structure: massive pier buttresses resisting vault forces through flying buttresses. He proposed a hypothetical alternative design in which the original interior configuration is unaltered but the buttressing system is considerably lightened by the substitution of steeply inclined arches. Besides requiring less material the alternative design implies a simpler construction process.

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Guadet published a graphical force analysis to substantiate his design, but it was a limitation of the current method of analysis that the interaction of the structural members could not be taken into account. For example, in the actual structure any deflection of the pier at its intersection with the arch must be accompanied by a corresponding deflection of the end of the arch. Considerable forces can be set up by these interactions and their effect should not be neglected. We accounted for these forces in a model test of the Guadet design. Although some further modifications might be necessary if wind forces were to be considered, the test showed that Guadet's design was reasonable for the deadweight loadings he applied. Hence we can consider the alternative St. Ouen design to represent a more advanced, theoretical Gothic form.

Juxtaposing the sections of the three similarly sized buildings reveals an obvious structural hierarchy [*see illustration on opposite page*]. The quantity of stone in the buttressing systems is progressively reduced from Chartres to Bourges to Guadet's St. Ouen. This reduction is achieved by carrying the vault and roof forces more directly to the foundations by raising the angle of the flying buttresses and consequently lowering the height of the pier buttresses. With only primitive machinery available for cutting the huge building stones and lifting them into place, the 60 percent reduction in weight of the Bourges pier buttresses compared with those of Chartres must have represented a tremendous economy in construction.

The final irony of Chartres is that instead of treating the flying buttresses as "integral parts of the overall design" the architect may actually have been attempting to conceal them behind the extremely heavy pier buttresses. It is a fact that the flying buttresses cannot be easily seen unless the viewer is quite close to the nave wall [*see top illustration on page 94*].

Clearly architecture can be misinterpreted if its technical aspects are not well understood. The problem is more acute when the scale of the project is large and the underlying technology assumes a more vital role in the design. The major contribution of Chartres was aesthetic; it provided the model for the great High Gothic buildings to follow. Yet technically Chartres was far less revolutionary than has been claimed. On the other hand, the structural solution adopted at Bourges was truly unique. It may, in fact, have been too far ahead of its time.

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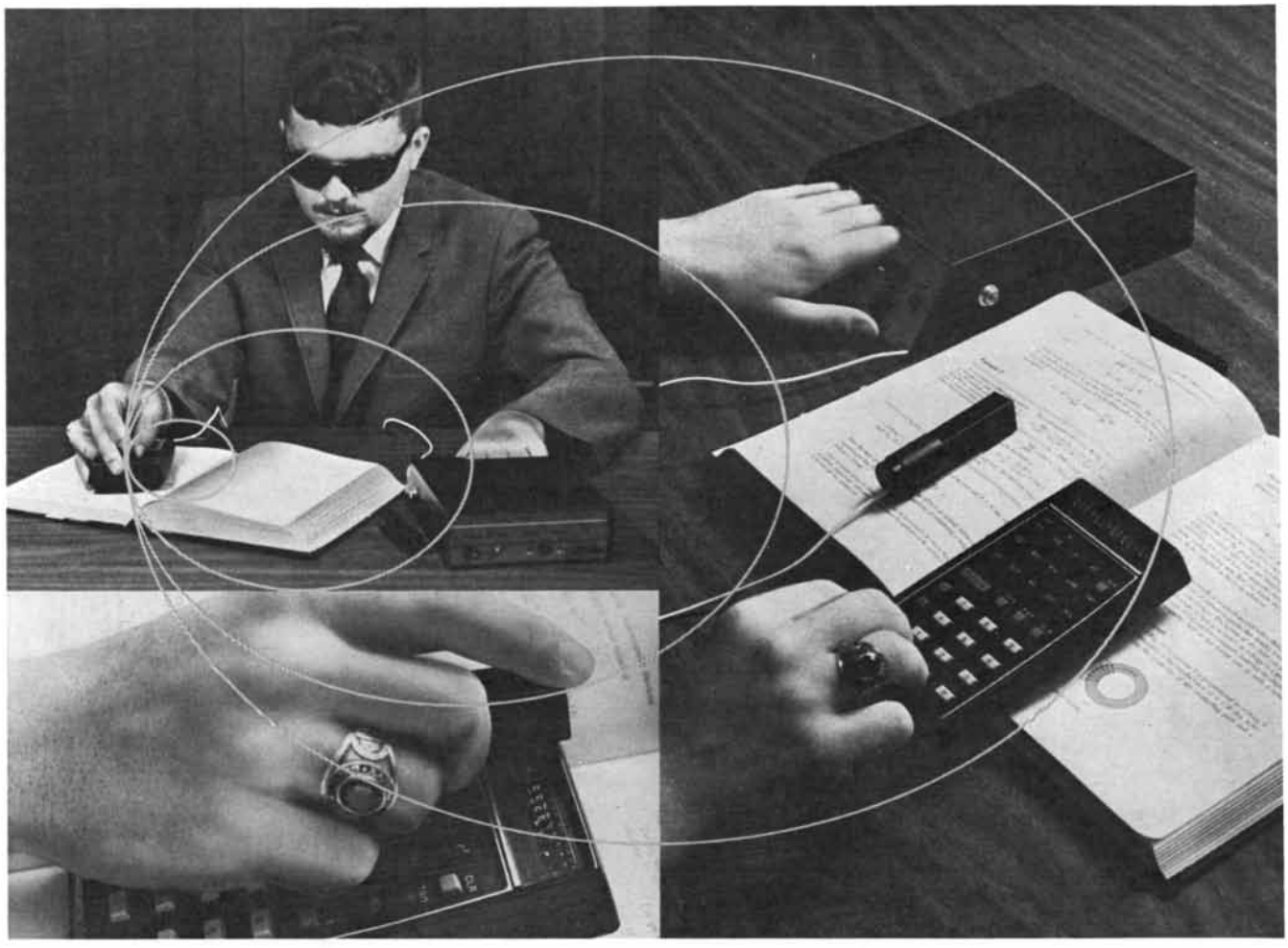

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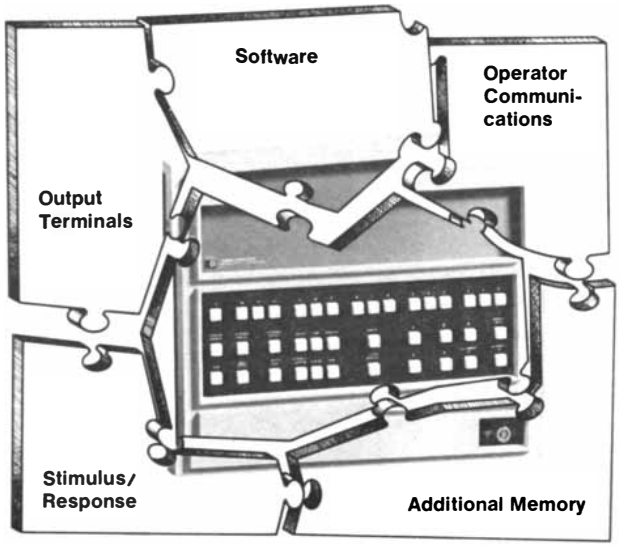

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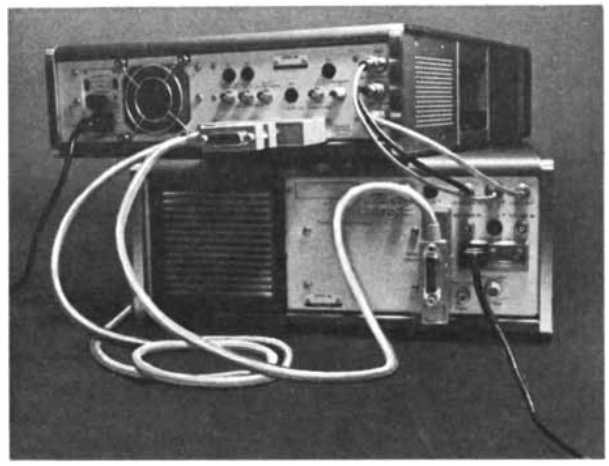

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EXOTIC ATOMS

An electron in an atom can be briefly replaced with another particle. The resulting new atom yields information on the nature of the nucleus

by Clyde E. Wiegand

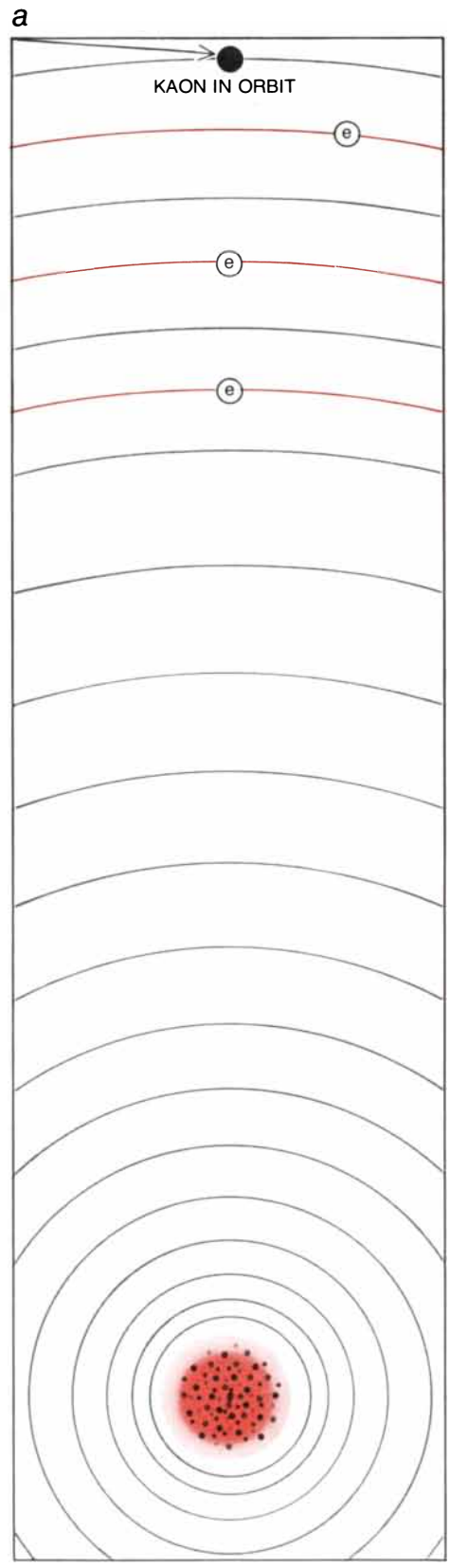
The atoms of ordinary matter consist of a cloud of negatively charged electrons surrounding a positively charged nucleus. The simplest of these atoms is hydrogen, with one electron and a nucleus consisting of one proton; the most complex is the latest element synthesized by nuclear chemists, which has 105 electrons and a nucleus made up of 105 protons and 157 neutrons. Most atoms are stable in the sense that they do not spontaneously change their properties. The exceptions are the natural and man-made radioactive atoms and what are called exotic atoms. In an exotic atom one of the electrons is artificially replaced with an entirely different negatively charged particle. Seven negative particles are capable of substituting for the electron, and so far five of them have been successfully implanted in ordinary atoms.

Although practically all the mass of an atom resides in the nucleus, the atom's chemical properties are determined by the number and configuration of the electrons. Until some 30 years ago the only elementary particles known were the proton, the neutron, the electron and the positron (a positively charged particle with the same mass as the electron). In the 1940's studies of cosmic rays revealed another class of charged particles: the mesons. Mesons are short-lived particles whose mass ranges between the mass of the electron and the mass of the proton (1,840 times the mass of the electron). The first man-made mesons were the pions, or pi mesons, created in the 184-inch cyclotron at the University of California at Berkeley in 1948. It was several years—and several cyclotrons—later that negative pions were successfully substituted for electrons in atoms.

Except for some special modifications all the exotic atoms resemble the hydrogen atom, and it will therefore be useful to briefly consider the properties of the hydrogen atom. The model of the atom proposed by Niels Bohr in 1913 puts the electrons in discrete orbits around the nucleus. An electron can occupy any one of these orbits but not the space in between. Each orbit is given a number called the principal quantum number and designated n. When a hydrogen atom is in its ground state, that is, its state of lowest energy, its electron occupies the first Bohr orbit, whose principal quantum number is 1. The radius of the orbit is 5×10^{-9} centimeter. The atom can be excited to higher energy states by absorbing a photon, or quantum of electromagnetic radiation, from an external source. The electron jumps to another Bohr orbit, and in 10^{-8} second the atom spontaneously emits a photon of its own and the electron returns to the ground state.

The orbit to which the electron jumps depends on the energy of the photon absorbed by the atom: a more energetic photon will cause the electron to jump to a higher Bohr orbit (for example, to one where $n = 4$ or $n = 5$) than a less energetic photon will. When the energy of the photon is sufficiently great to remove the electron completely, the atom is said to be ionized. For hydrogen the energy of ionization is 13.6 electron volts, corresponding to the energy of a photon in the far-ultraviolet region of the electromagnetic spectrum. A lone proton will ultimately attract a free electron or steal one from another atom. The new hydrogen atom will emit photons as the freshly attracted electron cascades down to the ground state from the orbits with large principal quantum numbers.

An exotic atom created by replacing the electron with another negatively charged particle behaves in much the



EXOTIC ATOM IS FORMED when one or more electrons of an ordinary atom are artificially replaced with an entirely different negatively charged particle. In this illustration the capture of a kaon (K meson) by a target atom to form an exotic atom is depicted schematically. The kaon is captured near the 100th energy level of the kaonic

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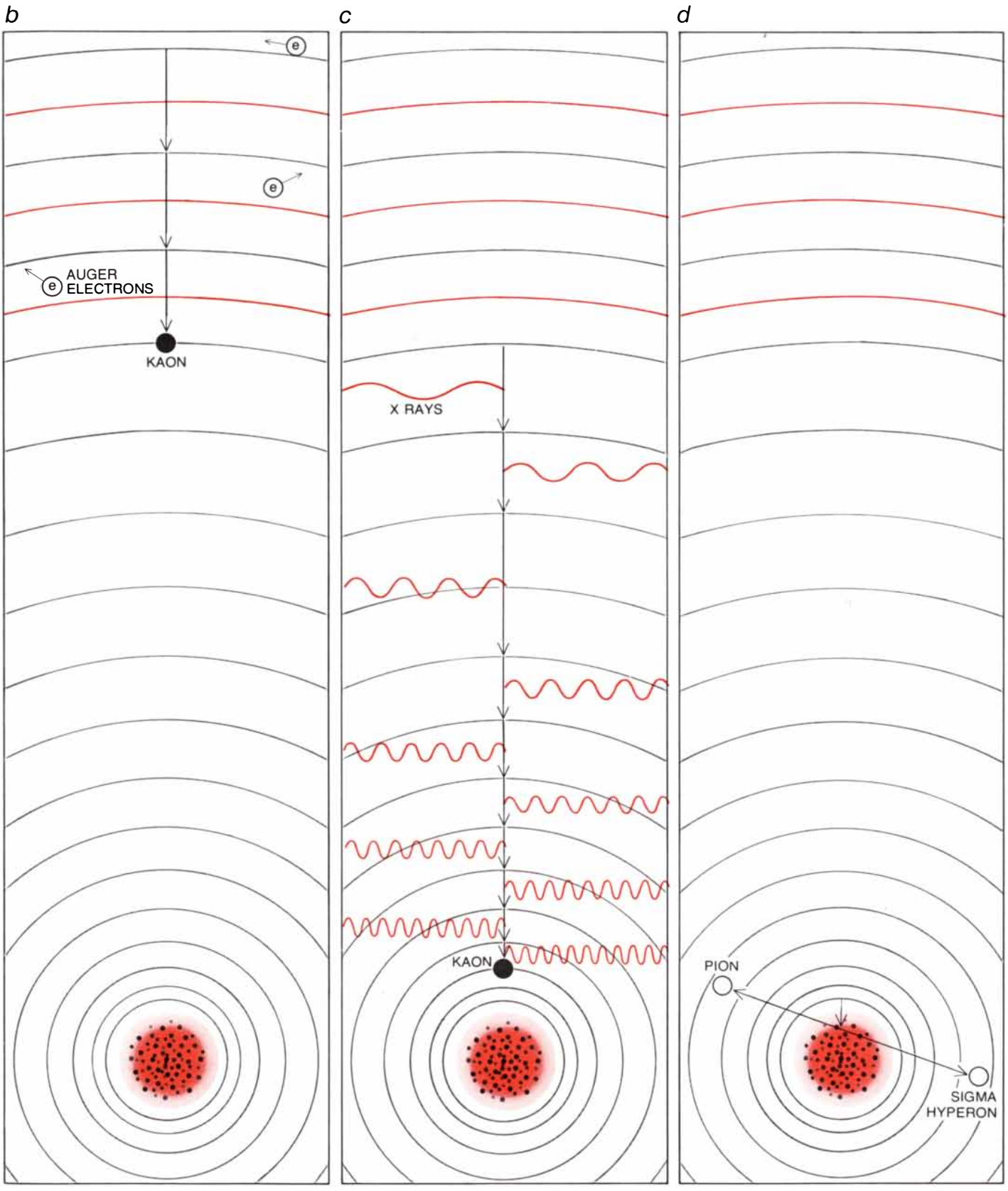

atom (*a*). As the kaon drops from one energy level to the next (*orbits in gray*), it falls within the electron orbits of the atom (*orbits in color*). The energy that the kaon releases during its fall ejects electrons from the outer reaches of the atom (*b*). These electrons are called Auger electrons. At each succeeding jump toward the nucleus the amount of energy lost by the kaon increases. Below the lowest energy level (ground state) of the electrons the energy is released in the form of X rays (*c*). The more energetic the X-radiation, the shorter the wavelength. Sometimes the kaon jumps more than one orbit at a time. Finally it enters a region near the nuclear surface, where it encounters a nucleon (a proton or a neutron). Both the kaon and the nucleon disappear, creating two new particles: a pion (pi meson) and a sigma hyperon (*d*). The distances of the drawing are exaggerated. If the atom were drawn to scale and the nucleus were represented by a dot one millimeter in diameter, orbit of the first electron would be almost one meter away.

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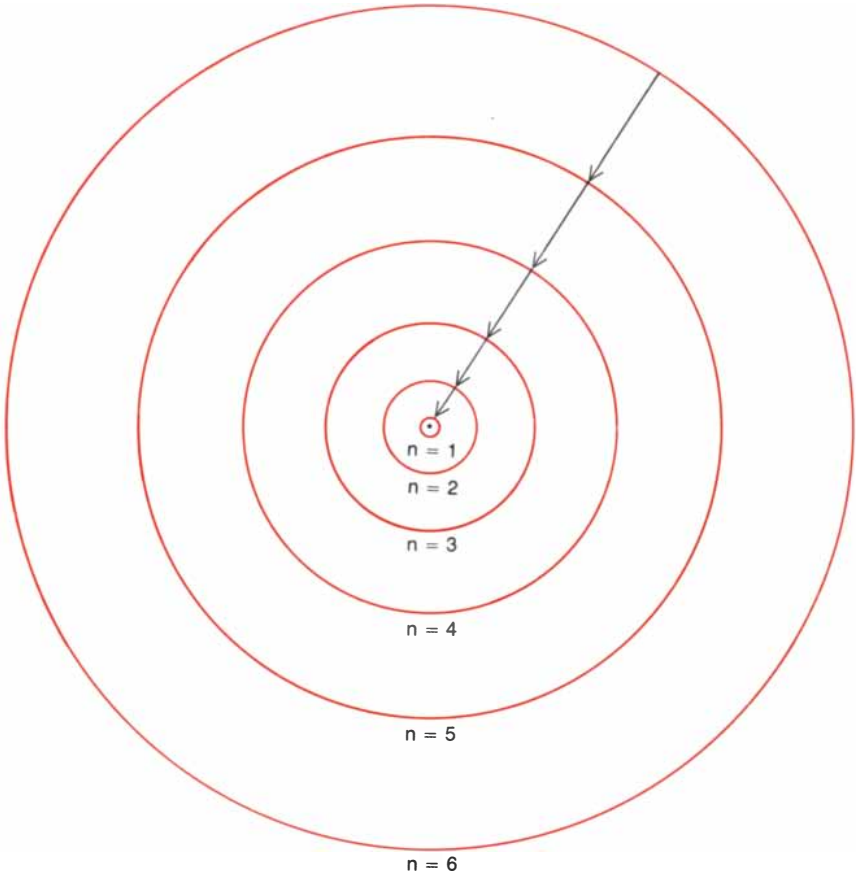
same way. Exotic atoms have two important characteristics. First, for the same quantum numbers the radii of the orbits are inversely proportional to the mass of the orbital particle. Second, the energy levels of the orbits are directly proportional to the mass of the orbital particle. For example, the pion is 273 times as heavy as an electron; therefore the diameter of the pionic atom is 1/273rd the diameter of the hydrogen atom, and the energy required to make the pion jump from one orbit to another is 273 times the energy required for an electron to make the same jumps in the hydrogen atom.

In order to make exotic atoms with negative mesons the mesons are created in an accelerator and directed at a suitable target. The mesons are slowed down and brought to rest by their interaction with the atomic electrons that are bound to the target nuclei. Ultimately the strong attraction of a positive nucleus draws the negatively charged meson toward it. In order for the atom to remain electrically neutral one of the atomic electrons is ejected as the meson is incorporated into the atom. The meson falls from one Bohr orbit to another as it approaches the nucleus that captured it. Mesons are generally caught in orbits larger than about $n = 30$, depending on the specific meson involved. The replacement process takes about 10^{-11} second; the capture time must of course be shorter than the lifetime of the meson. As the meson cascades through the orbits, it radiates photons in the form of X rays. It is by measuring the X-ray photons that we study exotic atoms.

In our experiments the mesons were produced in the Bevatron, the 6.2-billion-electron-volt accelerator at the Lawrence Berkeley Laboratory. X-ray detectors, the heart of the apparatus, were placed near the target. One of the most successful detectors was a single cylindrical crystal of ultrapure germanium two centimeters in diameter and four millimeters thick. The detectors and the associated electronic apparatus were perfected in the Lawrence Laboratory by the nuclear instrumentation group under Frederick Goulding, Richard Pehl and William Hansen. When an X ray is absorbed in the lattice of germanium atoms that make up the crystal, it excites many electrons in the lattice to higher energy levels. A vacancy in the lattice left by an excited electron can be regarded as a hole. The electron-hole pairs act as carriers of electric charge. In our experiments the X rays deposited their energy within the crystal in the form of electron-hole pairs, and the number of charges was proportional to the energy of the X rays. Electrical pulses produced by the charges were amplified and converted to digital numbers. The numbers, whose magnitudes were proportional to the energy of the X rays, were recorded on magnetic tape. A computer sorted the energies and tabulated them into the spectrum of the exotic atom [*see illustration on page 108*]. The excellent resolution of these spectrometers allowed a wealth of information to be recorded from the exotic atoms produced by the Bevatron.



BOHR MODEL of the atom assigns the electrons to discrete orbits around the nucleus. Each orbit is given a principal quantum number (n). The ground state of the atom is $n = 1$; higher levels are $n = 2$, $n = 3$ and so on. The radius of each orbit is proportional to n^2. Where n is large, the electron can easily be stripped from the atom. Radius of the $n = 1$ orbit of hydrogen is 5×10^{-9} centimeter. The Bohr model also applies to an exotic hydrogen-like atom except that all the radii are smaller in proportion to the mass of the orbital meson. For kaonic hydrogen the radius of the $n = 1$ orbit is 5×10^{-12} centimeter.

Two kinds of exotic atom have been known for almost 20 years. One is the pionic atom; the other is the muonic atom, made with muons, or mu mesons. X rays from pionic atoms were first studied by Morton Camac, A. D. McGuire, Joseph B. Platt and Harry J. Schulte at the University of Rochester in 1952. A year later Val L. Fitch and James Rainwater conducted experiments on muonic atoms at Columbia University. In more recent years interest in such atoms has been rekindled.

The behavior of muonic atoms has provided much information about the structure of the nucleus, particularly about the distribution of protons within nuclei. Muons are particularly valuable for probing the interior regions of nuclei because they interact only with the electric charge of the protons and do not "feel" the strong nuclear force that binds the nucleons (neutrons and protons) together. Since the size of the orbits is inversely proportional to the mass of the orbiting particle, some of the muonic orbits of low principal quantum number are so small that they actually lie within the nucleus [see "Mesonic Atoms," by Sergio DeBenedetti; SCIENTIFIC AMERICAN, October, 1956].

The most abundant of the particles that can make exotic atoms are still the pions. Like muons and electrons, pions feel the electromagnetic force of the nucleus, but in addition they are agents of the nuclear force. This force between

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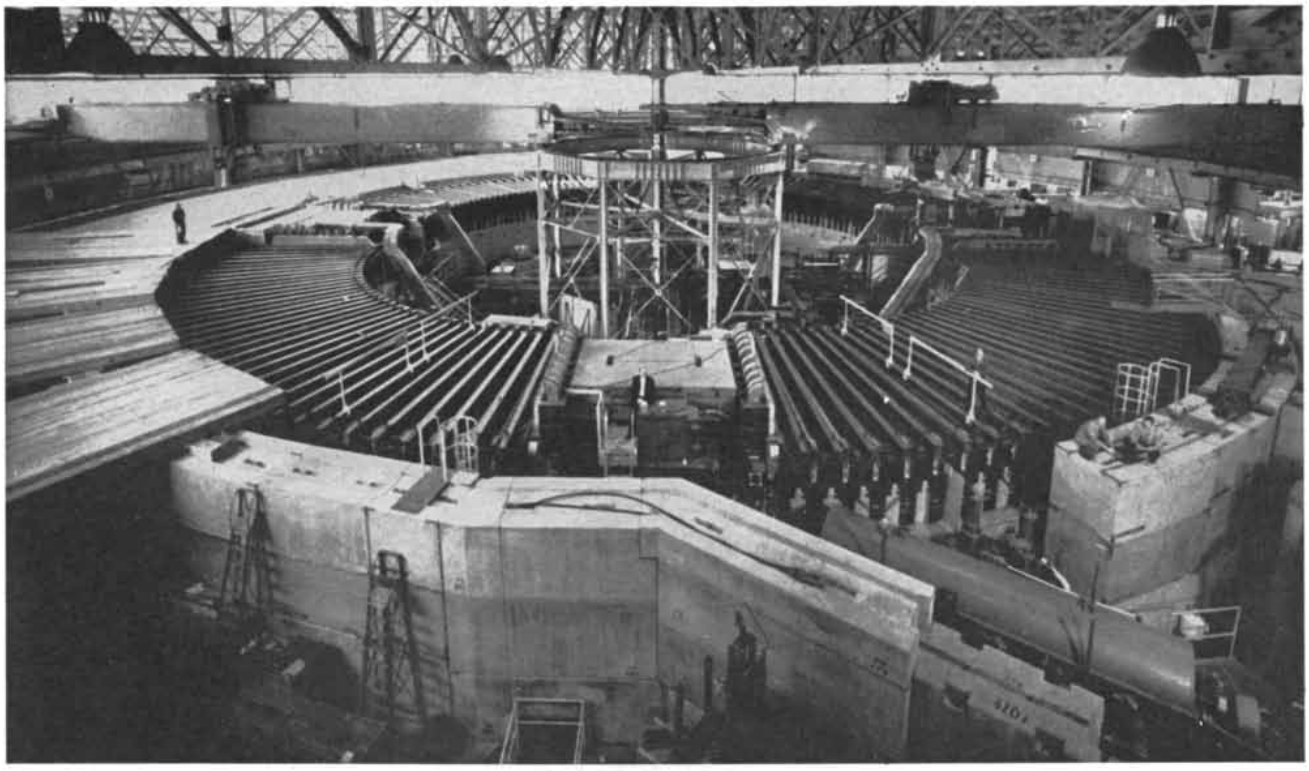

BEVATRON at the Lawrence Berkeley Laboratory of the University of California is one accelerator that has produced mesons for the study of exotic atoms. It is capable of accelerating particles up to an energy of 6.2 billion electron volts (BeV). At lower right is a linear accelerator that injects protons into a chamber within the huge circular magnet. The magnet is 120 feet in diameter and weighs 10,000 tons; the men standing on top of the machine indicate its scale. Particles circle the chamber four million times in 1.8 seconds, close to speed of light. In that time they travel some 300,000 miles, farther than the distance from the earth to the moon.

nucleons, and between pions and nucleons, acts only over a very short range: some 10^{-13} centimeter. It manifests itself in violent interactions that can cause particles to change from one species to another. Some 1,000 times stronger than the electromagnetic force, it is often called simply the "strong force." In this terminology many particles are said to react "strongly."

The precise energy levels of pionic atoms should be predictable from knowledge of the pion-nucleon interactions. Up to now, however, some of the calculated levels have not agreed very well with the levels observed in experiments. The study of pionic X rays has nonetheless yielded the most accurate value for the mass of the pion.

My own primary interest has been in exotic atoms formed with the particles known as kaons (*K* mesons) and sigma hyperons. The investigation of these atoms and the atoms formed with antiprotons (negatively charged protons) has begun only quite recently. After pions and muons had been put in orbit around nuclei, negative kaons were logically the next particles to be tried. Some evidence that kaonic atoms could be formed was provided by the tracks of kaons stopped in specially prepared photographic emulsions. Although the emulsion experiments did not reveal X rays, they did show that electrons and the reaction products of kaons were ejected from the silver atoms of the emulsion in a manner consistent with the formation of kaonic atoms. To the best of my knowledge the first attempt to observe the X rays from kaonic atoms was made by Joseph Murray and Nahmin Horwitz at the Berkeley Bevatron in 1958. They saw one line in the X-ray spectrum of carbon, but because the resolution of the detector was inadequate the experiment was discontinued. (Germanium semiconductor detectors had not yet been invented.) The first report on "K^--mesonic" X rays was published in 1965 by G. R. Burleson, David Cohen, Richard C. Lamb, Daniel N. Michael, R. A. Schluter and Thomas O. White, who were working at the Argonne National Laboratory. They used as a target helium: one of the most difficult but important elements to try. Again the results were not entirely convincing, mostly because the resolving power of the detector was inadequate and the level of background "noise" in the data was high. In 1966 Dick A. Mack and I, working with silicon semiconductor detectors at the Bevatron, succeeded in measuring several X-ray lines from kaons injected into targets of the light elements lithium, beryllium, boron and carbon.

Beams of kaons are much more expensive to make than beams of pions or muons. Pion and muon beams can be produced with cyclotrons of moderate energy; for all practical purposes negative kaons can be made only by machines that can accelerate particles to energies of more than five billion electron volts.

Negative kaons interact violently with both neutrons and protons. The investigation of kaonic atoms therefore yields information on the nature of the surfaces of nuclei. Are the surfaces smooth or granular? Do they show equal numbers of neutrons and protons? Or do they have more neutrons than protons, as was proposed by Montgomery Johnson and Edward Teller in 1953 on the basis of theoretical considerations [see "The Texture of the Nuclear Surface," by Chris D. Zafiratos; SCIENTIFIC AMERICAN, October]? We already know the distribution of protons from earlier investigations that showed how electrons are scattered by nuclei and how muonic atoms behave when the muons orbit within the nucleus. Electrons and muons do not,

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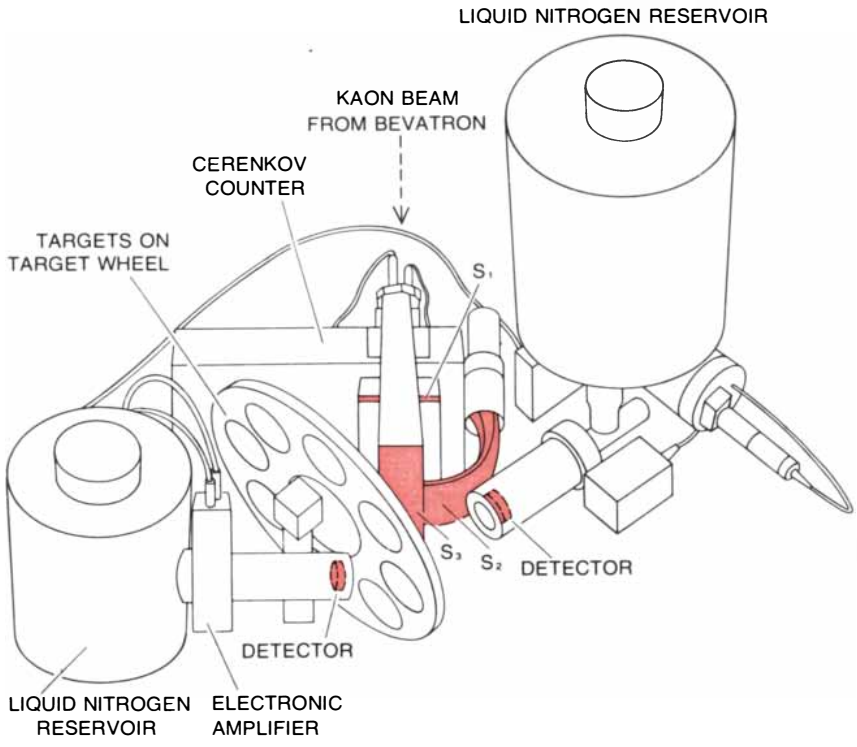
however, sense the presence of neutrons.

Observations of low-energy kaons in their encounters with neutrons and protons in bubble chambers suggested that the kaons could be used as probes because their behavior at the nuclear surface could be predicted. The number of reactions involving kaons at certain distances from the nuclei should in some way be proportional to the number of nucleons encountered at those distances. Whenever a kaon encounters a nucleon, both particles disappear and two new particles appear: a pion and either a sigma hyperon or a lambda hyperon. As in chemical reactions we must be careful to balance the equation: the electric charge and the pertinent quantum characteristics of the particles must be equal on both sides of the equation.

Let us imagine the sequence of events from the moment a negative kaon is captured by an atom. The kaon has replaced one of the inner electrons of the atom and is established in an orbit of about $n = 30$. The kaon is strongly attracted to the positively charged nucleus. It jumps down to a lower orbit, and at this stage of the process the energy liberated is most likely to eject additional electrons from the outer regions of the atom. These electrons are called Auger electrons. At each succeeding jump toward the nucleus the amount of energy lost by the kaon increases, until X rays become the dominant means of shedding the energy. Each jump of the meson between certain orbits results in the emission of an X-ray quantum of an energy and wavelength belonging to that transition. Finally the kaon enters a region near the nuclear surface, where it has a chance to encounter a nucleon in the "rarefied nuclear atmosphere" [*see illustration on pages 102 and 103*].

We interpret the disappearance of the X-ray lines in the spectrum of our measurements as a signal that the kaons have reacted with nucleons on the nuclear surface. For example, in certain elements the intensity of the X-ray lines for transitions between lower orbits (such as from $n = 4$ to $n = 3$) is less than the intensity for transitions between higher orbits (such as $n = 5$ to $n = 4$). This decrease in intensity means that some of the kaons were absorbed from the $n = 4$ orbit. If the intensity had dropped by half, we could say that half of the kaons were absorbed from the fourth orbit and thus could not make the jump from $n = 4$ to $n = 3$. For a transition starting from an orbit of a given principal quantum number the intensity had been predicted to drop quite suddenly as heavier nuclei (nuclei with more charge) were used as the target. Increasing the charge of the nucleus shrinks the kaonic orbits and brings the kaons closer to the nucleus; in addition the radius of the nucleus itself increases slightly. On the assumption that protons and neutrons are equally distributed on the nuclear surface, theory predicted that the termination of the series of X-ray lines would be a function of the number of protons. Our kaonic X-ray experiments of 1968 indicated, however, that kaons encountered nucleons at distances farther from the nuclear surface than had been anticipated. We theorized that the kaons reacted with a low-density halo of neutrons above the main nuclear surface.



X RAYS FROM KAONIC ATOMS were detected by the apparatus depicted in this drawing. The targets were mounted on a wheel and could be selected at will. Two (sometimes three) germanium or silicon detectors were placed near the target. The detectors were cooled by liquid nitrogen to suppress background "noise" in the data. Beam counters (S_1, S_2 and S_3) signaled the arrival of the kaons at the target. Response from detectors was amplified electronically and recorded on a chart as the X-ray spectra shown on page 108.

There is no complete agreement among theoreticians concerning the interpretation of the experiments. At the European Organization for Nuclear Research (CERN) in Geneva, T. E. O. Ericson has devoted considerable effort to the understanding of pionic and kaonic atoms. He believes the observed decreases in X-ray intensity can be calculated on the assumption that protons and neutrons are present at the nuclear surface in equal numbers. On the other hand, the notion that nuclear surfaces are dominated by neutrons has been put forward by several physicists since Johnson and Teller made their original prediction. The theoretical calculations are based on the concept that the nucleons will arrange themselves in a configuration that allows the total energy of the system to be at a minimum. An analogy is the fact that a free drop of liquid takes the shape of a sphere if it is not disturbed by outside forces. When all the known properties of nucleons are applied to the picture of nuclear matter, the configuration that results is one in which the neutrons have a slightly larger radius of distribution than the protons.

There are further complications in the simplified conclusion that the observed kaonic X-ray spectra show that nuclei have a skin of neutrons. The negatively charged kaons and positively charged protons attract each other with particular strength under special circumstances. This effect might cause the kaons to react more strongly with protons bound in nuclei than had been anticipated.

The early demise of kaons might then

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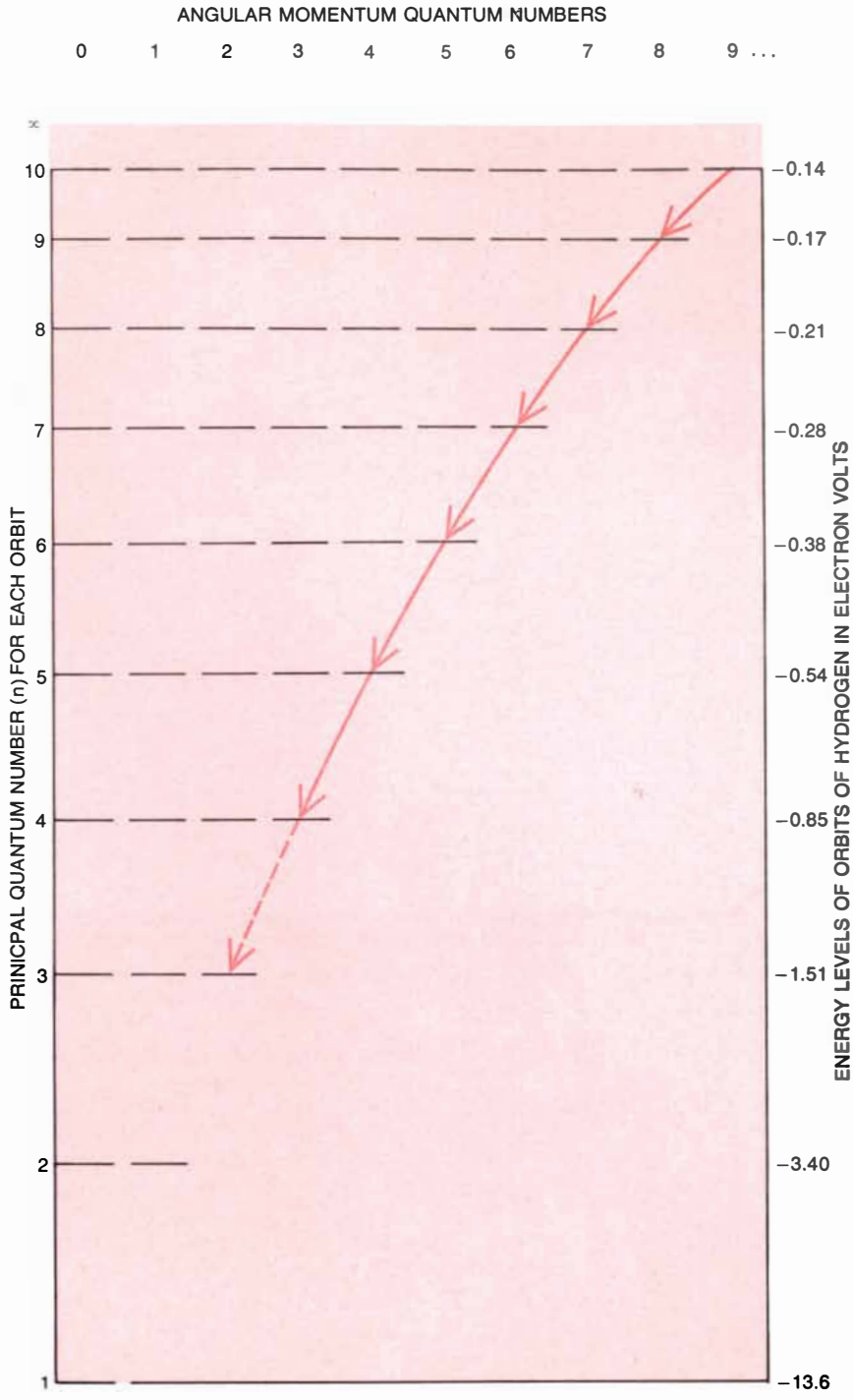
be attributed to a voracious appetite of some protons rather than an overpopulation of neutrons. Another factor that comes into play is that the affinity of kaons for nucleons is so strong the orbits of the kaons are pulled in closer to the nucleus than they would be for particles that do not react so strongly. These effects and others would modify the simple picture suggested by the exotic hydrogen atom.

Quantitative estimates of these effects are controversial. It is apparent that additional data and calculations will be needed to resolve the details of the structure of the surfaces of nuclei and the distribution of neutrons within the nuclei. Up to the present time most of the experiments on kaonic atoms have been done at Berkeley and at CERN, where an active group is directed by G. Backenstoss. Other groups at Argonne and at the Brookhaven National Laboratory have recently joined in the investigations. In spite of the complications physicists working on exotic atoms are confident that their studies will lead to a clearer picture of nuclei.

X-ray spectra of exotic atoms made with antiprotons were first observed by the CERN group in 1970. The antiproton was discovered with the Berkeley Bevatron, but the machine does not make a beam of antiprotons with sufficient intensity to produce antiprotonic X-ray spectra. Antiprotonic atoms emit X-ray spectra that are similar in appearance to kaonic X-ray spectra, but there is one significant difference that has recently been observed. If we could see all the lines at high resolution, we would almost certainly find that each line is a doublet, that is, it is made up of two separate lines. The lines are split because antiprotons and protons possess spin and magnetic moment. They behave as if they were spinning magnets. Some have their north pole "up" with respect to their orbital motion around a nucleus and some have it "down." In antiprotonic atoms the energy levels of the various orbits of the antiproton around the nucleus are slightly different depending on whether the spin is "up" or "down." The X-ray lines of the spinning particles are thereby split into two components, and the amount of splitting can be calculated.

The magnetic moments of protons and antiprotons are believed to be exactly equal except for their algebraic sign. This assumption is based on some of the most sacred symmetry principles in physics. The belief is that if all the



ENERGY LEVELS and angular-momentum quantum numbers of a hydrogen-like atom are shown. The principal quantum number (n) for each orbit is indicated in the vertical scale to the left. The vertical scale to the right shows the energy level of each orbit in hydrogen; for example, it would require an energy of 13.6 electron volts to take an electron in the ground state ($n = 1$) completely out of the hydrogen atom. Exotic atoms can be considered hydrogen-like systems. The arrows show the main transitions a meson makes as it falls toward the nucleus after being captured. Some 10 percent of the particles skip an orbit as they fall, say from $n = 6$ to $n = 4$ without pausing at $n = 5$. The energy in electron volts of each orbit of an exotic atom is given by the relation $-13.6(Z^2/n^2) \times$ mass of the orbital particle divided by the mass of the electron. Z is the number of protons in the nucleus and n is the principal quantum number. For example, mass of a kaon divided by mass of the electron is 966. The $n = 4$ orbit of a kaon around a chlorine nucleus has an energy of 237,000 electron volts. For the $n = 5$ orbit the energy is 152,000 electron volts. The difference between these two energies is 85,000 electron volts. There is a tall peak in the X-ray spectrum of chlorine at this energy, corresponding to the transition from the $n = 5$ orbit to the $n = 4$ orbit (*see the carbon tetrachloride spectrum on the next page*).

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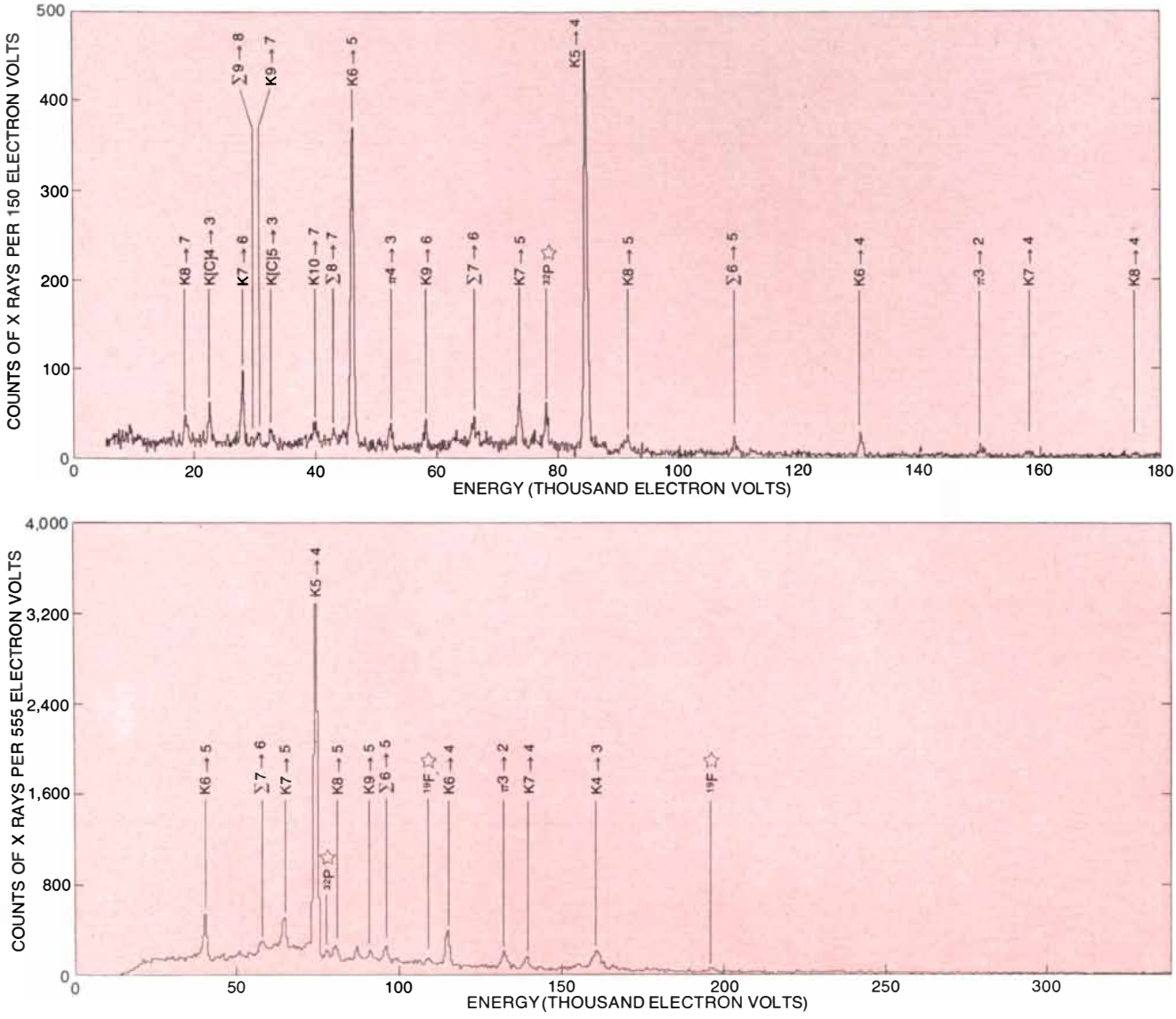
charges were interchanged (negative for positive), all the position coordinates were interchanged ($-x$ for $+x$ and so on) and time ran backward, the results of all experiments in the "negative" world would be the same as those in the "positive" one. Physicists like to test the theorem of invariance at every opportunity. A split X-ray line in the spectrum of antiprotonic uranium was observed last summer by a group of physicists at Brookhaven. They found that the magnetic moment of antiprotons was opposite in sign to the magnetic moment of the protons and agreed with the predictions of symmetry. It will probably be some time, however, before measurements are accurate enough to afford an ultimate test of the theorem by this method. Meanwhile antiprotonic atoms are expected to take their place alongside pionic and kaonic atoms as probes of the nucleus.

As I have mentioned, kaons react with nucleons to form pions and hyperons. Many of the hyperons are ejected from the nuclei in which they are formed. Their kinetic energy is sufficiently low for them to have a high probability of staying in the target in which they originate. They are slowed down, come to rest and are captured in the same way that kaons are captured by nuclei. Thus X-ray lines from hyperons were expected to appear along with the X-ray lines from kaons.

In a kaonic X-ray spectrum of potassium obtained in the Berkeley experiments of 1968 there was a line at 136,000 electron volts that corresponded to the transition energy of a sigma-minus hyperon when it jumps from the $n = 6$ orbit to the $n = 5$ orbit. Some two years later the CERN group confirmed the formation of sigma-minus hyperonic atoms by identifying several spectral lines of the transitions of sigma-minus hyperons in chlorine and zinc. The X-ray lines of sigma-hyperonic atoms have appeared in the kaonic spectra of elements as light as lithium and in the medium-heavy ele-



SPECTRA OF X-RADIATION from kaonic atoms are shown for targets of carbon tetrachloride (*top*) and sulfur (*bottom*). The energy of the spectrum in each case increases toward the right, and the intensity of the X-ray lines increases toward the top. K stands for a transition made by a kaon, Σ for a transition made by a sigma hyperon and π for a transition made by a pion. The numbers indicate which orbits were involved in the transition. For example, $K8 \rightarrow 7$ means that the transition was made by a kaon jumping from its $n = 8$ orbit to its $n = 7$ orbit. In the carbon tetrachloride target most of the transitions occurred in chlorine atoms. Transitions in carbon atoms are labeled $[C]$, for example $K[C]4 \rightarrow 3$. The stars stand above the spectral lines that were created not by kaonic X rays but by gamma rays that were emitted by excited phosphorus or fluorine nuclei returning to their ground-state energy level.

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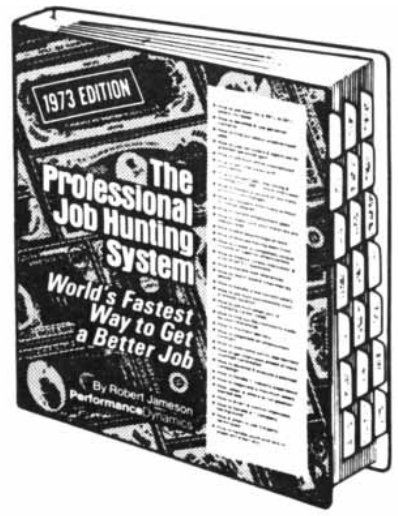

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ments. At the present time no lines have been found in the spectra of the heavy elements.

The intensity of the lines for sigma hyperons is about 2 percent of the intensity of the principal lines for kaons. Several factors contribute to the low intensity. First, only some 8 percent of the kaons react to make negatively charged sigma hyperons. Second, after the hyperons are created, many of them interact with the nuclei in which they are formed. Third, some of the hyperons decay into other particles while they are being slowed down or while they are in higher energy orbits.

Like many other subatomic particles, hyperons have spin and possess a magnetic moment. They are found in three forms: the sigma-plus (positively charged), the sigma-zero (uncharged) and the sigma-minus (negatively charged), and in the antiparticles of these forms. The magnetic moment of the sigma-plus has been crudely measured by observing how the particle precesses in powerful magnetic fields. The orientation of the sigma-plus particles in the field was determined by observing the direction taken by the particles into which the hyperons decay.

When sigma-minus hyperons decay, they do not emit particles that signal their orientation. Hence their magnetic moment cannot be measured by the method that works with sigma-plus hyperons. The measurement of the sigma-minus magnetic moment would be important to particle physics. The study of sigma-minus hyperonic atoms offers this possibility if we can observe the doublet structure of the X-ray lines. The amount by which the lines are split is proportional to the fourth power of the atomic number (the number of protons). Therefore the heavier the element, the easier it should be to resolve the doublet pairs of X-ray lines. The splitting will nonetheless be difficult to observe, particularly if few sigma-minus atoms are made in heavy elements. Even if the lines cannot be completely resolved, it may be possible to set a meaningful upper limit on the magnetic moment of the sigma-minus hyperon. Sigma-hyperonic atoms may also add to the information gained from other exotic atoms in the mapping of nuclear surfaces.

What is the possibility of making other exotic atoms? In the table of subatomic particles there are two more candidates: the xi-minus and the omega-minus. Their lifetime is roughly the same as the lifetime of the sigma hyperons. The xi-minus is 10 percent heavier than the sigma-minus and the omega-minus is 40 percent heavier. The two particles are so scarce and so difficult to produce, however, that the tracks of only some 10,000 xi-minus particles and of a mere 25 omega-minus particles have been identified in bubble chambers at the largest accelerators. Perhaps the more powerful machine now in operation at the National Accelerator Laboratory in Batavia, Ill., and the one under construction at CERN will produce sufficient numbers of xi-minus and omega-minus particles to make it possible to identify atoms of the last two candidates on the present particle list.

In conclusion I should like to relate how the study of one subject can lead to another subject in this fascinating research that involves both high-energy physics and nuclear physics. Let us return briefly to pionic and muonic atoms. In addition to X-ray lines the spectra of these atoms showed gamma-ray lines that had come from excited states of nuclei formed in the targets in which the mesons had stopped. The mesons carried energy to the interior of the nuclei and raised the protons and neutrons to excited levels, in somewhat the same way that the electrons of atoms are raised to excited states. When the nuclei fall back to their ground level, radiation is emitted in the form of gamma rays. Now, when we were getting our kaonic X-ray spectra, we were asked many times: "Why don't you see nuclear gamma rays along with the kaonic X rays?" In some of the spectra there were a few low-intensity lines that we had not been able to attribute to exotic atoms. We finally did identify these lines as nuclear gamma rays.

The relevance of gamma rays induced by kaons has not yet been assessed, but a significant aspect of kaonic reactions is the following. When a kaon encounters a nucleus, it sometimes transforms a neutron into a lambda hyperon, forming what is called a hypernucleus. For example, the hypernucleus lambda-helium 4 consists of two protons, a neutron and a lambda hyperon. Hypernuclei are expected to emit gamma rays that will be of considerable interest because the energy of the radiation will yield information on the force between the lambda hyperon and nucleons. That force is a manifestation of the strong force, the nature of which is one of the fundamental questions facing physics. It is possible that these gamma rays will be made accessible by a refinement of the techniques used to obtain the spectra of kaonic X rays.

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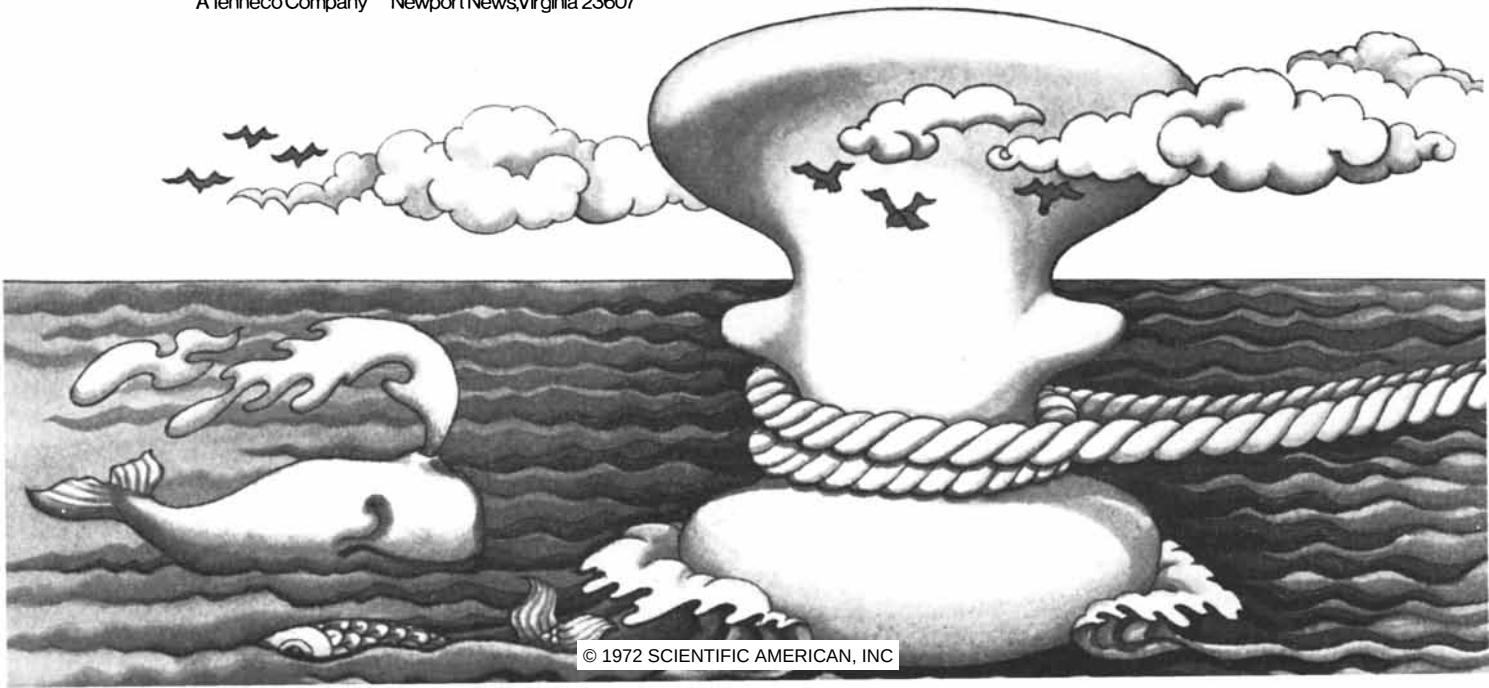

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MATHEMATICAL GAMES

On the practical uses and bizarre abuses of Sir Francis Bacon's biliteral cipher

by Martin Gardner

It is not hard to understand why philosophers and historians of science are so divided in their opinions about Sir Francis Bacon, the Elizabethan writer, philosopher and Lord Chancellor. On the one hand his insights into scientific method were primitive and defective. On the other he had a prophetic vision of science as a vast, collective and systematic enterprise that could provide humanity with undreamed-of knowledge. And knowledge, he insisted, is power. For the first time man would have the power to master nature and control his own destiny.

Although Bacon had little skill in mathematics, he did invent an ingenious cipher system of considerable interest to students of both recreational mathematics and word play. The "biliteral cipher," as Bacon called it, was one of the earliest demonstrations of how easily information can be transmitted by a simple binary code [see "Origins of the Binary Code," by F. G. Heath; SCIENTIFIC AMERICAN, August]. The system is related to a fascinating combinatorial problem that has practical applications to error-correcting codes. Not least, Bacon's cipher has been responsible for the funniest and most bizarre claims ever propounded by the Baconians—those never-give-up pseudoscholars who still labor mightily to convince the world that Bacon wrote the plays of Shakespeare.

There are hints about the biliteral cipher in Bacon's *Advancement of Learning* (1605), but he did not fully disclose the method until he expanded his brief remarks on ciphers for the later encyclopedic edition of this work in Latin, *De Augmentis Scientiarum* (1623). In Book 6 he repeats his earlier summary of the three virtues every good cipher should have: (1) "Easy and not laborious to write"; (2) "Safe and impossible to decipher"; (3) "If possible, such as not to raise suspicion."

A cipher with the third merit, known as a "concealment cipher," is one in which the very existence of the true cipher text is not suspected. Bacon first explains a whimsical concealment dodge using two cipher alphabets. The genuine message is written with one set of symbols, then a false message is written with a second set. The two ciphers are interwoven to make a single cipher text. If this is intercepted and a translation demanded of the sender, he strikes out the symbols of the true text, explaining that they are what cryptographers today call "nulls," meaningless symbols inserted only to make the cipher harder to break. He then reveals the key to the remaining symbols. Because an intelligible message now emerges, Bacon writes, who would suspect that the apparent nulls actually conceal another message?

"But for avoiding suspicion altogether," Bacon continues, "I will add another contrivance, which I developed myself when I was at Paris in my early youth." The contrivance, the biliteral cipher, is based on a key that assigns to each letter of the alphabet a different permutation of two symbols in groups of five. As Bacon explains, there are 32 such permutations, more than enough for the English alphabet, which in Bacon's day consisted of 24 letters. (*I* and *J* were interchangeable, as were *U* and *V*.) Bacon used *a* and *b* for the two symbols, assigning *aaaaa* to *A*, *aaaab* to *B*, *aaaba* to *C* and so on.

Bacon's plan was to use this cipher for concealing the plaintext (message to be enciphered) in an innocent looking "cover text." One has only to distinguish between two different ways of printing each letter. A crude method would be to let italicized letters stand for *a* and roman letters for *b*. The word "*B*acon," with only the first letter italicized, would represent the permutation *abbbb*, which in Bacon's alphabet means *Q*. It is obvious that any cover text, provided that it is five times the length of the plaintext, can be printed so that it carries the secret message.

The difference between roman and italicized letters is, of course, too obvious. Bacon proposed using two type fonts that differed in minute ways. Only someone aware of these subtle differences would know how to scan the printing, label each letter *a* or *b*, divide the letters into quintuplets and read the hidden message. To illustrate how "anything can be written by anything," Bacon reproduced a woodcut of a passage from a letter of Cicero's, mixing fonts known as Garamond and Imprint [*see illustration on page 116*]. When the letters are properly labeled *a* and *b*, the concealed Latin message (copied from one the Spartans had once sent by a cylindrical ciphering device called a scytale) translates into English as "All is lost. Mindarus is killed. The soldiers want food. We can neither get hence, nor stay longer here."

Elizabethan printing was so crude by modern standards that no two appearances of the same letter on a page, when examined under a strong magnifying glass, are exactly alike. Lead molds were imperfect, type was often damaged, ink dried irregularly on rough and dampened paper, and printers often mixed fonts on the same page. It is not surprising that anyone persuaded that Bacon wrote the plays of Shakespeare would suspect that Bacon might have used his own cipher to state the fact in early folios, perhaps even pepper the pages with other secret revelations.

Elizabethan printing has provided Baconians with a marvelous arena for the unhampered play of unconscious impulses. With a magnifying glass in hand, and flexible biliteral rules allowing *a* and *b* forms of each letter to be distinguished in any possible way (and in more than one way for each letter), a clever Baconian can extract from a long passage of Shakespeare's almost any short message he likes. The first appearance of a *T* may be labeled *a* because it has a slightly thinner upright line than other *T*'s; the next *T* may be labeled *a* because it has a tiny curl at the end of the crossbar, and so on. Cipher keys are allowed to vary from passage to passage. Assuming that a Baconian is not a mountebank, the secret messages he finds will spring from deep within his subconscious, like the messages spelled on Ouija boards or by automatic handwriting, or transmitted by mediums from the Great Beyond.

Strangely enough, the first major effort to decipher Shakespeare's plays did not exploit Bacon's cipher. The flamboyant Populist politician from Minnesota, Ignatius Donnelly, used a different system, even more farfetched, for his 1,000-

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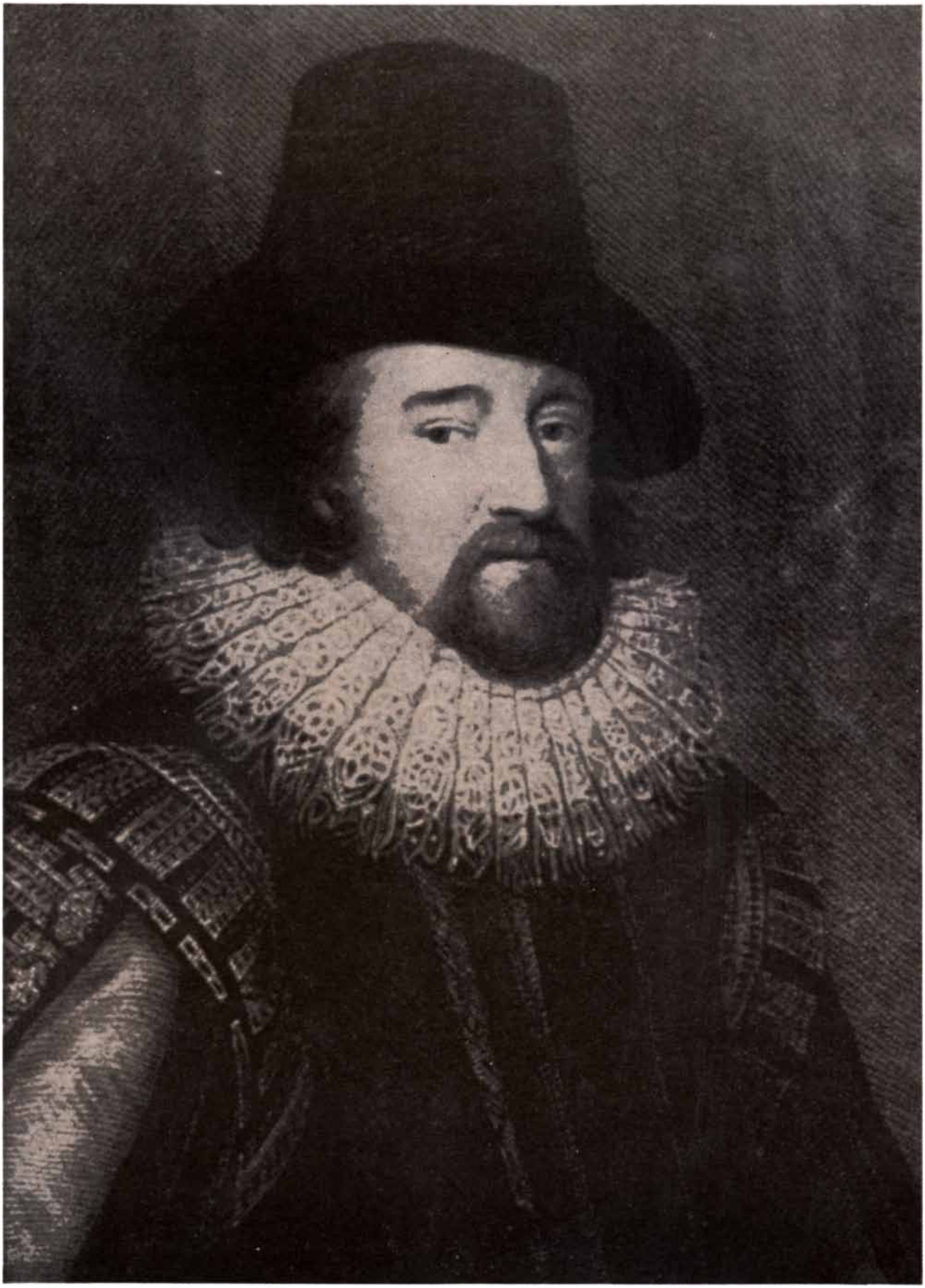

Sir Francis Bacon (1561–1626)

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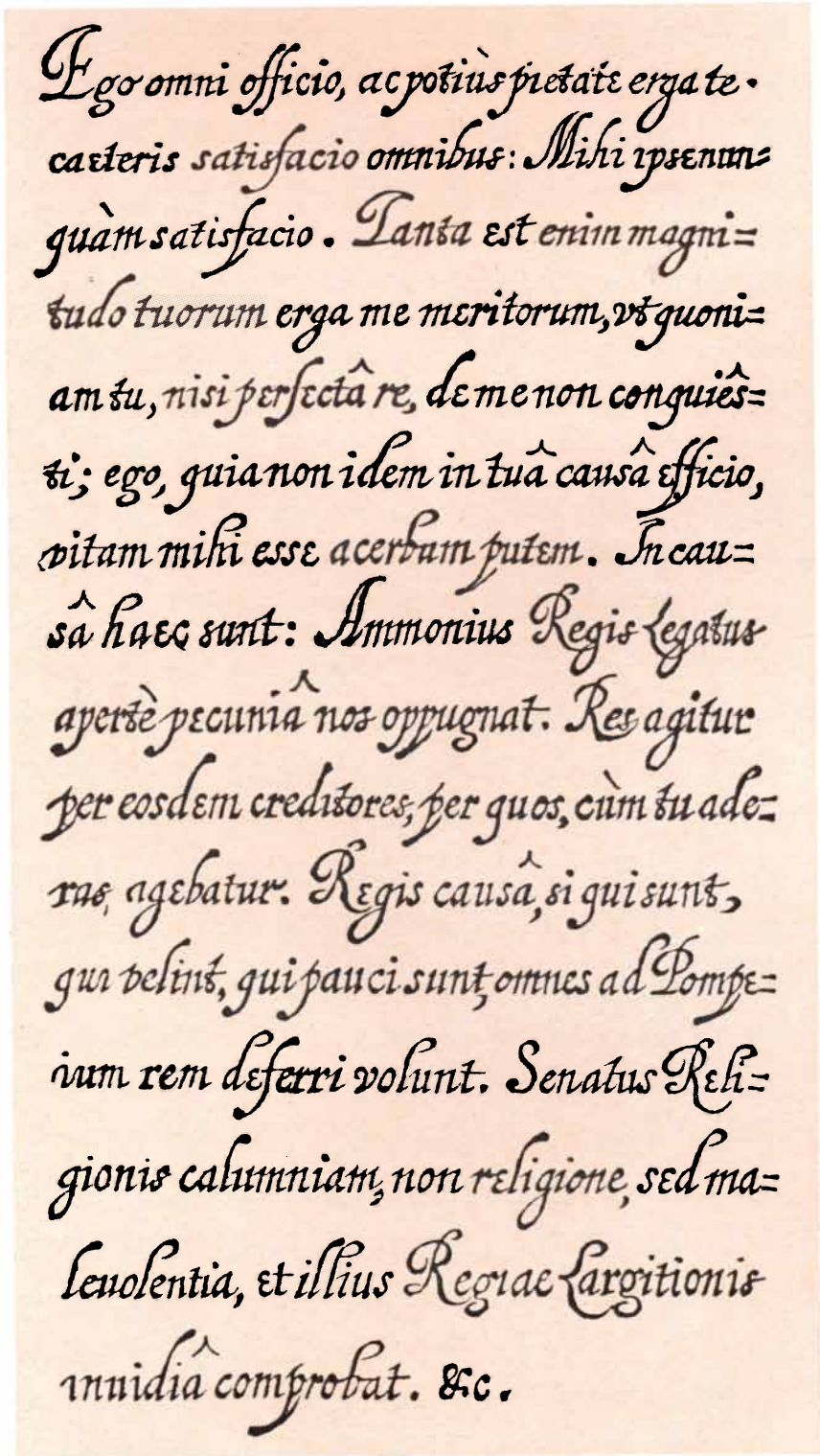
page crank work *The Great Cryptogram* (1888). (This tome and Donnelly's *Atlantis* and *Ragnarok* form the most impressive set of crackpot works written by an American before 1900.) It remained for Mrs. Elizabeth Wells Gallup (1846–1934), a Michigan teacher and high school principal, to apply Bacon's own cipher with unflagging persistence to Shakespeare's plays, producing the best and most hilarious plaintexts in the history of Baconiana.

Like Donnelly, Mrs. Gallup is a splendid specimen of the intelligent, learned, honest and thoroughly self-deluded crank. Her opus *The Biliteral Cipher of Sir Francis Bacon Discovered in His Works and Deciphered by Mrs. Elizabeth Wells Gallup* (Howard Publishing Co., Detroit, 1899) had a shattering impact on fellow Baconians. She found secret messages not only in the Shakespeare folios but also in the writings of Marlowe, Spenser, Burton and other writers whose books she believed had also been written by Bacon. "Queene Elizabeth is my true mother," one message read, "and I am the lawfull heire to the throne. Find the Cipher storie my bookes containe; it tells great secrets, every one of which, if imparted openly, would forfeit my life." Many of the great secrets turned out to be bawdy details of Elizabethan court life.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A letter of Cicero's in which the two type fonts conceal a secret war dispatch

"Surprise followed surprise," wrote Mrs. Gallup, "as the hidden messages were disclosed, and disappointment as well was not infrequently encountered. Some of the disclosures are of a nature repugnant, in many respects, to my very soul.... As a decipherer I had no choice, and I am in no way responsible for the disclosures, except as to the correctness of the transcription."

"Colonel" George Fabyan (the military title was honorary), a wealthy textile manufacturer, became Mrs. Gallup's convert and major benefactor. He brought her to Riverbank Laboratories on his 500-acre estate in Geneva, Ill., where he established a staff of cryptanalysts to work under Mrs. Gallup's supervision. She remained there for 20 years, studying photographic enlargements of Elizabethan manuscripts and trying to teach her bewildered staff how to decipher them.

Ironically, as David Kahn observes in his book *The Codebreakers,* it was at Riverbank that young William F. Friedman was first introduced to the art of code-breaking. Later he became one of the world's greatest cryptanalysts. (It was his team that cracked the Japanese "purple code" of World War II.) While he was at Riverbank he met and married another of Mrs. Gallup's assistants, Elizebeth Smith. The two eventually became the most illustrious husband-and-wife team in the history of cryptanalysis. Both, I hasten to add, quickly caught on to how Mrs. Gallup was deceiving herself. Indeed, the chapters devoted to Mrs. Gallup in their book *The Shakespearean Ciphers Examined* totally demolish Mrs. Gallup's monumental and pathetic lifetime labors.

Back to mathematical reality. In recent decades mathematicians have developed many ingenious procedures for forming cyclic chains in which all possible permutations of n symbols, taken k

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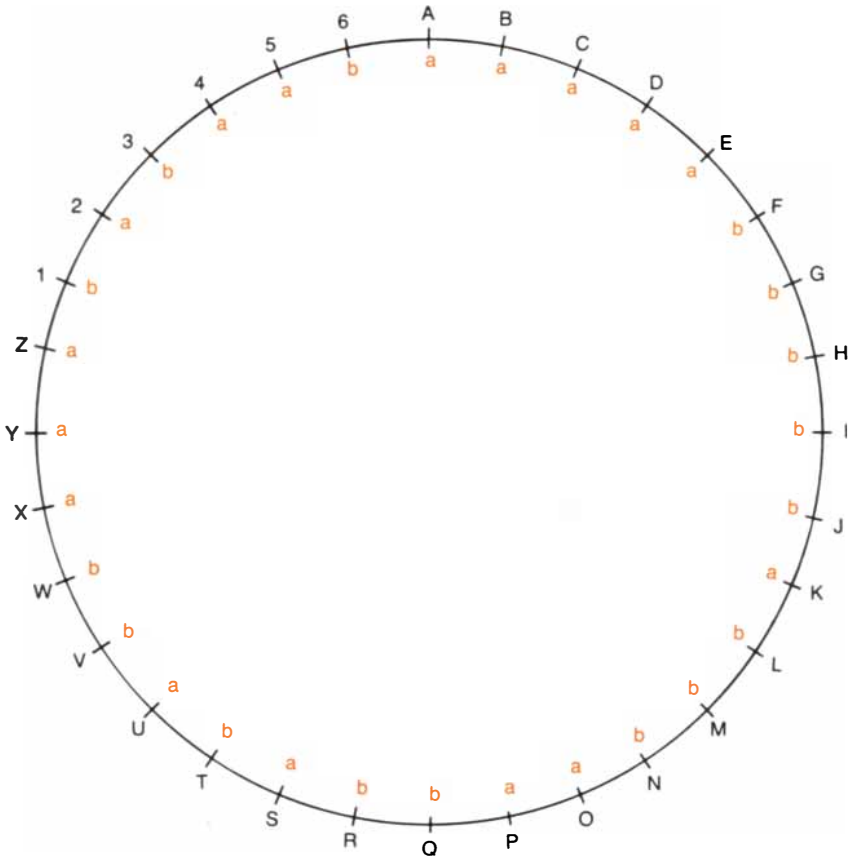

A concise key for a biliteral cipher

at a time, are given once only by each set of k adjacent symbols. For example, consider the following 32-symbol chain:

aaaaabbbbbabbbaabbababbaaababaab

If you view the chain as cyclic (end joined to beginning), every group of five adjacent symbols is one of the $2^5 = 32$ permutations of a and b in sets of five. There are 2,048 ways to construct such a chain, if reversals are considered different. For two symbols the formula giving the number of chains is

$$2^{(2^{k-1}-k)},$$

where k is the number of symbols in a group. Any of the 2,048 chains provides a convenient way of recording the key to a biliteral cipher. Simply print the alphabet, with the first six digits appended to bring the number of symbols to 32, in a circle and add the chain of a's and b's in a concentric circle [*see illustration above*]. To obtain the permutation for, say, R, check the set of five symbols that start at R and go clockwise (or the other way if you prefer) around the circle.

The cipher has many unusual applications. A deck of 52 playing cards, for instance, can be arranged so that the colors (or odd and even values, or high and low cards, or any other binary division) will encipher a 10-letter word or phrase. Of course, three-symbol chains provide triliteral ciphers, four symbols provide quadriliteral ciphers (the genetic code!) and so on.

Although it is a defect of Bacon's system that a cipher text must be five times as long as the plaintext, a remarkable merit of the system is that more than one message can be hidden in the same cipher text. One has only to choose letters carefully so that they can be divided into a's and b's in more than one way. Consider, for example,

GkwRt ceUya porrE.

Our cipher key will again be the concentric circles in the illustration above, reading clockwise. If a stands for letters whose positions in the alphabet are odd (a, c, e, ...) and b for even-positioned letters (b, d, f, ...), the text deciphers as *aaabb aaaaa babba*, which spells CAT. If a refers to a letter in the first half of the alphabet and b to letters in the second half, the same text deciphers as *aabbb aabba bbbba*, which spells DOG. And if a means uppercase and b lowercase, the

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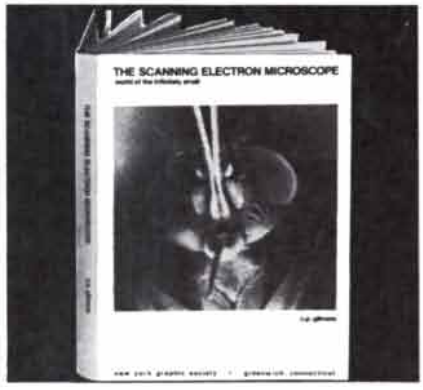

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translation is *abbab bbabb bbbba,* or PIG.

Here is an exercise to be answered next month:

QUZGF MTXYX JLUIY XNEEN WLREW TSNJE

Using the same key as before, can you determine three ways of bifurcating the alphabet so that the above cipher text can be translated in three ways, each giving a six-letter last name of a famous mathematician? (Hints: The three divisions have to do with the name of a poet, legs and topology.)

Although Bacon himself did not make the metaphor explicit, his cipher may be taken as symbolic of the curious way he viewed scientific knowledge. It is an attitude still held today by many philosophers and scientists. Bacon did not believe that the laws of science were infinite in number. Like his fellow Anglicans, he was convinced that God had created a natural world that was sharply cut off from the supernatural. In *this* world a finite number of simple principles combine, like the variables of an n-literal cipher, to form all the laws of nature.

The 19th-century English logician John Venn made this point in his *Empirical Logic* (page 357), where he described Bacon's position as an "*alphabetical* view of the Universe, in its extremest form.... We find [the universe] all broken up, partitioned, and duly labeled in every direction; so that, enormously great as is the possible number of combinations which these elements can produce, they are nevertheless *finite* in number, and will therefore yield up their secrets to plodding patience when it is supplied with proper rules."

Science, to pursue the metaphor, is one stupendous task of cryptanalysis. Bacon was persuaded that eventually, and not far in the future either, all the ciphers would be broken and mankind would know not all truth by any means but all the basic natural laws. The future of science would then be merely a filling in of details and the exploitation of laws by new inventions.

Although few scientists today would venture such a prediction, more limited Baconian sentiments are often expressed with reference to a particular science. Nigel Calder, in his vivid survey of the new astronomy, *Violent Universe* (Viking, 1969), suggests that our century may turn out to be unique in the history of astronomy as the century in which astronomers first became "know-alls," omniscient in the sense of having mapped the fundamental outlines of the entire cosmos. "Or," Calder adds, "will our descendants smirk about our ideas as we do about those of our ancestors?"

Who can be sure, even with reference to a single science, whether in the long run (whatever that means) Bacon will be proved right or wrong? We *can* say that at the moment nature appears to be far shaggier and more complicated than the Lord Chancellor suspected. There are ciphers within ciphers within ciphers, and there is not a clue in sight about whether any of these regresses has an end.

Neither of the two numerical oddities at the close of last month's department are coincidences.

S. N. Collings, in *The Mathematical Gazette* (December, 1971, page 418), generalizes the fact that joining consecutive squares 4 and 9 produces the square 49 as follows: Let $(n-1)^2$ and n^2 be two consecutive squares. Join them to form a two-digit number in a notation with a base of n^2+1. (In the case of 2^2+3^2 the base is $3^2+1=10$.) The new number will be $(n-1)^2(n^2+1)+n^2$, which equals the square number $(n^2-n+1)^2$.

Philip G. Smith, Jr., discovered that a reverse procedure always yields the same square. Interpret each of the squares in a base equal to the smaller square plus 1, put the larger of the two squares in front of the smaller and interpret the result in a base equal to the smaller square plus 1. In decimal notation: consecutive squares 9 and 16 join to produce square No. 169. If the opposite procedure is followed, the result is 9 followed by 16, with 16 regarded as a single symbol in base-17 notation. The number's decimal equivalent is $(9\times 17)+16=169$, the same square that was obtained before.

On the surface it seems surprising that both procedures always give the same result but, as Smith showed, it is merely a special case of the following general theorem. Let x and y be any positive real numbers. If both are expressed in base $x+1$, and x is appended to y, the value is the same as expressing the numbers in base $y+1$ and appending y to x. In the first case the value is $y(x+1)+x$, and in the second $x(y+1)+y$. The two expressions are clearly equivalent.

The pattern that Benson P. Ho found for the series 8547196320 is a hoax. It is not hard to show that any series of digits ending in 0, subjected to Ho's procedure, will give the same result.

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WHAT TO DO WITH WINE BESIDES DRINK IT.

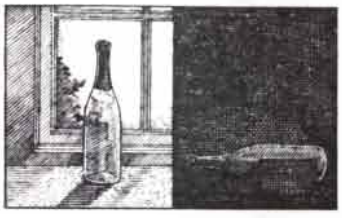
Unfortunately, wine doesn't come with instructions. And lots of people have never known much about its proper care.

We at Inglenook Vineyards would like to take this time to give you a few pointers on the subject.

We spend a lot of time and money in the making of our wine. And once it passes out of our hands, we'd like to feel that it's being given the best possible treatment.

DON'T MAKE THIS COMMON MISTAKE.

Wine should always be stored lying down on its side, never standing up. That's so the cork will always be moist. If the cork dries out, air will get to the wine and spoil it.



Bad. Good.

Keep wine in a cool, dark place. About 55–60 degrees is just right. But the most important thing is that the temperature be constant. It should vary no more than a few degrees year 'round.

DECANTING WINE.

If you have wines five years old and older, they may have a little sediment in them. In order to serve the wine without the sediment getting mixed up in the wine, you should decant it.

To do this, just pour the wine very slowly into another bottle or carafe. Place a candle behind the neck of the bottle and the second you see a little sediment coming across, stop.

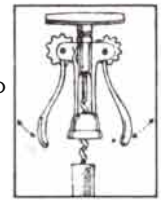
THE ROOM TEMPERATURE MYTH.

White wines and sparkling wines such as Champagne and rosé should be served cold. How cold is cold? 45 degrees is just right. If you don't have a thermometer, put the wine in the refrigerator for 2½ hours before serving. Or in a bucket with ice cubes and water for 15 minutes.

Red wines should be served at room temperature. But this doesn't mean 72 degrees. The "room temperature" standard was established in Europe long before the invention of central heating. At that time, rooms in Europe were about 65 to 68 degrees, which is the perfect temperature for serving red wines. You can bring a wine's temperature down to that level by placing it in the refrigerator five minutes before serving. But never heat a bottle of red wine in order to get it up to the proper temperature. There's no quicker way to destroy a bottle of wine than to heat it up.

AVOIDING THAT METALLIC TASTE.

Remove the metal capsule from the top of the wine bottle below the lip. With a napkin, clean off the top between the cork and the glass. This is done because it's impossible to pour wine from a bottle without spilling a little on the lip. And since the metal cap is sometimes corroded, the wine could pick up a metallic taste if it were to spill over the edge.



Now remove the cork, gently, so as not to disturb the wine. We recommend the wing-type corkscrew because you don't have to jerk it to get the cork out.

A FINAL WORD OF CAUTION.

Now that you know the basics of how to treat wine, you should also know there aren't many wines around that deserve this kind of treatment.

Because there's nothing you can do at home to save a wine if it's been mishandled at the winery.

Which brings us to Inglenook.

We take elaborate precautions to make sure our wine is handled properly.

For instance, the walls of our wine cellar are 3 feet thick limestone, which keeps the temperature constant.

Our wine casks rest upon a dirt foundation, instead of concrete, the usual practice. This promotes fresh air circulation, and it also stabilizes the humidity.

If you look on the label of our wine, you'll see the words, "Produced and Bottled by Inglenook Vineyards".

This means we produce the wine from start to finish, in order to make sure that our wine is never mishandled.

Naturally, this kind of extra care costs extra money.

And we pass the extra cost right on to you.

Inglenook is the most expensive wine made in America. So when you pick up a bottle of it, take good care of it.

And it'll take good care of you.

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THE AMATEUR SCIENTIST

Sound waves and radio waves are recorded on film by means of a precooling process

Conducted by C. L. Stong

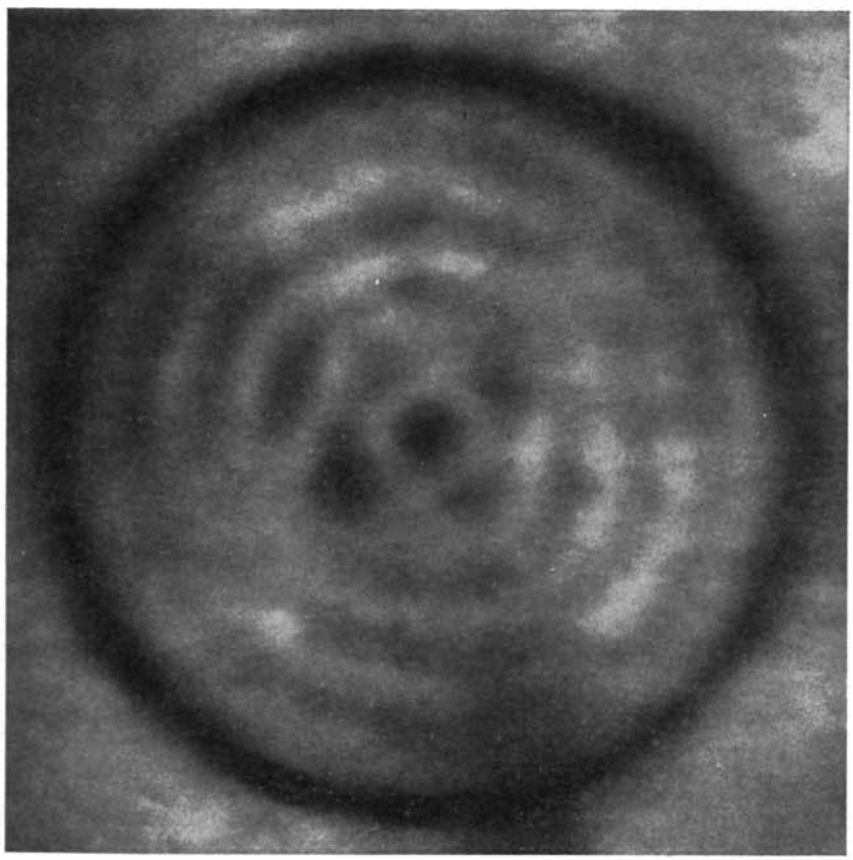
Many an experimenter has hankered for a way to record sound waves and radio waves as conveniently as he can record light waves with a photograph. It now appears that all that is needed is a new method of processing a material that has been at hand for many years: Polaroid film. The method was discovered in 1968 by Keigo Iizuka, who was then a lecturer at Harvard University and is now associate professor of electrical engineering at the University of Toronto. His procedure opens up several new fields of experimentation, including microwave holography. Iizuka writes:

"Fields of ultrasonic waves and microwaves have ordinarily been investigated by two classical procedures. The wave pattern can be scanned mechanically by a probe that picks up a signal that varies in amplitude with the energy in each increment of the field. The resulting data are plotted to display the distribution of the energy. Alternatively, the field can be simulated in two dimensions by an appropriately shaped film of moving water. Streamers of dye in the water record the force potentials in the field [see "The Amateur Scientist," SCIENTIFIC AMERICAN, July, 1967].

"Both techniques are tedious and time-consuming. Moreover, the accuracy of the scanning technique can be degraded to the extent that the probe disturbs the field. The results of the fluid-mapping technique can be no better than the similarity of the fluid model to the field it represents. In contrast, Polaroid film can be employed to map the fields directly in less than five minutes. The method is both convenient and inexpensive. The intensity of a field can be measured simply by holding the film in the path of the waves.

"The procedure is based on the fact that the rate at which an emulsion develops after it has been exposed to light varies with its temperature or with the degree of mechanical agitation of the reagent. A microwave generates heat and an acoustic wave agitates the reagent. To record a wave pattern the emulsion is exposed uniformly to light of a certain color, precooled to an optimum temperature, coated with developing reagent and immersed in the pattern of waves to be recorded. The emulsion darkens at rates proportional to the local heating or agitation to form an image of the wave pattern. Development is interrupted when the darkest parts of the image reach maximum density.

"Polacolor Type 58 film, which is designed for making four-by-five-inch color pictures, is particularly appropriate for recording fields of sound and radio waves because the interval required for developing the resulting image varies with the color of the light to which the film is pre-exposed. The relation between development time and color arises from the structure of the negative. The negative consists of three major layers of dyed emulsion on a plastic base [*see upper illustration on page 122*]. After exposure to light the film pack is drawn between a pair of rollers that break a pod containing developing reagent in the form of a viscous jelly. This action also distributes the reagent as a thin film between the negative and positive emulsions.



Pattern of vibration of sound from a horn

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"The layer of the negative emulsion that contains yellow dye is in intimate contact with the positive emulsion. The magenta and cyan layers lie progressively deeper in the sandwich. The time required for the reagent to reach each layer of dye and migrate to the surface for transfer to the positive emulsion varies with the depth of the layer.

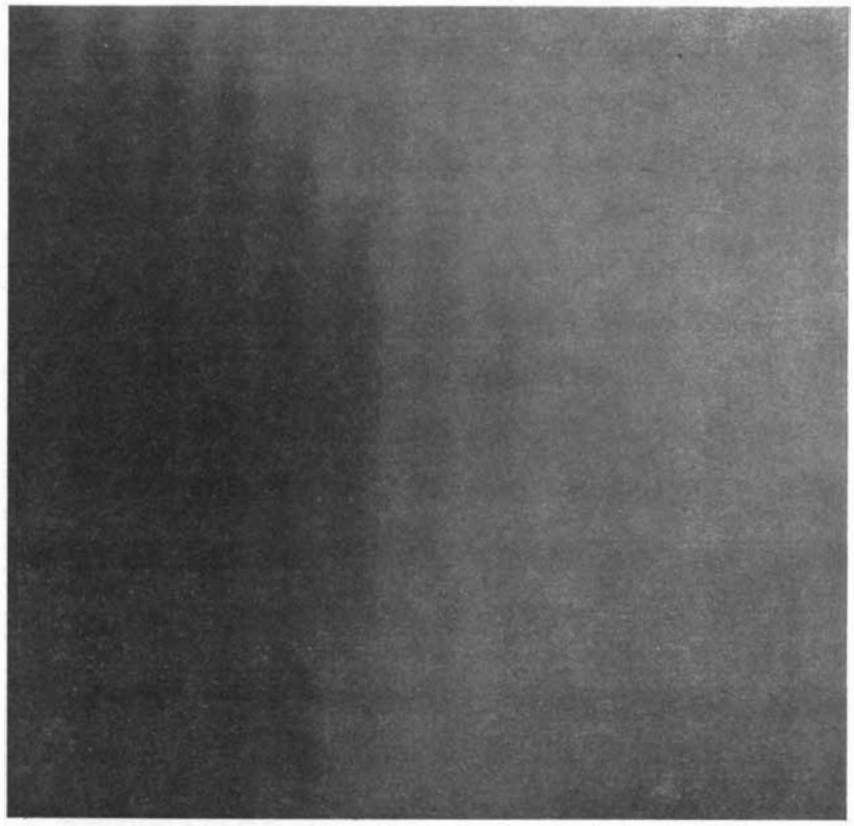
"A negative emulsion that has been pre-exposed to yellow light develops in less time than one exposed to magenta or to cyan. For this reason I pre-expose with dark blue when photographing weak fields of microwaves (fields on the order of 60 milliwatts per square inch at a frequency of from one to 10 gigahertz). Conversely, pre-exposure to yellow light is used for relatively strong fields.

"Pre-exposures can be made with any camera that fits the Model 545 Polaroid four-by-five-inch Land film holder. The camera is focused on a screen of white paper that is uniformly illuminated from the sides by a pair of carbon arc lamps. I check the intensity by supporting a Kodak Neutral Test Card at the position of the screen. With an exposure meter I measure the light reflected by the card. The arc lamps are adjusted for a reflected intensity of approximately 50 footcandles. The camera is equipped with a holder for supporting Wratten light filters.

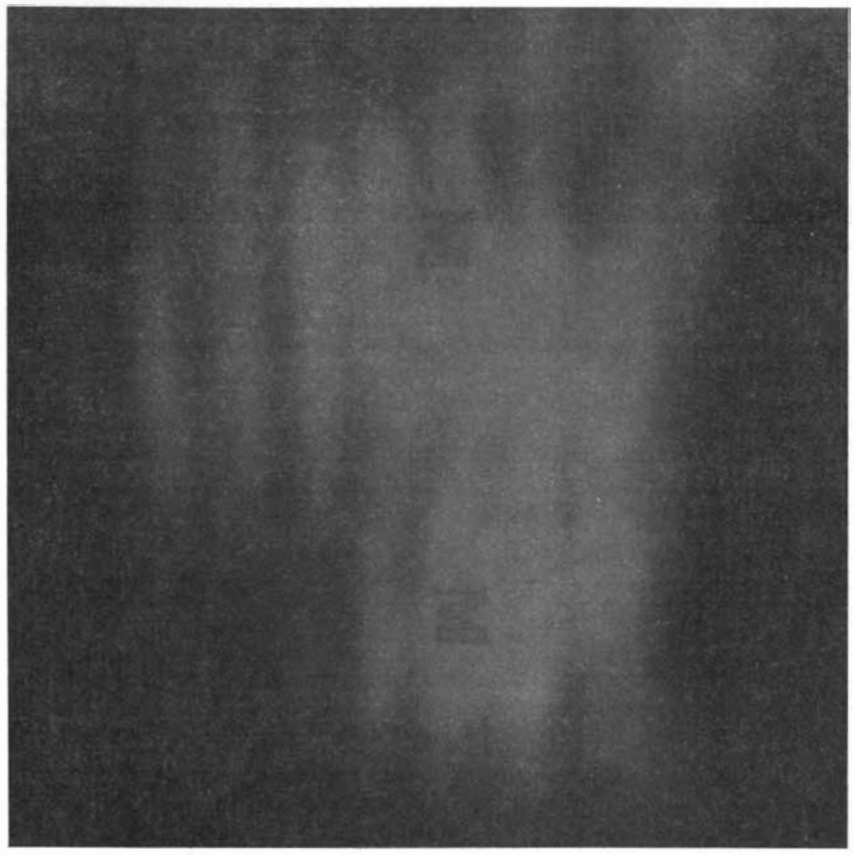
"To make a pre-exposure I set the lens opening at *f*/9.5 and adjust the shutter for an exposure of 1/2 second. I use a No. 13 Wratten filter for yellow and a No. 35 for magenta. Cyan is made by double exposure. In my experiments I first expose through a No. 47 Wratten filter (blue) for 1/10 second at a lens opening of *f*/9.5 and then through a No. 61 (green) for 1/5 second at the same lens opening.

"After making the pre-exposure I cool the film either with dry ice or with an instant-freeze aerosol can of Freon. During subsequent handling in air the film warms to a temperature of about 25 degrees Fahrenheit. That is the optimum temperature at which to make exposures of radio or sound waves.

"A small box in which the film can be refrigerated with dry ice can be made from a sheet of foam plastic. Make the box somewhat larger in area than the film. Cut a rectangle of plastic to serve as a cover. Put crushed dry ice in the box. Place the film on top of the ice. Close the box with the cover for a few minutes. Care must be taken to keep the portion of the film packet that contains the reagent pod outside the box. The



Fringe pattern of 24.26-gigahertz microwave



***Microwave hologram* (M's *are not holographic*)**

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reagent solidifies at 32 degrees F. Do not freeze it!

"Alternatively, the film pack can be cooled by spraying it with Freon. Aerosol cans of the refrigerant, such as those manufactured by the Cryokwik Company for freezing biological specimens, are available for about $1 per container from dealers in biological and pharmaceutical supplies. Avoid spraying the reagent pod.

"I have experimented with several types of black-and-white Polaroid film. Types 52, 57, 55-P/N and 107 work, but they are less sensitive than color film. In cases where interest is confined to a small area of the field the Polaroid eight-exposure color pack can be used to advantage. The image area of this film measures 3¼ by 4¼ inches. The pack is less convenient to use than the individual packs of four-by-five-inch film because it is difficult to cool the film without freezing the reagent pods that are encased in the pack. Microwave fields of larger area can be mapped with Polaroid Radiographic Packet Type TLX. This emulsion was developed for X-ray work, but it responds well to heat or agitation induced by microwaves or ultrasonic waves. The image area measures 9⅝ by 10½ inches.

"The pre-exposed and cooled film is placed in the Land film holder and pulled through the steel rollers that break the pod and spread reagent between the negative and positive layers. The pack is promptly removed from the film holder and inserted in the field to be photographed. In the case of microwaves the component of the electric field in the plane of the emulsion generates heat in the silver halide by means of induced current. The current raises the temperature of the emulsion in proportion to the square of the field intensity. A thermal field thus appears in the film. It is a replica of the intensity distribution of the electromagnetic field.

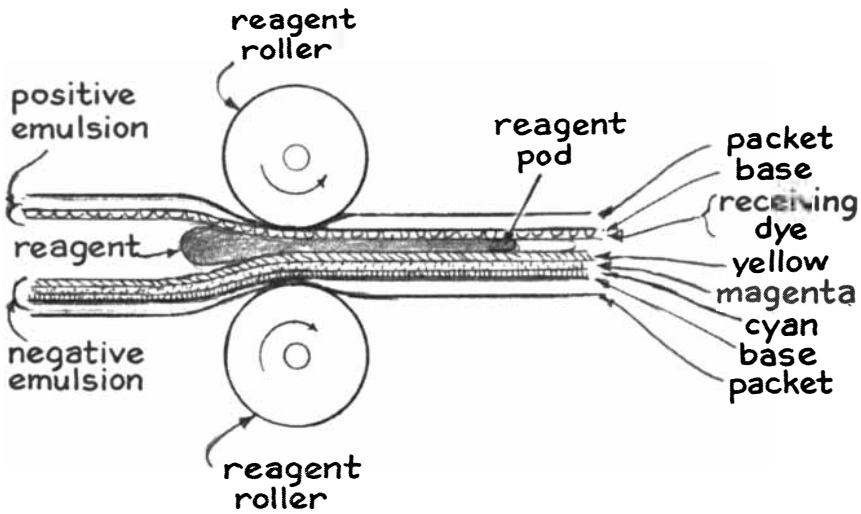
"The localized heating increases the localized rate at which developing reagent diffuses to grain sites of the silver halide and in addition accelerates the chemical reactions of the development. If development continued to completion, the film would turn uniformly dark. The chemical action is interrupted at an intermediate stage by stripping the positive emulsion from the negative emulsion. Development stops at once. The positive emulsion is then insensitive to light. The proper interval of exposure to microwaves or sound waves must be determined experimentally because it depends on the strength of the field.

"Most of my experiments have been made with microwaves, the field of my primary interest. In a typical experiment two beams of microwaves that vibrate at a frequency of about eight billion (8×10^9) cycles per second are projected from a pair of horns. The beams cross at right angles and interfere at the zone of intersection.

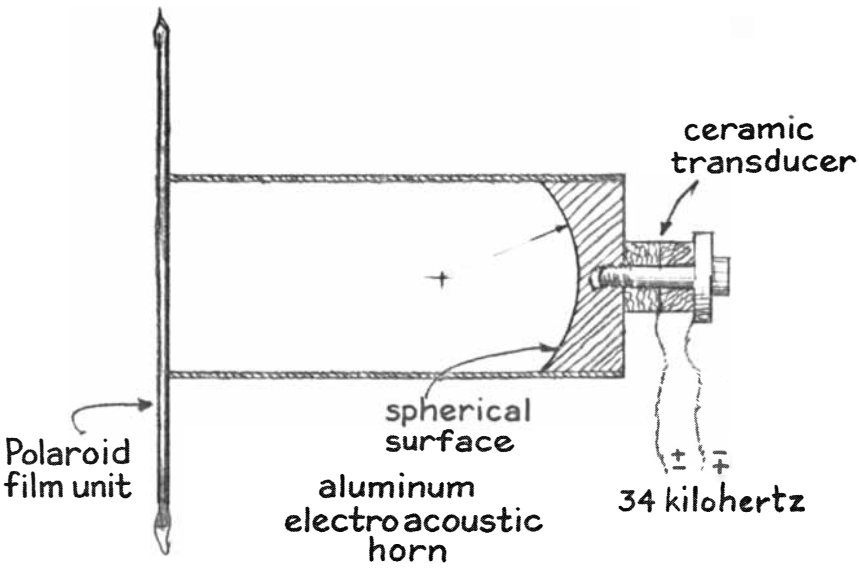
"The film pack is placed in this zone at an angle of 45 degrees with respect to each of the beams [*see top illustration on opposite page*]. The pattern of standing waves that results from the interference is a grid made up of alternate strips of warm and cool emulsion. The developed image consists of alternately dark and light fringes comparable to the fringes that appear when two beams of light similarly interfere.

"I have made a microwave hologram of a small coin and a triangle of metal inside a leather purse. Three steps are involved in the technique. The purse is illuminated by microwaves that vibrate in the vertical plane. The waves are projected by a horn, as in the interference experiment. The energy is generated by a klystron oscillator at a frequency of 34.26 gigahertz (equivalent to a wavelength of 8.756 millimeters). The oscillator develops an output power of 10 watts.

"The beam of microwaves is directed at a right angle to the plane of the purse. The pack of Polaroid film, prepared by pre-exposure to cyan light, is placed directly behind the purse at an angle of 45 degrees with respect to the plane of the purse. The time of exposure to the



Elements of Polaroid color-film pack



Keigo Iizuka's apparatus for demonstrating interference of sound waves

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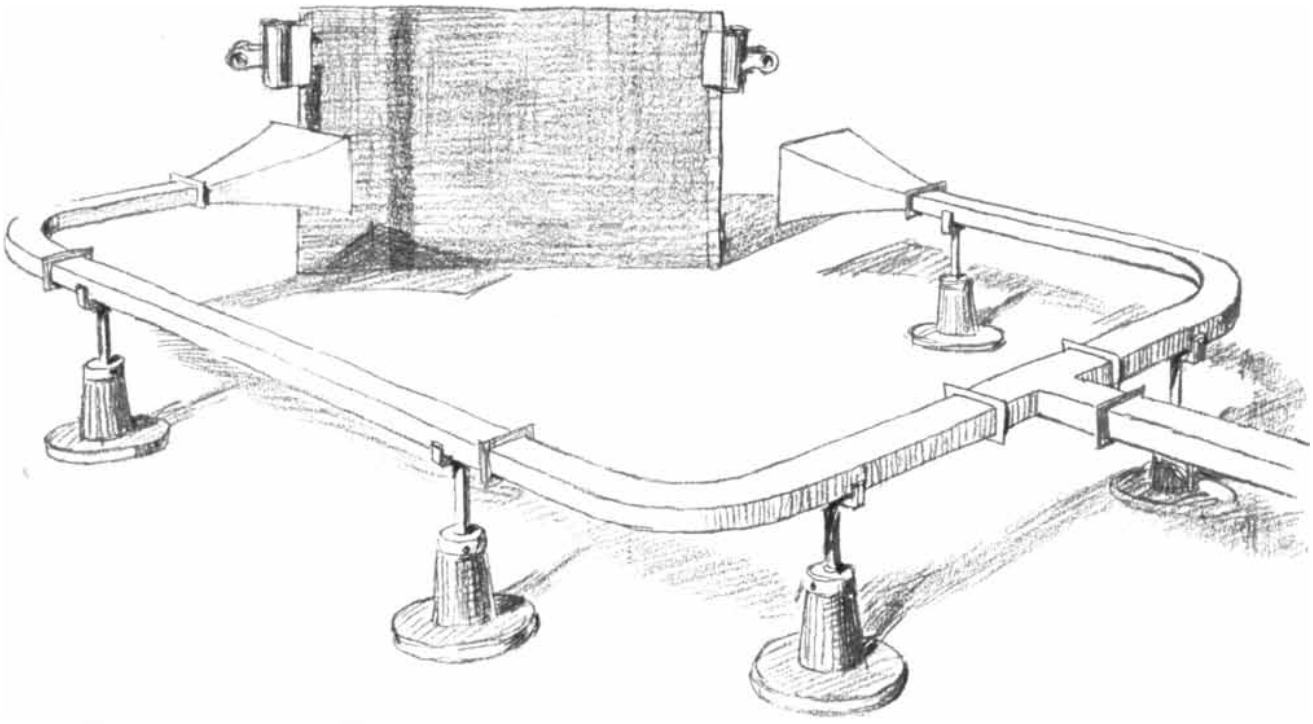


Apparatus for demonstrating microwave interference

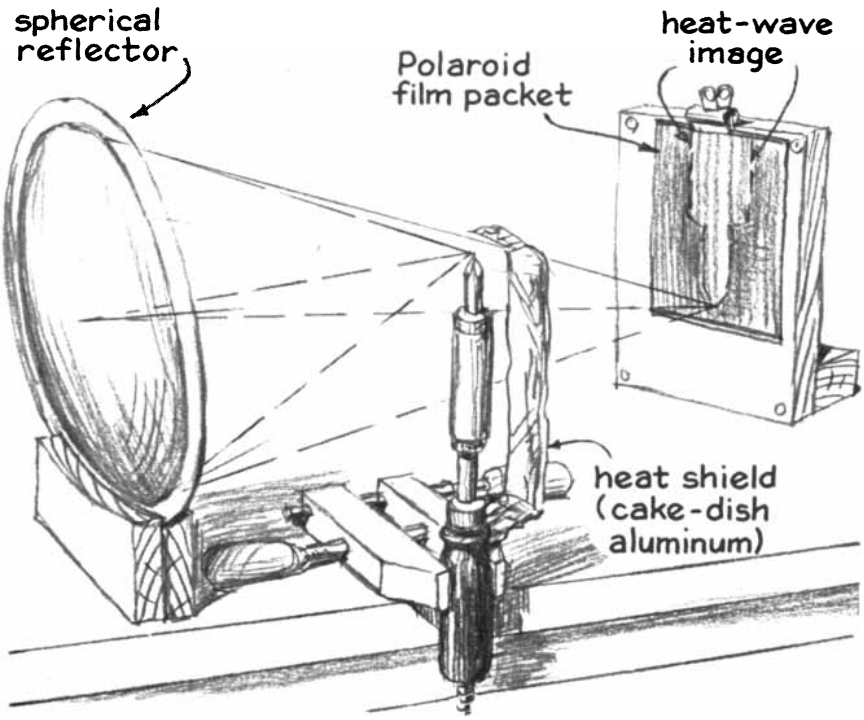
microwaves ranges from 45 to 60 seconds.

"The developed image displays a series of interference fringes. They constitute a hologram of the purse and its contents. The hologram cannot be used directly for reconstructing the image of the object with microwaves because the positive print is transparent to electromagnetic radiation.

"To reconstruct the image a copy of the hologram is made in metal. I use aluminum foil reinforced by a cardboard backing. Slits are cut from the foil that correspond to the darkest portions of the fringes of the image, as judged by eye. A more accurate copy can be made in metal by substituting copper foil for the aluminum and utilizing the photoetching technique employed for making halftone engravings. Replicas made of aluminum foil by hand are adequate, however, for illustrating the procedure.

"The holographic image is reconstructed by illuminating the metallic hologram with the same beam of microwaves that was used to make the original hologram. The image can be made visible by either of two techniques. It will appear on a liquid-crystal film that is placed behind the metallic hologram. The liquid-crystal film consists of four layers: a Mylar sheet, a radio-frequency-absorbing layer, an active layer of cholesteric material and a top surface of polythene sheet. A water-soluble carbon paint applied to the back of the liquid-crystal assembly was found to be suitable for absorbing radio-frequency energy.

"The reconstructed image is reasonably good but, as one might expect, the resolution is inferior to that of holograms made with the far shorter wavelengths of coherent light. The image can also be made by substituting sensitized Polaroid film for the liquid crystal, although the film is less sensitive. Even so, the faint image is sufficiently recognizable to demonstrate that microwave holograms



Equipment for photographing an object by emitted heat

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can indeed be made by this technique.

"It is well known that a field of sound waves accelerates the development of photographic emulsions. Localized vibration in the emulsion increases the rate at which the developing reagent migrates to the sites of silver halide grains, thus speeding the chemical development in regions of high sound intensity. The effect can be demonstrated with any device capable of generating a loud monotone for a few minutes.

"Interesting patterns can be made in a small area with an ultrasonic generator. For example, I generate sound waves about a third of an inch long with a piezoelectric transducer of the ceramic type that is coupled to an electroacoustic horn [*see lower illustration on page 122*]. The transducer operates at a frequency of about 34,000 vibrations per second and develops a sound volume of 160 decibels at the mouth of the horn. The wave pattern is recorded by placing the sensitized film over the mouth of the horn. Clear images of the acoustic field resulted from exposures of 75 seconds for Type 58 Polaroid film and 10 seconds for Type 51.

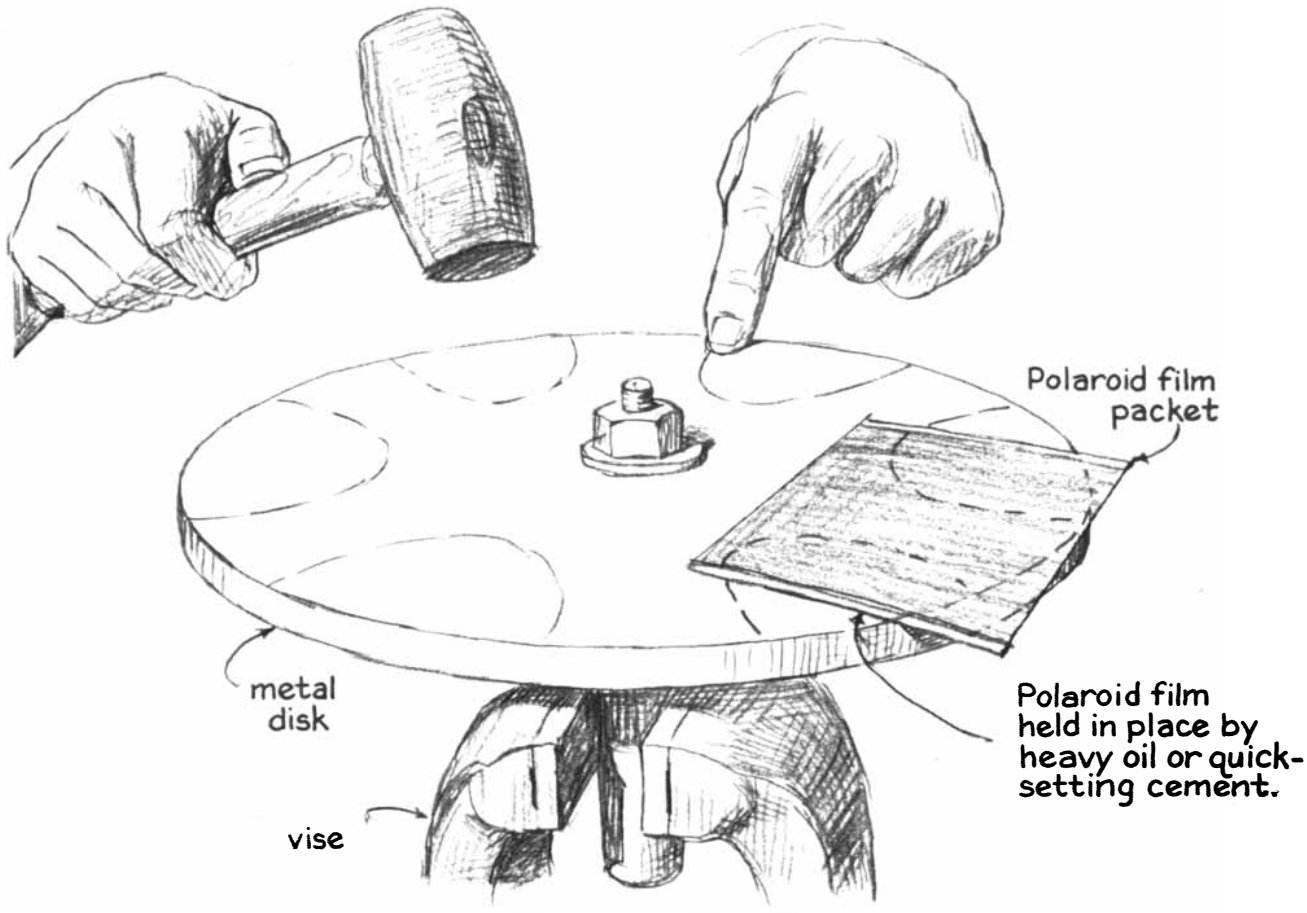
"The minimum intensity required to register an image is about 80 decibels. Similar experiments have been made successfully at much lower frequencies. For example, I have mapped the field-intensity pattern inside an acoustic resonator that was generated by driving an ordinary loudspeaker with a signal of six watts at a frequency of 315 cycles per second.

"It is apparent that a pattern of wave interference could be recorded by superposing a reference field of sound waves on waves from a primary source. This method would be useful as a new means of visualizing acoustic fields as well as a possible method of making acoustic holograms. The relative insensitivity of the film to sound would seriously limit the usefulness of the technique, however, unless the experimenter had access to an acoustic source of high power.

"Numerous experiments can be undertaken to demonstrate the sensitivity of the pre-exposed films to heat. For example, the distribution of heat within the flame of a candle can be mapped by holding the sensitized pack vertically in the flame for a few seconds. The temperature distribution within the flame generates a corresponding distribution within the emulsion. To make a photograph of a candle flame I pre-exposed the film to magenta light. The bottom portion of the flame did not register in the image because it was in the margin of the film.

"A hot object, such as a soldering iron, can be photographed by focusing the heat rays on the film with a parabolic reflector [*see bottom illustration on preceding page*]. The contrast in the resulting image can be improved by inserting a heat shield between the hot source and the film. The shield prevents unfocused rays from reaching the sensitized emulsion.

"The presensitized film will respond even to mechanical vibrations. This effect can be demonstrated by attaching the film to a Chladni plate with fast-curing cement and striking the plate with a hammer [*see illustration below*]. The experiment works best with a plate of aluminum at least 1/4 inch thick. Regions in which the plate vibrates at maximum amplitude appear as dark bands in the resulting image."



A means of recording mechanical vibrations on film

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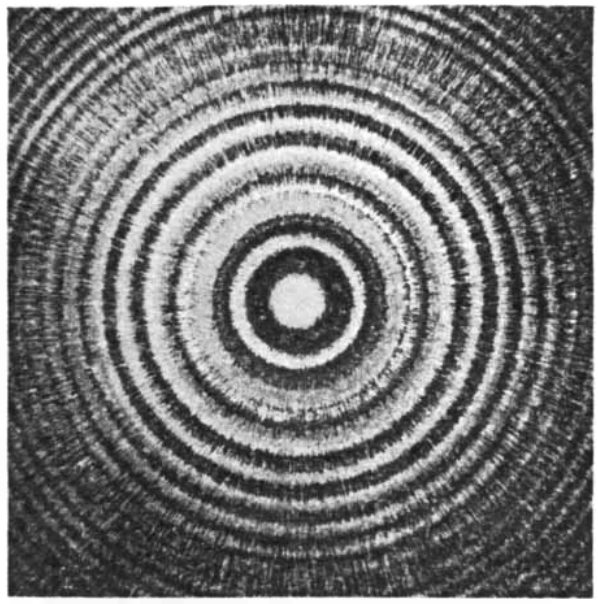
"LASER LIGHT"

A SCIENTIFIC AMERICAN FILM



Almost everyone has heard of lasers, but relatively few people have seen them in action. The Editors of SCIENTIFIC AMERICAN now present "LASER LIGHT," a 16-millimeter sound film about lasers: what they are, how they work, the marvelously pure and curiously scintillating light they produce, how they are being used and how they may be used in the near future. The film is in color and lasts 37½ minutes. It is now available for sale or rent.

A few highlights of the film are:

- **Computer-generated animation explaining stimulated emission and resonant optical cavities.**
- **Ripple-tank and oscilloscope demonstrations explaining the wave principles underlying laser action and holography.**
- **Holograms, their three-dimensionality dramatically evoked by the moving camera.**
- **A 600-foot, 8.8-kilowatt laser in action.**
- **Tunable lasers.**
- **A television picture transmitted by laser beam.**
- **The laser chalkline for the San Francisco Bay tunnel.**
- **Laser interferometry.**
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- **Original musical score.**

"LASER LIGHT" is recommended for general audiences with an interest in science and technology, and for use in conjunction with the teaching of physics and optics. The film is accompanied by a selection of five SCIENTIFIC AMERICAN articles on lasers and holography, written by leading authorities in these fields.

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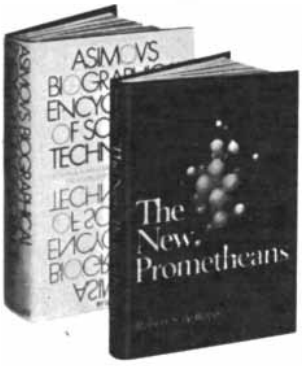

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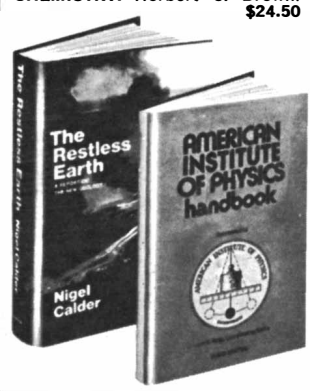

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BOOKS

The locust, artificial cells, domestication and how to get pictures made by satellite

by Philip Morrison

THE DESERT LOCUST, by Stanley Baron. Charles Scribner's Sons ($7.95). "And Moses stretched forth his rod over the land of Egypt, and the Lord brought an east wind upon the land all that day, and all that night; and when it was morning, the east wind brought the locusts.... For they covered the face of the whole earth, so that the land was darkened; and they did eat every herb of the land, and all the fruit of the trees which the hail had left: and there remained not any green thing in the trees, or in the herbs of the field, through all the land of Egypt." So it is told in Exodus, of a time 3,500 years ago, and so it has been ever since, absent the rod. "Out of sixty-one years since 1910, some forty have been plague years" somewhere in the vast range of the desert locust. That species, *Schistocerca gregaria,* a big hard-skinned winged grasshopper, has no area of permanent outbreak. It is uniquely adapted to the chances of desert life; like men in the desert, it is nomadic, opportunist, following the wind and the rain, explosively expansive whenever conditions suit. (A year's rainfall in the central Sahara—1.6 inches—may come within one hour!) Its range is that empire of rock and sand of which the Sahara is the biggest province; the Red Sea is only a firebreak in a varied desert that stretches across Africa and Asia from the Atlantic surf to the valley of the Ganges, and north from Lake Chad to the Zagros Mountains on the Anatolian border: an area nearly four times that of the U.S.

A major swarm of these metallic black-and-yellow locusts can shadow an area of 500 square kilometers or more, their layers up to a kilometer deep. There will be fully 10^{10} finger-length insects in such a swarm, a flying mass of 50,000 or 100,000 tons. From a distance the swarm looks like the streaked smoke of a bush fire, pillars of locusts here and there rising in the convection currents like dust devils. From above one often sees "an intense and unmistakable glitter caused by reflections from the wings." A swarm can fly 3,000 miles overland, normally in 10-hour daily flights at airspeeds of only a few miles an hour. The locusts hold reserves of fat adequate even for overseas flights (up to 17 hours by wind-tunnel tests). The Canary Islands are well within their range, and around the Red Sea "so often has the despairing farmer seen locusts apparently flying in from the sea that many Arabians believe that they originate in the stomachs of whales."

This fascinating eyewitness account is written with verve by a skillful travel writer who personally followed the campaigns against the desert locust carried out by the Food and Agriculture Organization of the United Nations in the empty quarters of the desert where locusts breed, among the oases and the cultivated margins where they bring ruin to hard-pressed farmers and in the laboratories in London where the latest tactics for this 10,000-year war are devised. As a travel book alone its narrative would be diverting and impressive. Consider the little party south of Tamanrasset early in 1966, some seven men in three UN Landrovers. Three were young Algerian "locust prospectors." One was a gifted Tuareg desert guide, full-veiled, tall, "a whipcord of a man" who knew every furrow of the runoffs and the "date and duration of every rainfall within his own lifetime and those of his father and grandfather" for a range of 500 miles, beyond which "the world ceased to exist for him." Then there were the zoology professor from Algiers, grown gray in 40 years' study of desert life, and the writer. "We had been going some hours... when faint specks... began to take shape as a file of fifty or sixty camels head to tail.... We pulled up... and waited. The caravan came on steadily... for no caravan stops for a chance encounter. Camels fight, entangle their linked ropes and displace their loads at the slightest opportunity. The Tuareg leader, on foot, marched ahead... while eight of his companions... detached themselves to greet us. They were evidently well known to [our guide], whom they welcomed warmly yet with a kind of formal politeness, accompanied by much handshaking all round. Where were they bound for? To Timbuktu, twenty days' march away."

Around such tales, with plenty of daring low-altitude flying in light aircraft amidst the swarms of locusts, Baron builds a clear account of his war. It is truly a war, waged in behalf of the hard work and bread of millions, by a coalition of 42 nations through the UN with field stations, radio links, trucks, aircraft, stores of insecticides and skilled teams of combatants who must know the enemy, the land and the farmers for whom they fight. The locust is in recession now; it has been proved controllable by present knowledge, at least while men work together across the national boundaries so little visible down the long wadis of the desert.

The cycle of the insect is extraordinary. The species is found in two phases: the solitary and the gregarious. For a long time its generations may go by with the insect remaining small, harmless, never concentrating, just another green grasshopper. In the swarming phase it is larger, stronger, migratory, gregarious, yellow-uniformed. The phase change was first seen in 1929; until then the two forms were held to be distinct species. The change may go in either direction. Whereas desert plants have the ability to thrive in suspended animation, ready to germinate and blossom once the dry wadi springs to life after about an inch of rain, the locust cannot quite do that; it must move on once its swarms have fed on the local green. It seems probable that somewhere one of two events must occur. Either a set of solitary insects has the good fortune to multiply, by successful hatching, to a density large enough to trigger the phase change or a swarm beaten back by events remains gregarious in some remote spot, lays its eggs synchronously and so finds success. In either case the immature hoppers hatch out in numbers, march together using up

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food and fly in a swarm to seek their fortune. They fly downwind, and it has become pretty plain that the wind systems gather them along the long, seasonally shifting line of the great intertropical front, where the desert rains are favored. It is not only in poetry that the Koran speaks of locusts as "the teeth of the wind." Three fortunate hatchings and the swarm is a plague, growing tenfold in each generation, some four to six months to a generation. Disturbances cause the hoppers to become more gregarious, for example a disturbing antelope or camel herd, come from nowhere to seek out the greening wadi. Even the desert incense, the aromatic terpenes of the shrubs that yield frankincense and myrrh, can trigger egg-laying, anticipating the rains. The hoppers hatch a couple of weeks later, just as the rains come. (The shrubs can become fragrant before the rains, perhaps because the overcast skies result in lower temperature underground.) South of Tamanrasset in 1967 there was what may have been the first witnessed rise of a plague originating from solitary insects.

There are misgivings even in this tale of a moral war. The insecticides kill more than locusts. Although the governor may rejoice in the dead locusts, the local people mourn their dead goats. In the long run there will be too much dieldrin used over and over again in the same wadis. The locusts are themselves part of the chancy life of the desert. We need a more specific insecticide, even if it costs more to develop than the market can pay for. There is work for radar, new aerial cameras, even satellites. It should be recalled that the entire decade of hopeful effort, leaving behind a few plagues well fought, an organization in reserve, the locusts dormant and a solid basis of knowledge, cost the UN about the same as a couple of the supersonic fighter-bombers they make in St. Louis.

ARTIFICIAL CELLS, by Thomas Ming Swi Chang. Charles C Thomas, Publisher ($16). In 1956 a McGill undergraduate, surprised that no one there had thought of his idea of artificial cells, "proceeded to look into this in a corner of the physiology teaching laboratory." Now a professor in the same department, with three dozen papers behind him and his co-workers, founder of a worldwide subdiscipline, he presents the idea and what has and may yet come of it in a clear, modest monograph centered on its clinical potential.

Like the living cell, the artificial cell is not a specific physical entity at all; rather it is a concept of structure and scale. The proposal is to prepare capsules of cellular dimensions that might replace or supplant specific deficient functions. Size is the key; the point is that the surface area of a tablespoonful of microcapsules 20 microns in diameter is equal to that of all the diffusing membrane of an artificial kidney machine. Whatever the future may bring, the simple artificial cells currently within reach are no more like real cells than a wooden limb is like a real leg, but they may be equally useful as biochemical prostheses.

It is not hard to prepare artificial cells. The equipment is simple enough: glassware, a magnetic stirrer, a centrifuge. Still, the process is not for the careless. You add a lot of ether to a small sample of a buffered solution of hemoglobin in water and emulsify by magnetic stirring; it is a kind of mayonnaise. Then add an ether solution of cellulose nitrate. If the beaker stands for a while, a thin layer of collodion will form at the surface of each of the microdroplets of the aqueous hemoglobin solution that are dispersed throughout the organic solvent. The cells will settle out; decant, centrifuge, wash until no more hemoglobin leaks out, then sieve and you have a set of strong uniform spheres whose diameter can be controlled by stirring conditions and emulsifiers. The hemoglobin solution is the standard internal medium; its large molecules do not leak through unbroken walls and it can carry easily and stably such other proteins as enzymes. Nylon membranes are even stronger than collodion, and they can be prepared in a related manner. Chang has made his cells with diameters of from five microns up to a few hundred, with a variety of wall membranes whose thickness is a couple of hundred angstroms. The thin membranes are highly permeable to a number of important small molecules and are remarkably strong and uniform. Break the wall and the cell drains, the wrinkled membrane floating off through the microscope field, looking like the familiar debris from living cells.

There are strains of mice that lack the blood enzyme catalase. Injected with artificial cells containing the enzyme, the mice were protected from the peroxide-like poisons given them. The free enzyme in solution would of course do as well, but injected proteins eventually induce the immune response, whereas the enclosed catalase is protected from the globulins of the immune system by the thin membrane. One can enclose in the cells particles of ion-exchange resins or of activated charcoal that absorb many toxic molecules from the blood while the cell walls prevent the foreign

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material from affecting the complex reactive subcellular components of blood. Dogs provided with such cells and perfused by a shunted external flow of blood have been cleared of toxic loads.

Direct clinical use of an artificial organ made up of artificial cells has been successful in a recent case. A patient who lacks adequate kidney function but whose overall condition does not allow either a transplant operation or treatment with an ordinary kidney machine is being maintained by a blood shunt through a much smaller and less elaborate unpumped flow system past a few hundred grams of artificial cells loaded with activated charcoal, their collodion walls coated with human albumin. This 1971 experience is in the nature of a successful feasibility test; engineering for wide clinical use lies ahead. There seems to be hope, however, that the imaginative and elegant notion of one undergraduate will become the evolutionary forerunner of a complex artificial kingdom of human microsymbionts.

PLANTS IN THE SERVICE OF MAN: 10,000 YEARS OF DOMESTICATION, by Edward Hyams. J. B. Lippincott Company ($6.95). ANIMALS IN THE SERVICE OF MAN, by Edward Hyams. J. B. Lippincott Company ($6.95). A WEST AFRICAN COOK BOOK, by Ellen Gibson Wilson. M. Evans and Company, Inc. ($8.95). The civilized diner, since Brillat-Savarin and before, knows that conversation at table can well turn on the art and craft of the kitchen. Is not cooking the most widely practiced craft of humankind? What requires one step more of insight is the recognition that the food on the table is not the work of artifice on "raw materials," naturally evolved species of plants and animals that are our food. Not at all; "our cultivated plants *are* man-made" as surely as the spoon on the table. They are organisms entirely distinct from their wild ancestors; many cannot even breed without human aid. Nearly as much is true of domestic animals. Only the fishes of the sea, with an occasional mushroom or berry, still represent the species of the long years of our hunting before we had symbiont species produced by culture. "In a sense, domesticated plants and animals are artifacts."

Edward Hyams is an experienced English writer, the author of worldly and expert works on gardens and gardening, with one or two volumes already behind him devoted to such history as that of grapes and wine, and a still more general study of soils. Here he has given us two companion books, each of about

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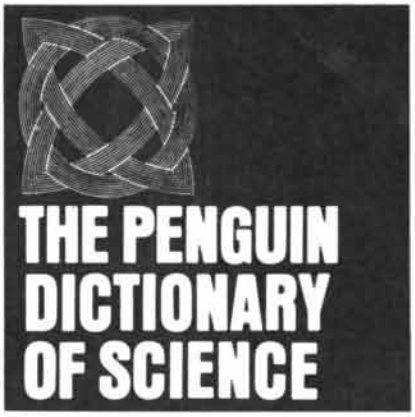

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200 pages, that sum up the history of the domestication of plant and animal species, largely, but not entirely, for food. The unfortunate wooden titles belie the smooth, well-argued, informed prose the two books offer. The content of the volumes is not in general novel. Although Hyams has paid modest attention to old authors, particularly from classical antiquity, and to the scientific periodical literature, most of his sources are the big, authoritative, if secondary, studies familiar to the expert. He draws much from Alphonse de Candolle (put into English in 1884, still first-rate, republished in this country by Hafner) for the use of linguistic evidence of origins, and from N. I. Vavilov, whose New York edition was published in 1951, for genetic and distribution arguments more modern than De Candolle's. He uses J. W. Purseglove's handbook of tropical crops and E. J. H. Corner's remarkable natural history of palms, both of which have been reviewed in these columns within the past few years. For animals he relies heavily on the standard volume by F. E. Zeuner and on the technical symposium edited by Peter J. Ucko and Geoffrey W. Dimbleby, also treated here. From these sources and others he takes his facts and his reasoning, displaying them with good temper and clarity unmarred by the eccentric judgments often seen in general prehistory, where conjectures abound. The result is a model of utility; every club and college dining hall would benefit from the ready presence of this pair of books, whose minimal set of footnotes and unprofessorial sentences invite the unspecialized reader.

What will he learn? That the earliest "doggy canids" are from earliest Neolithic Jericho (two different breeds, wolf dogs) and that at Mount Carmel at a similar time one finds the domestic jackal. The oldest breed of dog still with us is the saluki of Mesopotamia. Cats, still equivocal as domestic pets, were widely maltreated as being diabolical in the European Middle Ages. They were taken into controlled breeding in Egypt less than 4,000 years ago; the Athenians still kept not cats but house weasels against their mice. The chewing of betel, the nut of a palm, may have been spread from Malaysia by sea rovers of the Moluccas, people whose descendants praise them as being red-mouthed.

That betel-chewing has not spread worldwide is a model argument for much else in evolution: it requires a number of independent ingredients, so that it can be transplanted as a habit only if all of them go along. It is attractive enough to rival tobacco or tea or coffee or cannabis, all of which have become global. Witness: "'The late Professor J. B. S. Haldane, on being asked what betel-chewing was like, rolled his eyes up to Heaven and continued chewing.'" Hyams is sensible about diffusion processes: Independent invention is likely, although not universal. He is weak, however, on the great tropical root crops that nurture the peoples of the rain forest: yam, cassava and the rest. Canaries and snails, chinchillas and dormice, camels and silkworms, rubber and hemp are briefly treated, all with reason and cheer. Of course, the evidence is far less explicit here than it is in the big books, but it is only infrequently denied us entirely. In exchange for long, hard words, tempting footnotes and cryptic drawings of bone fragments we gain easy reading, the stark framework of the argument and brevity.

Cookery itself can still hold novelty, even in these days of a flood of cosmopolitan recipes and restaurants. It was the pioneer American Africanist Melville Herskovits who perceived 35 years ago that the American cuisine, like American speech, American music and American blood groups, owes a great deal to the Guinea coast, from which the ancestors claimed by a tenth of our people were taken. All those legacies came with men and women who could bring no material goods save perhaps a few seeds but who could not leave behind the treasures of their minds and hearts.

Mrs. Wilson, the author of *A West African Cook Book,* learned her cooking in each of four English-speaking countries of that low, hot coast: Sierra Leone, Liberia, Ghana and Nigeria. She has remembered well, has used the literature of West African kitchens and has given a set of recipes and comment that bring the art squarely into the American kitchen, sometimes in two versions, one with indigenous African ingredients and one sensibly adjusted to the supermarket. She studied our Southern cookbooks too, and spent a season in Georgia, coming to the conclusion that "distinctive features of Southern cooking are African in origin": gumbos and burgoo, hush puppies and pot greens, to begin with.

One should note that the west coast of Africa has been related to the maritime world, particularly to the Americas, for 500 years, so that such American staples as cornmeal and peanuts were welcome and commonplace in the Gulf of Guinea before the slave trade began.

Baking is a cooking method foreign to this cuisine and dairy products are

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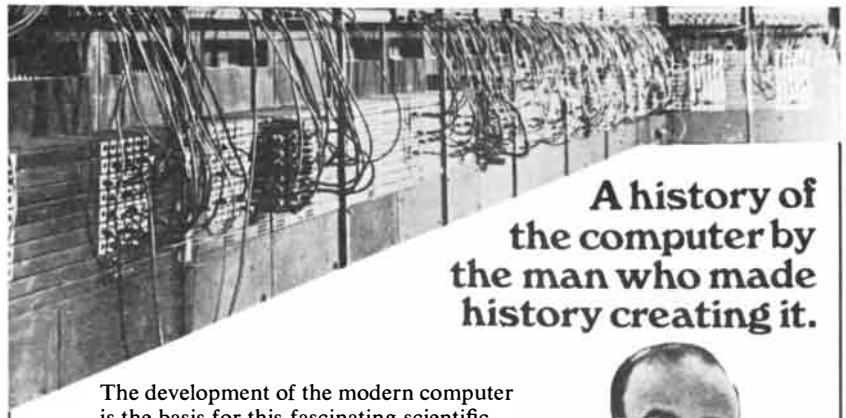
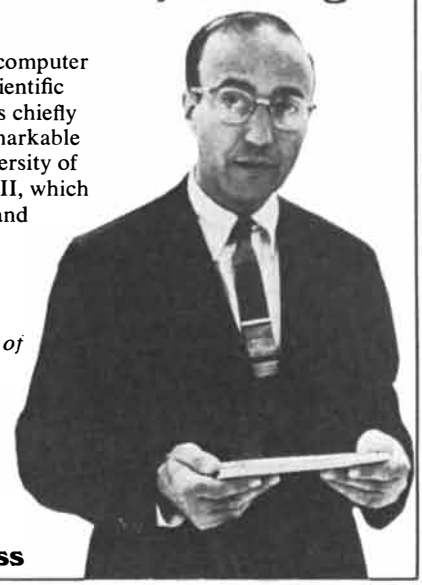
absent. The staples include those almost pure starches—foo-foo, or "white food"—made from cassava or yam that slide down without chewing, the mark of the classical West African dish. The graceful but taxing rhythm with which women pound the root with mortar and pestle to a fine flour evokes in West Africa by sight and sound the same sense of the beloved home that we associate with the smell of oven-fresh bread. The matter is explained here quite well, with details about eating the hearty one-dish meals, deftly scooping up varied sauces in a finger-held lump of the loaf. (Never fear: in the book as on the scene, variety and warm consideration for the guest ease the task.) The fad of the future, a real protein gain over French fries and the myriad tidbits of the fast-food world, may well come to be West African *akara:* little balls of a spicy mixture of mashed beans with onion, crisply deep-fried.

Ordering ERTS Images, EDCDM Forms 5 and 6. EROS Data Center, U.S. Geological Survey, Sioux Falls, S.D. 57198 (free). A Guide to Earth Satellites, edited by David Fishlock. American Elsevier Inc. ($7.95). Remote Sensing of Earth Resources. Committee on Science and Astronautics, U.S. House of Representatives. Superintendent of Documents, U.S. Government Printing Office ($1.25). If an earth satellite is placed in true polar orbit, it will circle the earth, the plane of its orbit holding a fixed direction in space. The earth meanwhile turns below the satellite and as the days go by the earth progresses along its grand round about the sun. Suppose the polar satellite is first orbited at noon. Then the sun lies in that unchanging orbital plane, and the satellite sees the ground below always at local noon (or midnight). After three months the earth's position in orbit will have shifted a quarter-revolution and the satellite plane will have become perpendicular to the earth-sun line. Now it will view the earth below at 6:00 A.M. (or 6:00 P.M.) local time. If instead the satellite is launched into a near-polar orbit that passes, so to speak, over the earth's shoulder some 10 degrees west of due north, the perturbations arising from the bulge of the earth will cause the orbit to precess slowly. The direction can be chosen for any orbital altitude so that the orbital plane drifts at the same rate as the apparent motion of the sun with the seasons. Then the orbit is said to be sun-synchronous, and the satellite will continue to see the ground point below it always at the same local time.

In late July the National Aeronautics



A history of the computer by the man who made history creating it.



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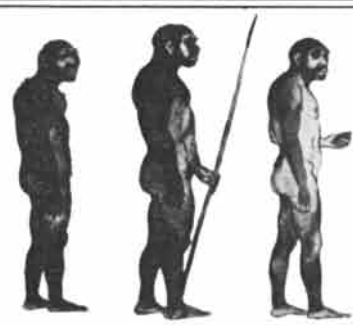

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and Space Administration launched a one-ton satellite into a sun-synchronous orbit some 560 miles up with a period of 103 minutes. Every period the satellite crosses the Equator at about 9:30 A.M. local time on the daylight side. The spin of the earth during each satellite period causes the ground under the orbit to slip westward about 1,550 nautical miles each period. After a full day the orbit precession, combined with the fact that the orbital period is not an exact submultiple of the day, ensures that the satellite traces out a track on the ground in which each orbital sweep lies about 85 nautical miles west of the corresponding sweep of the day before. Thus every 18 days the satellite will revisit nearly the same ground points, always by morning. The first Earth Resources Technology Satellite, now called ERTS-1 (it bore the name ERTS-A until it was successfully launched), carries two elaborate imaging systems, each of which records a field of view 100 nautical miles square, so that the camera swath catches every spot on the earth during one 18-day cycle, with overlap (except for small regions near the pole).

ERTS-1 is representative of a technology that is now self-assured and mature. The launch rocket was a two-stage liquid-fuel Delta, souped up with nine strap-on solid-fuel rockets. It was the latest (and heaviest-payload) version of the Thor-Delta combination, which goes all the way back to 1960, with 80-odd launches now recorded. The spacecraft, made by General Electric, is much the same as the one used in the four Nimbus experimental meteorological satellites of the past eight years.

The meteorological cloud-cover photographs made by those satellites are higher-grade versions of the ones that are by now familiar on the daily television weather programs; they have a resolution of about one kilometer on the surface by day and five to 10 kilometers even at night with the deep infrared. The images taken by ERTS-1 are much more detailed.

Their aim is the study not of insubstantial air and cloud but of surface features: geology, crops, forest fires, locust breeding grounds, sediment in streams, coastal changes, city growth and whatever else can be seen in photographs with a resolution of 100 meters or better on the ground. They show few of the discrete works of man: some bridges, wide roads, airport runways. Large built-up areas appear as faint tonal smudges. ERTS-1 maps the surface of the entire earth, except for the high seas and the landmasses of the U.S.S.R. and China, over which the satellite's cameras are turned off.

ERTS-1 carries three five-inch lenses that produce television images of the same scene in three distinct color bands. This is exceptionally good television, with 4,000 lines, about 10 times the detail of home or weather-satellite television. The RCA-developed system is called the RBV channel, for return-beam Vidicon. The satellite also has a second image system. It is a Hughes Aircraft development called MSS, for multispectral scanner. Here the field is scanned not electronically but mechanically by an oscillating mirror. More complicated, the scheme allows the use of many detectors, one for each of four wave bands in ERTS-1, without any problem of registration since every detector samples one and the same scanning spot.

The image pulses reach the ground by microwave link, either immediately or—when the satellite is out of sight of all its ground stations—after storage on video recorders aloft. Video tapes made by receivers in Alaska and California are sent by air to the Goddard Space Flight Center in Maryland (which can also receive), where all the images are automatically corrected and converted to 70-millimeter black-and-white positives, with a modulated electron beam used to expose the film. All seven color bands are recorded on separate frames; some scenes are selected for being made into composite color images. It is, to be sure, "false color"; neither system incorporates a set of three colors to match the eye; infrared bands provide three of the seven images. Pointing, image quality, almost everything, worked perfectly as of Labor Day; the RBV recorder alone is suspected of malfunction, so that for the time being only the MSS system can produce images from beyond the view of the three U.S. ground stations.

Pictures flood in. Every 18 days the system, whose bit output is about that of three continuous commercial television channels—an encyclopedia's worth each minute or two—images most of the world. Goddard prepares a computer index of all the photographs made in the cycle, and prepares a sample of a couple of thousand of them on 16-millimeter microfilm. Some 300 research groups in countries throughout the world—one even in the U.S.S.R.—get all the pictures they want for a wide variety of developmental purposes.

Now for once this kind of technology can touch the reader directly. No American who uses maps is unaware of the U.S. Geological Survey, the agency whose topographic quadrangles are the

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basis of our cartography. That same agency has just opened its Earth Resources Observation Systems Data Center (the acronym seems forced), which makes the ERTS world view accessible quickly, sensibly and economically to anyone who cares. Goddard transfers all the master films to EROS for reproduction and distribution. The order form listed at the beginning of this piece is your entree. The best buy would seem to be the 1/1,000,000 size in a nine-by-nine-inch black-and-white print. The red filter band yields tone values like the familiar aerial panchromatic film; it is RBV Band 2, or MSS Band 2. You can obtain such a photograph of any point in the world, politics aside, for $1.75 postpaid. The EROS staff will "exercise judgment in completing your order," seeking the most recent good coverage with the cloud cover you specify as acceptable and choosing the right framing to suit your needs. There are many options, such as smaller formats for projection, from $2.50 up. A 1/500,000 print is a fine display at only $3.50. The stunning color composites are of course more expensive and more selective of scene.

One can suggest to this new service only one improvement. The photographs come with a computer-printed legend in the margin. It is easy to decipher some of it, such as the direction of the sun and the position of the center, but the rest of the coded lines deserve a page of key, which could be supplied—far less than the heavy manual the research users undoubtedly enjoy.

A Guide to Earth Satellites is a good overall review, meant for the general reader, of the entire technology, its history, skills, costs and prospects. Its chapters, largely by expert British authors, survey the satellites by type: communication, weather, earth resources, navigation, military and the rest. It is as up to date as such a book is likely to be, bringing the account of events up to 1970, with useful graphs, photographs and drawings. Orbit and sensor design for ERTS are included in the volume, for instance.

The timely Congressional-committee brochure (unfortunately lacking index and references) is a compilation of some 16 papers presented by experts early in 1972. It treats the whole question of ERTS and its successors from a wide range of viewpoints, particularly the viewpoint of potential for world economic benefit from such observations. There is both jargon and clear prose, useful data and plain conjecture, in a fair crosscut of disparate opinion.

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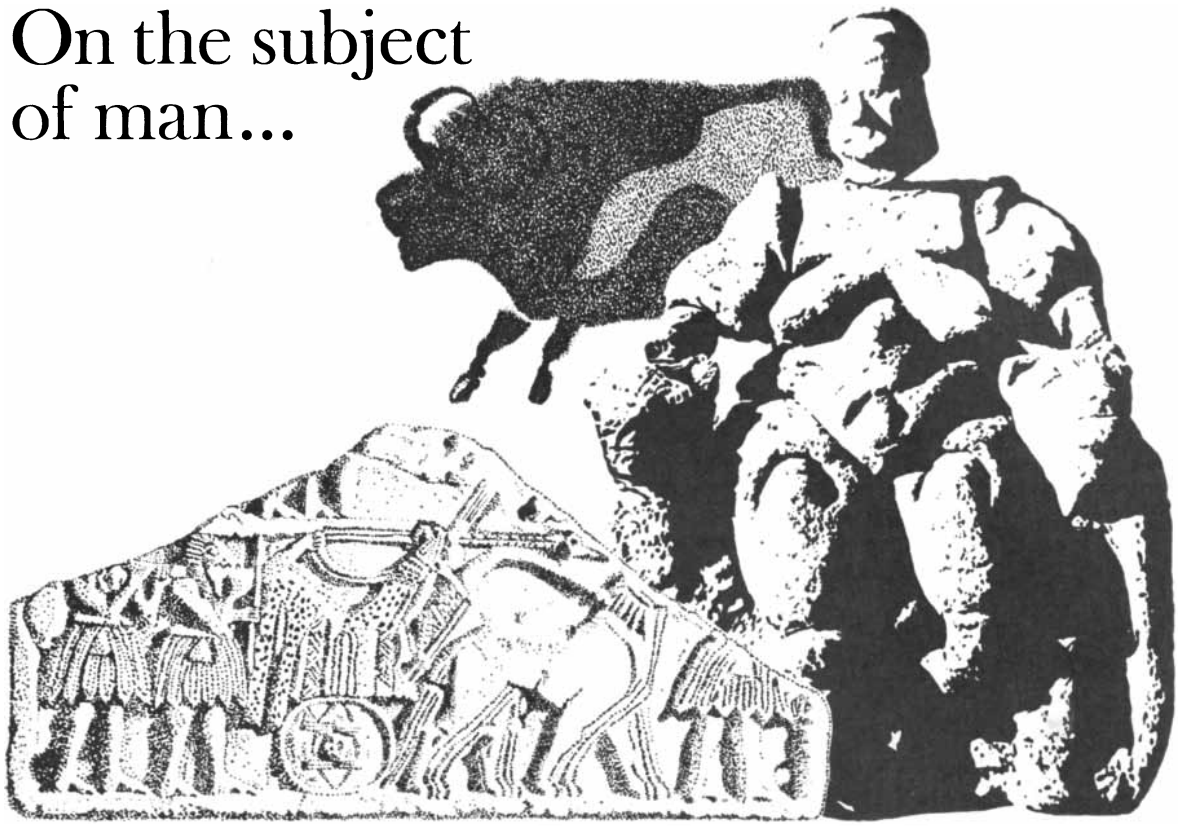

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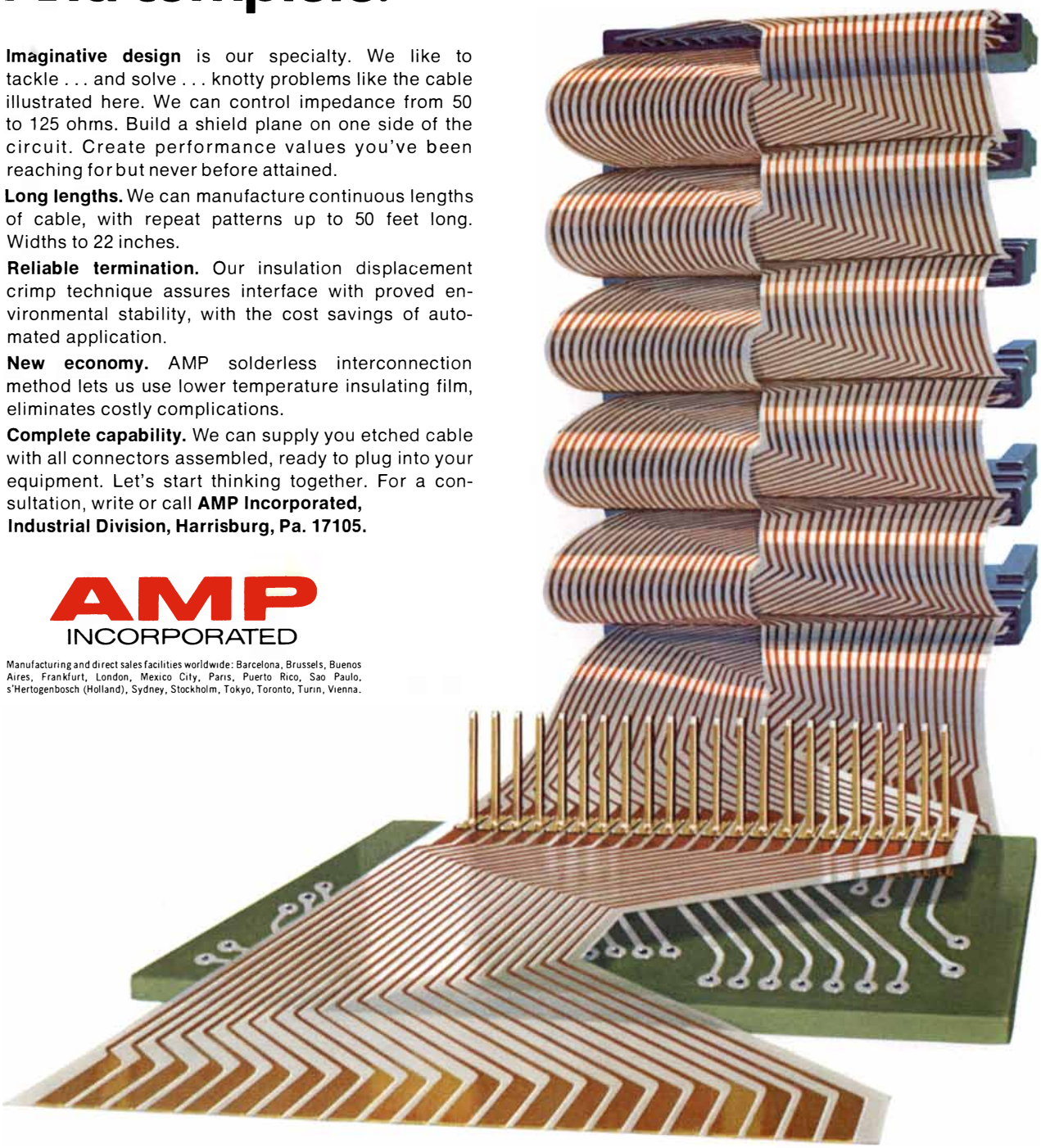

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