SCIENTIFIC AMERICAN

SAGE GROUSE MATING DISPLAY

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May 1978

BMW BRINGS THE THRILL OF PERFORMANCE TO THE STUFFY WORLD OF THE VERY EXPENSIVE LUXURY SEDAN.

INTRODUCING THE BMW 733i.

It would seem that the majority of the world's auto manufacturers assume that by the time one is able to afford an expensive luxury sedan one has somehow lost the craving for extraordinary performance.

Which may well explain why so many of the world's luxury sedans are infinitely more stimulating to sit in than to drive.

At the Bavarian Motor Works in Munich, Germany, we reject this sedentary approach to the building of automobiles.

It is our contention that—however luxurious the accommodations—extraordinary performance is the only thing that makes an expensive car worth the money.

And so while the BMW 733i provides all the creature comforts one would expect to find in a costly European sedan—supple leather, AM/FM stereo cassette, full power accessories, etc.—it also provides a total driving experience so unusual, so exhilarating, it will spoil you for any other car.

THE TACTILE SENSATION OF A TRUE SPORTS SEDAN.

The genius of the BMW 733i lies not in the fact that it is—by European standards—large and luxurious.

Indeed, the technical feat involved here is that the engineers at BMW have managed to incorporate these qualities into a car that performs like a BMW.

Its engine—a 3.3-liter, fuel-

injected masterpiece of evolutionary design—has been called by no less than the editors of Road & Track magazine, "...the most refined in-line six in the world."

Its four-speed transmission (automatic is available) slips precisely into each gear. Its acceleration comes up smoothly with the turbine-like whine peculiar to BMW.

Its suspension system—independent on all four wheels—with a new and patented double-pivot front axle—is astonishingly quick and clean through the corners.

Rather than reduce or distort driver "road feel"—as do the steering systems found in many of today's passive luxury sedans—the suspension system of the BMW 733i is designed to provide the driver, through the steering wheel, with instant, precise information at all times, under all conditions.

THE INTERIOR, ENGINEERED NOT DECORATED.

Inside the BMW, where conventional luxury sedans throw function to the wind, the engineers at the Bavarian Motor Works have achieved what the editors of Motor Trend magazine describe as "...a study in ergonomic excellence."

There is virtually nothing in the BMW 733i that does not in some way contribute to comfort, convenience, security and efficiency.

Careful study has been made of the critical interrelation between seat location, visual position, steering wheel angle, pedals and controls.

Instruments are clearly visible; controls readily accessible.

All seats have an orthopedically molded shape. Individual seats are adjustable forward and back—with variable-angle seat back and cushion supports.

The steering wheel is telescopically adjustable to compensate for variations in arm length.

Pedal direction and pedal pressure have been carefully balanced to reduce fatigue and facilitate effortless gear changing.

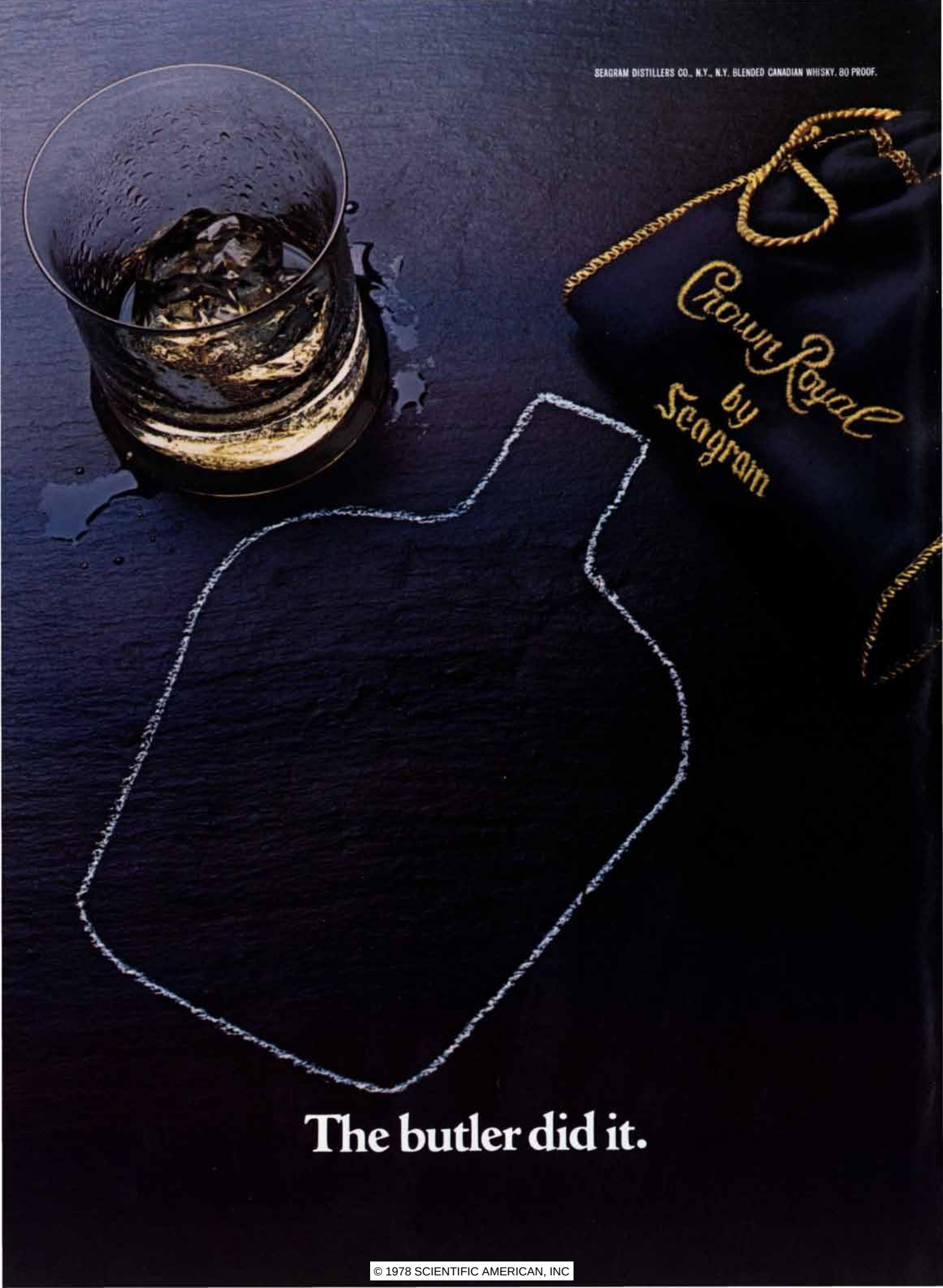
So successful is this integration of man and machine that when you drive the BMW 733i for the first time, you will experience an almost total oneness with the car.

As the editors of Motor Trend magazine once observed, "The reaction to a BMW is always the same. The first time driver takes the wheel and after a few minutes no other automobile will ever be the same again."

If the thought of owning such a car intrigues you, call us anytime, toll-free, at 800-243-6000 (Conn. 1-800-882-6500) and we'll arrange a thorough test drive for you at your nearest BMW dealer.

THE ULTIMATE DRIVING MACHINE.

Bavarian Motor Works, Munich, Germany.



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ARTICLES

DEPARTMENTS

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RCA SUGGESTS:

7 intelligent questions to ask when comparing video cassette recorders.

If you've decided on getting a video cassette recorder, your next decision is which one to get. After all, there are differences. These questions will help you find them. Which ought to make your decision a lot easier.

What's the maximum time on a single cassette?

Notice we said "on a single cassette." You don't want to be changing tapes in the middle of things. Check the controls on an RCA SelectaVision Video Cassette Recorder and you'll see that you can record for two hours or even *four hours on a single cassette.* Compared to the Beta-system recorders, SelectaVision gives you more flexibility and more time—you can't buy more than four hours on one cassette.

How much time do I get with the timer?

Some recorders offer a timer which attaches to the top of the machine. Many of these can only be set to start the recorder up to 19 hours in advance. SelectaVision, on the other hand, has an electronic digital timer that's *built in.* It makes for a very handsome design. What's more, you can set the SelectaVision timer to record up to *24* hours in advance.

Where is the pause control?

If the answer to your question is "third button from the left," you've got a problem. When you want to eliminate an unwanted segment while recording, you have to jump up and run over to the machine. And, if you want to put the playback on "hold" while you get another bag of chips, you'll have to stop at the recorder on your way to the kitchen. Here's a better way: SelectaVision's *remote* pause control. You can use it from your chair—up to twenty feet away. Now isn't that more sensible?

What are my options?

Make sure you take a good look at optional equipment. There are some really exciting things here. SelectaVision, for instance, offers a black-and-white camera so you can make your own television productions. You simply aim, pull the trigger and you're recording. A built-in microphone handles the sound. And you can see what you're getting on the screen while you get it.

Another SelectaVision option: a separate mike lets you do your own audio track. You can even plug into your hi-fi.

Is the recorder direct drive or belt driven?

Here's where video recording is a lot like audio recording. To maintain a steady picture, the speed of the head wheel and tape must be precisely maintained. A tolerance of five tenths of one percent for audio recorders is considered excellent. But a variation of more than five *hundredths* of one percent in a video cassette recorder will cause distortion in the color picture. Belts can loosen and wear out—affecting head wheel speed. But SelectaVision's direct-drive system is designed to provide precise control now and for years to come.

How's the color?

Remember, a video cassette recorder is like a TV set without a screen. It receives its own signal. SelectaVision is made with special circuitry that automatically compensates for changing signal strength.

What about service?

Let's face it. A video cassette recorder is a precision piece of equipment. And if something isn't operating precisely, you'll want to know that help is nearby. So you ought to know that SelectaVision has the largest network of factory-authorized service centers—over eight hundred—in the country.

Now that you have the right questions to ask, shopping for a video cassette recorder ought to be a lot simpler. You might even want to take this ad along. And if you still have a few questions, write to us: Mr. William F. Gillis, Merchandising Manager, RCA Consumer Electronics, Dept. SA, 600 N. Sherman Dr., Indianapolis, Ind. 46201.

The way we see it, the more you know about video cassette recorders, the more you're going to like SelectaVision.

Let RCA turn your television into

SelectaVision.™

RCA

Caution: The unauthorized recording of television programs and other materials may infringe the rights of others.

Myth:
It takes a lot of fuel to move a heavy load.

Fact:
On today's railroads, one gallon of fuel moves a ton of freight 280 miles.

Most automobiles made in Detroit can go about 100 miles to the gallon—if they move by railroad. The same goes for most other goods that move by rail. Today, railroads use less than one-third as much fuel as trucks, on the average, to move big loads.

And railroads are working to save even more fuel in the future—with entire trains of grain or coal that require less energy than either barges or pipelines, with new space-age technology, with improved operating practices.

Piggybacking—the movement of truck trailers and containers on railroad flatcars—is the fastest growing part of the railroad business. It not only saves fuel, it reduces traffic congestion and improves highway safety by taking more than 2 million truckloads off the roads each year.

The Department of Transportation expects the nation's freight load to double by the year 2000 and the railroads' share to grow even faster. One important reason for this is that the existing rail system already has the capacity to handle many more trains. Another is the railroads' proven fuel efficiency.

Last year the railroads spent a record $9 billion for track and equipment improvements that will allow them to handle more freight with greater efficiency than ever before—saving both fuel and money.

Association of American Railroads, American Railroads Building, Washington, D.C. 20036.

Surprise:
We've been working on the railroad.

THE COVER

The painting on the cover shows a male sage grouse displaying on its breeding ground in Wyoming early in the spring. The male has reached the stage in a repetitive three-second display called the strut when its inflated esophageal sac, located beneath the two prominent bulges of bare skin, is about to be contracted with a popping sound much like the sound produced by pulling a cork out of a bottle. When the male sage grouse is strutting in the presence of prospective mates, it may display more than 30 times during six minutes (see "The Lek Mating System of the Sage Grouse," by R. Haven Wiley, Jr., page 114).

THE ILLUSTRATIONS

Cover painting by Enid Kotschnig

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147	Camillo Peracchia (*top*); Barbara E. Hull (*middle*); *The Journal of Cell Biology,* Rockefeller University Press (*bottom*)
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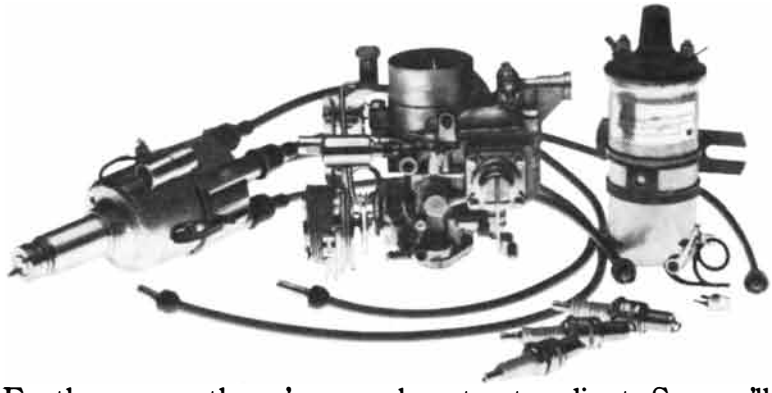
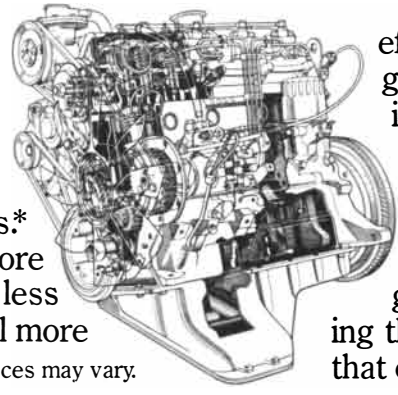
159	Norman Smith
160	Tom Prentiss
162	Design Photographers International, Inc.
164–171	Michael Goodman

What you should know about diesels. From the people who've been making them 50 years.

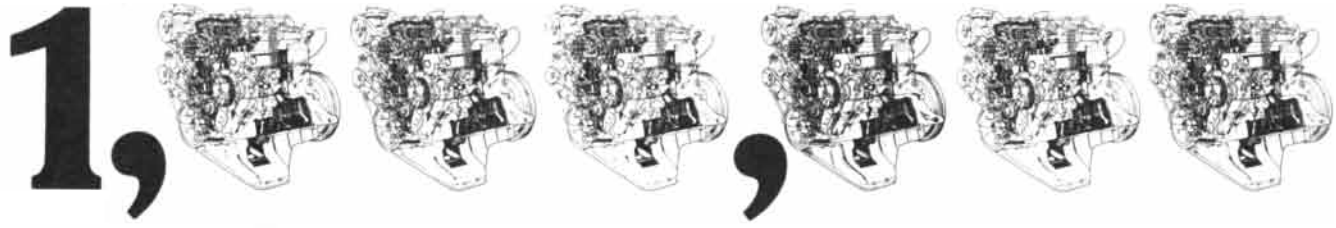


Less is more. You're seeing a lot more diesel cars on the road. Partly because they give you a lot less things to worry about. No spark plugs, points or condensers to replace. And no distributor, coil or resistors. If these parts aren't there, they can't break down. Furthermore, there's no carburetor to adjust. So you'll never need a tune-up. You won't need many fill-ups, either.

An engine with ingenuity. The diesel not only runs on less parts. It runs on less money. Because it doesn't run on gas. Diesel fuel nationally averages about 10¢ less a gallon than lead-free gas.* The more driving you do, the more saving you do. And you'll fill up less often. Because a diesel burns fuel more efficiently. Especially in stop-and-go city driving. If you have to idle in a traffic jam, the diesel engine burns only about one-fourth the fuel a gas engine burns. This is why diesel cars get better mileage in the city than most cars get on the highway. It's the coming thing for going places. We knew that over a million diesels ago.



*Federal Energy Review Jan., 1978. Local prices may vary.



How we made our first million. Diesel cars are not only new to you. They're new to many carmakers. But not to Peugeot. We've been producing automotive diesels since 1928. Since then, we've made over a million light diesel engines. We've made them strong—much stronger than any comparable gas engine. We've made them from the ground up—not by converting gas engines. We've made them durable—to match the rest of our car. We've made them carefully—with every critical part inspected and tested more than any car made in America. And we've made them to give you better mileage than any other luxury car you can buy.† This is the kind of experience built into a Peugeot diesel. It's a tough act for other automakers to follow. We're not the only ones who think so.

†1978 EPA Estimate mileage. 34 mpg highway, 28 mpg city, 30 combined. Transmission M-4. Actual mileage depends on how and where you drive, optional equipment, car maintenance and other variables.

Listen to the experts. "The concept of a lifetime car is a great one, and if *any* car should be on top of the short list of those cars, the Peugeot 504 diesel is it."
—*Road Test*

"...your Peugeot 504D can be hammered down even so awful a road as Manhattan's infamous FDR Drive while retaining precise control." —*Car and Driver*

"The competition for diesel sales should become increasingly fierce, but Peugeot will undoubtedly maintain a strong position, thanks to its pioneering position and the quality of its product." —*Road and Track*

This year some automakers are introducing their first diesel. This year is the 50th Anniversary of ours. Fifty years ago Peugeot produced its first automotive diesel engine. That's a long time to be working on the "engine of the future" some automakers are introducing today. We've had a half century to perfect ours – and the cars they go into. And we've learned a few valuable lessons. For example, we will never produce a hybrid diesel—those gas converted engines the newcomers like GM and Volkswagen are introducing. They're just not as strong as ours. And there's another thing we've learned. There's no point in putting an engine that can take it into a car that can't. So we make our cars every bit as tough as our engines. Combine that with our superior handling. Now add to that the interior room of a full size sedan. And the luxuries: power-assisted four-wheel disc brakes and steering, electric front windows, tinted glass, fully reclining front seats, four-wheel independent suspension, and a sunroof as standard equipment. And optional automatic transmission. That's not all that's optional—in addition to a luxury sedan, we also make a diesel station wagon. Nobody builds diesels the way we build diesels.

Now you know about diesel cars.
And the more you know about diesel cars, the more you'll want to own a Peugeot. The Peugeot Diesel. It's a 50th Anniversary for us. But it can be a real celebration for you.

For information on buying, leasing, or overseas delivery see your Peugeot dealer. Or call toll-free 800-243-6000 (In Connecticut call 1-800-882-6500). Peugeot Motors of America, Inc., Lyndhurst, New Jersey 07071.

PEUGEOT

No one builds cars the way we build cars.

LETTERS

Sirs:

Peter P. Luff's article "The Electronic Telephone" [SCIENTIFIC AMERICAN, March] provides an excellent introduction to the functions of the telephone set and to the complex technical and economic factors that have affected the timing of technological change in this field. The almost unbelievable longevity of the carbon-button transmitter (microphone) particularly illustrates the power of these factors.

Luff mentions that the practical introduction of the "one piece" telephone set, with the transmitter and the receiver in a single handle, was delayed by the problem of acoustic feedback between the transmitter and the receiver. An equally strong factor came from another peculiarity of the carbon-button transmitter: its sensitivity to changes in orientation with respect to gravity. In the desk-stand ("candlestick") telephone set the transmitter is held in a relatively constant attitude during normal use. Mounted on the more mobile "handset" of the one-piece telephone, the transmitter behaved erratically as the carbon granules in it shifted. A more sophisticated design, with the carbon placed between spherical shell electrodes instead of between parallel plates, eventually solved the problem.

The long quest to make the replacement of the carbon-button transmitter economically practical is particularly ironic in view of the fact that Alexander Graham Bell's first instrument (which was essentially similar to the one shown on page 60 of the article) was of the dynamic-transducer type. As Luff points out, without an amplifier (which was unknown at the time and subsequently too costly until today) the signal from such a transmitter was far too feeble for practical use.

It is worth noting that the problem of acoustic feedback between the transmitter and the receiver in a one-piece (handset) telephone surfaced again in the 1940's. As the first step toward today's proliferation of "decorator" telephones, colored instruments were offered. The colored handsets were made of a thermoplastic material, whereas the black ones until that time had been made of a thermosetting material. As a part of the required design change the handset handle was hollow, and this introduced an unanticipated acoustic path from the rear of the transmitter to the rear of the receiver, again causing a feedback situation. The solution was to put a pledget of cotton in the handle bore, a technique still used today in the handset of the "500" instrument.

Although Luff does not dwell on the fact, the telephone ringer ("bell") is also entirely unchanged in its operating principle from the days of Bell, and indeed its design is generally ascribed to Thomas Watson, Bell's assistant. Contrary to Luff's description, and in distinction to the mechanism of, say, a doorbell, the usual telephone ringer does not have a make-and-break mechanism but rather acquires its vibratory motion from the alternating current sent to it from the telephone switching equipment. It is this use of alternating current that makes it possible for the ringer to receive its energy (through a capacitor) while the telephone is idle and is thus, as Luff writes, unable to pass direct current.

D. A. KERR

Dallas, Tex.

Sirs:

H. Arthur Klein's article "Pieter Bruegel the Elder as a Guide to 16th-Century Technology" [SCIENTIFIC AMERICAN, March] interested me both for its technological content and for its information about the artist himself. (Klein's *Graphic Worlds of Peter Bruegel the Elder* has been on my bookshelf for several years.) His discussion of the building crane in the cover illustration, however, was a bit puzzling. It appears from the illustration that the crane consists basically of two coaxial drums, the larger drum serving as the treadmill and the smaller one (probably the axle itself) receiving the lifting rope, which wraps

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around it. If that is the case, then the question raised in the text ("Could such cranes have raised all the massive stones of the tower?") can surely be answered without difficulty. If the radius of the treadmill drum is 10 times that of the axle, then six 200-pound workers exerting a force equal to their weight would suffice to lift a three-ton stone (without allowances for frictional losses). If, as is more likely, they exert their weight at a point about 30 degrees away from a vertical dropped from the axis, they could still lift a 1.5-ton stone. Even allowing 20 percent for frictional losses, they could lift 1.2 tons. If the crew were increased to eight, even larger weights could be handled.

LLOYD C. KANNENBERG

Department of Physics
University of Lowell
Lowell, Mass.

Sirs:

I thank Professor Kannenberg for his observations on the role of power in relation to the lifting abilities of man-powered devices. The problem of the power a crew can exert in the long run is very much the name of the game. I hope to make that clear, clearer perhaps than my article did.

The same cast and props suggested by Professor Kannenberg are used in the following scenario. Six 200-pounders are preparing to raise a three-ton stone, let us say 100 feet. Their man-powered crane has a mechanical advantage, or ratio, of 10 to one.

The rope from the hoisting drum is made fast to the great stone, and as the six men enter their cage we consider that in this apparatus they can together develop .6 horsepower, or 330 foot-pounds per second. They quickly climb until they are clinging vertically to the walkway at the level of the axle. Thus their combined weight of 1,200 pounds presses down on the drum tangentially, and the rope pulls up on the stone with a force of 1,200 times 10, or 12,000, pounds.

A net upward force of 6,000 pounds now accelerates the stone. Its mass is such that the acceleration rate is 32.2 feet per second per second. In less than .001 second the stone has attained an upward speed of .0275 foot per second, and the walkway of the drum moves with respect to the laborers at .275 foot per second. This is a kind of limit, since a tangential force of 1,200 pounds exerted at a velocity of .275 foot per second means a power flow of 330 foot-pounds per second (as noted above).

The laborers accordingly drop down to, or near, the 30-degree position in the drum. They walk upright, as if they were climbing a 30-degree slope. For each foot of motion along the drum it is as if they lifted their 1,200-pound weight .5 foot. Their combined force on the circumference is hence 600 pounds, and the rope now pulls upward on the stone with a force of only 6,000 pounds, just enough to offset the weight of the stone. Consequently the stone continues to rise .0275 foot per second, neither accelerating nor decelerating.

The result is that a 100-foot lift requires about 3,636 seconds, or a little more than an hour. (The periods of time for the initial acceleration to .0275 foot per second and the final deceleration from that speed back to zero again are too small to need taking into account. Moreover, we follow the fiction that the crane and its tackle are free from friction. We also disregard the mass of the drums, the ropes and so on.)

An hour to lift the three tons 100 feet is mighty slow going. Even an eight-man crew would need more than 45 minutes. The six-man crew could raise six tons 100 feet in some two hours, 1.5 tons in 30 minutes and so on. All these figures assume that the power limit per crew member is .1 horsepower, but an exceptionally powerful and well-trained crew whose members could generate .2 horsepower each, or 1.2 horsepower together, could raise three tons in about 30 minutes, a rise still by no means rapid. In other words, estimates are impossible without considering the power the crew could generate.

A word of caution: If the six-man crew with a combined capacity of .6 horsepower wanted to lift the original three-ton stone 100 feet, but without climbing at steeper angles than they would climb in the 30-degree position, they could do so, provided they used a crane whose mechanical advantage or ratio was, for example, 20 to one rather than 10 to one. It is essential that every lift begin with the rope's pulling the load upward with greater force than gravity pulls it downward. At 30 degrees six 200-pound workers exert a tangential force of 600 pounds on the drum. This force must be multiplied until it is substantially greater than the stone's weight of 6,000 pounds. A 20-to-one ratio would do that.

Narrowly considered, mechanical advantage or leverage relations enable patient children to jack up trucks, or could ideally enable a hummingbird to haul a hippopotamus. Once such relations emboldened Archimedes to boast that he could move the earth itself if he were given a proper fulcrum for his superlever. In actual lifting operations, however, the element of elapsed time cannot be ignored. This means that consideration must be given to power: the rate at which work is accomplished or energy is transformed.

H. ARTHUR KLEIN

Malibu, Calif.

IT'S THE ONE THING MUSIC LOVERS ALL OVER AMERICA AGREE ON.

PIONEER'S SX650. THE NUMBER ONE RECEIVER TODAY WITH PEOPLE WHO CARE ABOUT MUSIC.

When it comes to buying a good high fidelity receiver, music lovers can be unmerciful.

If a receiver has the least bit of audible distortion, a music lover won't buy it.

If a receiver isn't powerful enough to drive at least two sets of speakers, they'll pass it right by.

If a receiver doesn't have an absolutely superlative FM section, they won't bother to consider it.

And if a receiver doesn't leave a music lover with enough money to buy still more records and tapes, they'll find one that will.

Last year, America's music lovers had well over 150 different high fidelity receivers to choose from.

The receiver they chose to buy more often than any other was Pioneer's SX650. A receiver designed to deliver a minimum of 35 watts per channel into eight ohms, from 20 to 20,000 hertz, with no more than 0.3% total harmonic distortion. A receiver that costs almost $100 less than similar 35 watt receivers built by our competition.

You can hear the SX650 at your local Pioneer dealer.

It's the one receiver designed for people who appreciate great value as much as they appreciate great sound.

High Fidelity Components

PIONEER®

WE BRING IT BACK ALIVE.

50 AND 100 YEARS AGO

SCIENTIFIC AMERICAN

MAY, 1928: "A large percentage of the injuries resulting from automobile accidents are due not to the smash-up of the car itself but to the flying glass from the windows and windshield. Consequently the adoption of triplex glass this year by two well-known automobile manufacturers has aroused great interest. The type of triplex used in the windows and windshields of automobiles is identical in appearance with ordinary plate glass and consists of three layers. The two outside layers are the finest obtainable plate or sheet glass, and the middle layer is a binding composition known as pyroxylin plastic. This is a perfectly transparent sheet of cellulose material. Under ordinary impact triplex will not shatter or create fragments because the flexible center layer holds tightly to the outside layers."

"In no field of chemistry has there been greater recent progress than in the production and utilization of new alcohols. Ten years ago the purchaser of alcohols for industrial uses was limited to three substances, namely methyl alcohol, ethyl alcohol and amyl alcohol from fusel oil. Isopropyl alcohol, which until a few years ago was merely a laboratory chemical, is now available on a large scale for solvent use. This material is being manufactured as a by-product of oil-cracking operations. Secondary butyl alcohol is now produced on a considerable scale in this country from the waste gases in oil refineries. Ethylene glycol, made from natural gas, is an alcohol many of whose chemical derivatives are valuable solvents for the natural cellulose used in lacquers. The alcohol family is almost as numerous as the Smith family, and those mentioned above are only a few of its members especially important in industry."

"Speeding at a terrific rate in what have been termed 'storms of their own making,' two automobiles, specially constructed and equipped with powerful motors, early in February attempted to break the record for earth-bound vehicles set last year by Major Segrave on Daytona Beach in Florida. The contenders for the title also ran on that beach, and one of them, Captain Malcolm Campbell of England in his *Bluebird,* beat Segrave's record of 203.79 miles per hour by setting a new record of 206.956 miles per hour. The other contender, Frank Lockhart, came to grief when his Stutz *Black Hawk* raced into the sea while unofficially making 225 miles per hour after a four-mile start. It is thought by many that if Lockhart's car had not swerved into the sea, he would have gained for America the coveted record."

"Good radio programs are so frequently spoiled by man-made static that the town of Fairfield, Iowa, has recently passed a city ordinance that makes it a punishable offense to create interference with radio reception. A fine of $100 or 30 days in jail has been set as the punishment for violation of the ordinance, the text of which reads: 'It shall be unlawful for any person to operate any instrument, device or machine of any kind whatsoever the operation of which shall cause electrical interference with radio reception, within the city limits of the City of Fairfield, Iowa, between the hours of 12 o'clock noon and 12 o'clock midnight, on any day after taking effect of this ordinance, save and excepting only such as may be necessary in making X-ray pictures or examinations in emergency cases of injury.'"

SCIENTIFIC AMERICAN

MAY, 1878: "American manufactures are better in quality than those of any other nation, are highly appreciated almost everywhere and are in the main as cheap as or cheaper than any others. But the trade in them is pushed with but little skill and energy by our people; our exporters act carelessly and do not in such matters adapt themselves to the necessities of different countries as carefully as do the English and the Germans. Dealers abroad complain that descriptive circulars and price lists are not full enough. Our manufacturers do not adapt their goods to different markets as readily as do those of other countries. Besides these general complaints there are two others that appear in almost all the reports. One is that our manufacturers and exporters do not maintain fixed prices but vary them frequently, being compelled to do so by the fact that we here are cursed with a currency of fluctuating value. European and South American dealers say that it is impossible for them to order American goods, even where these are greatly preferred and cheaper, because prices are thereby unsettled. The other complaint is made against our high tariff, which disables us from buying and importing foreign products and thus forces merchants abroad to trade with England, because the outward freight on their purchases is lessened by the fact that the ship is sure of a return freight."

"The United States commercial agent at Gadoon reports to the Department of

OMNI'S TOPS.

Motor Trend magazine thinks so. Which is why Dodge Omni became *Motor Trend* Car of the Year.

Veteran car critics and testers have been reporting some very nice things about Omni. Like the confident feel of its front-wheel drive. And the kind of space front-wheel drive gives Omni's occupants. So, the nation's automotive press also thinks so.

We think you're going to think Omni's tops, too. Because Omni can get so much done... lots more in fact...than it did for the car experts. We say that because it will take thousands of miles around the town and out in the country to put Omni to its truest test. With you at the wheel.

$4135:* (CAR AS SHOWN)
$3706:* (BASE STICKER PRICE)

Dodge
A PRODUCT OF CHRYSLER CORPORATION

Now, car testers don't worry too much about price. But you have to. So it's nice to know Omni prices start at just $3706:* Which includes such standard items as an AM radio, vinyl body-side moldings, and whitewall radial tires. With a little judicious selection of options and trim packages, you can own an Omni like the one in the picture for just $4135:*

For that kind of money, you get a lot of versatility. First of all, Omni is built for American-sized folks. There are four wide doors for easy entry. There is a great big 10.2-cubic-foot storage compartment when the rear seat is in place. Fold the seat down, and you get a cavernous 35.8-cubic-foot area that'll take on a surprising lot of cargo. Omni is roomier than you might expect.

You can make your Omni roomier yet. More versatile. Order it with an optional factory-installed multipurpose carryall roof rack. With appropriate attachments, it'll handle bikes, skis, baggage, or other cargo up to 150 pounds After all, the more you carry outside, the more you can carry inside.

EPA ESTIMATES:
38 MPG HIGHWAY/25 MPG CITY.

Omni is also very obliging on gas mileage. EPA estimates are 38 MPG (highway)/25 MPG (city). That's when your Omni is equipped with its standard 1.7 litre engine and four-speed transmission and 3.3 transaxle ratio. Your mileage may vary. Depends on how you drive, your car's condition, and its equipment. And California mileage is lower.

With so much waiting for you to see, and try, and feel, why not get down to your Dodge Dealer's soon. We think you'll end up buying or leasing the car so many experts say is tops in its class for 1978.

MOTOR TREND CAR OF THE YEAR

DODGE OMNI.
IT DOES IT ALL.

*Does not include taxes and destination charges.

Why is Diamond Shamrock one of the strongest chemical companies on earth?

Because it is so strong under the earth.

The roots of Diamond Shamrock's remarkable success go deeper than good people and creative chemistry.

Root fashion, they reach deep into the earth.

Into our huge salt domes. For the brine we electrify into chlorine and caustic soda. Which in turn yield literally thousands of useful products. Useful to us. Useful to you.

And into our oil and gas leases in the U.S. From Alaska to the Gulf of Mexico, Diamond Shamrock is at work expanding its domestic reservoirs of petroleum.

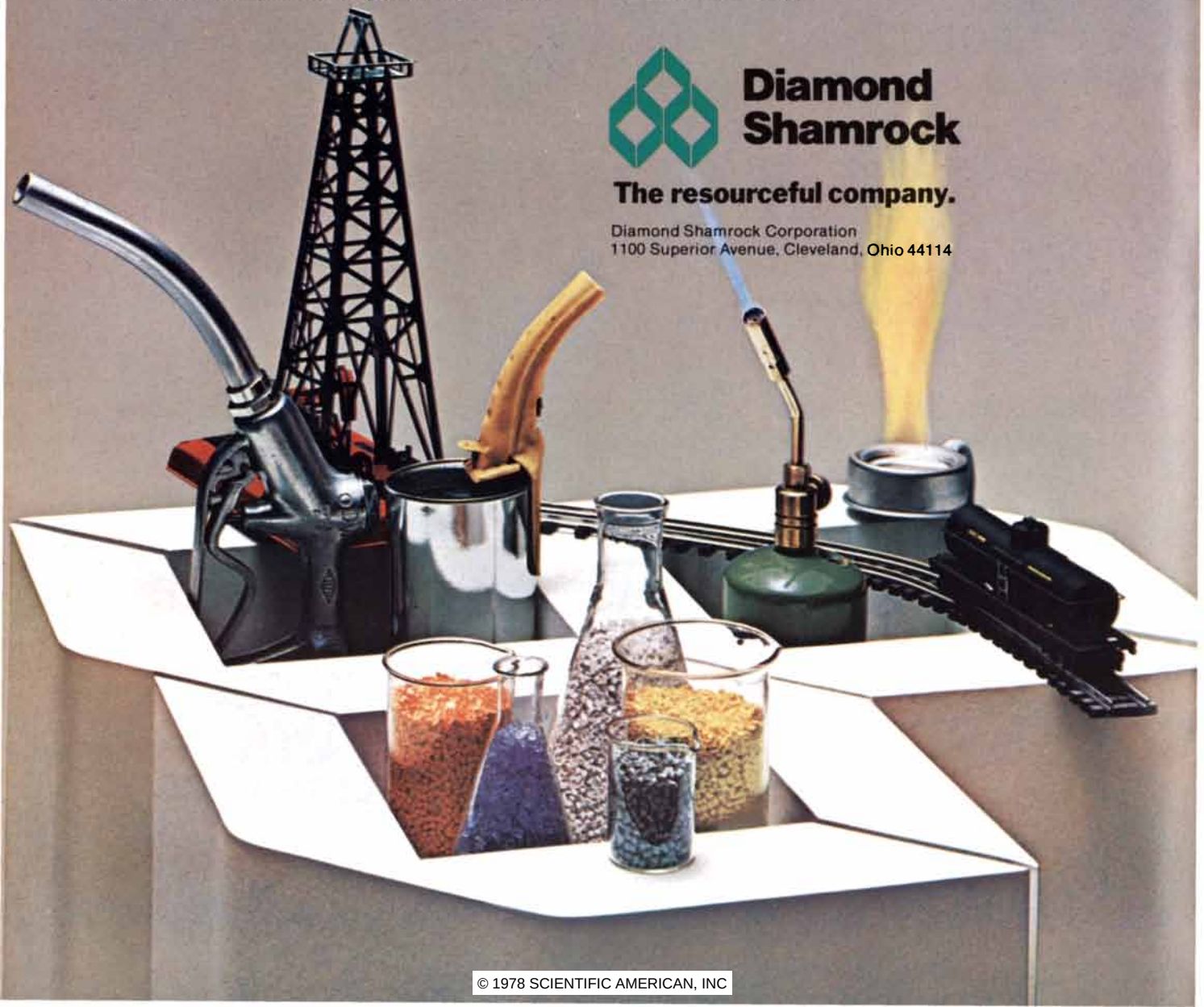
For Diamond Shamrock brand motor oil and gasoline.

For natural gas and propane.

And, importantly, for the petrochemicals out of which we pull products that range from fertilizer to fungicides, from asphalt to plastics.

Want a handle on Diamond Shamrock? Here it is. Day by day, this technologically innovative company's strong presence in domestic natural resources from under the earth — oil, gas, salt — is giving it a stronger role in the world's chemical future.

And in your own.



Diamond Shamrock

The resourceful company.

Diamond Shamrock Corporation
1100 Superior Avenue, Cleveland, Ohio 44114

State that the knowledge derived from Stanley's discoveries on the Congo is already bearing practical fruit. English missionaries have followed the course of the river as far as the first series of rapids and are about to establish a station at that point. It is reported that a modified form of the slave trade still exists between that region and the Portuguese islands of St. Thomas and Prince, through former agents of the slave trade between Gadoon and St. Paul of Loanda. A British gunboat recently captured a brig with more than 100 men, women and children on board, in a miserable condition, who had been captured, baptized and shipped near St. Paul as 'free laborers.' The spirit of the slave trade still exists, and if it is not carefully watched, it will revive and increase."

"Mr. W. B. Woodbury has proposed an ingenious idea for taking photographs of an enemy's works from a balloon, without necessitating the presence of an aeronaut in the car. Electrical wires are run along the cable by which the air ship is held captive. Instead of a car a box is provided, inside of which another box is pivoted so that it will keep horizontal. In the inner box is the photographic apparatus, and over the lens is an ebonite shutter moved by the current, to open or shut instantaneously. There is also a sensitized tissue on rollers in the rear of the lens, which is operated by clockwork, also controlled by the current. When the balloon is elevated to the required height, with the lens properly focused and the tissue in position, the shutter is set in motion by the current, giving instantaneous exposure. A photograph is thus obtained, and by further controlling the clockwork fresh sensitized surface may be exposed and additional images taken."

"M. Claude Bernard, who died in France in February at the age of 65, is justly entitled to the credit of having raised physiology to the dignity of a separate science. He it was who proved that the infinite variety of functional phenomena, with relation to the endless diversity of organic forms, is based on fundamental truths, which collect on common ground all living things, without distinction of classes or orders, whether vegetable or animal. The liver, he showed, makes sugar the same as does the fruit; beer yeast is subject, the same as man, to anaesthesia when submitted to etherized vapor. For the physiology of animal mechanism he showed that anatomical deductions are insufficient and often erroneous, and that only experiment can lead to certainty. He pointed out that the experimental physiologist not only analyzes and demonstrates but also dominates and directs, and that he may be a 'conqueror of nature' to the same degree as the chemist or the physicist."

ONE OF THESE CAMERAS WAS MADE JUST FOR YOU. HERE'S HOW TO TELL WHICH ONE.

If you've considered buying a 35mm single lens reflex camera, you may have wondered how to find the right one out of the bewildering array of models and features available.

And you have good reason to wonder, since the camera you choose will have a lot to do with how creative and rewarding your photography will be.

Of course, what you pay for your camera is important. But it shouldn't be your only consideration, especially since there are very expensive cameras that won't give you some of the features you really need. So before you think about price, ask yourself how you'll be using the camera and what kind of pictures you'll be taking. Your answers could save a lot of money.

How automatic should your camera be?

Basically, there are two kinds of automatic 35mm SLR's. Both make use of advanced electronics to give you perfectly exposed pictures with point, focus and shoot simplicity. The difference is in the kind of creative control you get.

For landscapes, still lifes, portraits and the like, you'll want an *aperture-priority* camera. It lets *you* set the lens opening, while *it* sets the shutter speed automatically.

This way, you control depth-of-field. That's the area of sharpness in front of and behind your subject. Many professional photographers believe that depth-of-field is the single most important factor in creative photography.

At times you may want to control the motion of your subject for creative effect. You can do this with an aperture-priority camera by changing the lens opening until the camera sets the shutter speed necessary to freeze or blur a moving subject. Or you can use a *shutter-priority* camera, on which you set the shutter speed first and the camera sets the lens opening automatically.

Minolta makes both types of automatic camera. The Minolta XG-7 is moderately priced and offers aperture-priority automation, plus fully manual control. The Minolta XD-11 is somewhat more expensive, but it's the world's only 35mm SLR with both aperture and shutter-priority automation, plus full manual. The XD-11 is so advanced that during shutter-priority operation it will actually make exposure corrections that you fail to make.

Minolta makes all kinds of 35mm SLR's, so our main concern is that you get exactly the right camera for your needs. Whether that means the Minolta XD-11, the most advanced camera in the world. Or the easy-to-use and moderately priced Minolta XG-7. Or the very economical Minolta SR-T cameras.

Do you really need an automatic camera?

Without a doubt, automation makes fine photography easier. But if you're willing to do some of the work yourself, you can save a lot of money and get pictures that are every bit as good.

In this case, you might consider a Minolta SR-T. These are semi-automatic cameras. They have built-in, through-the-lens metering systems that tell you exactly how to set the lens and shutter for perfect exposure. You just align two indicators in the viewfinder.

What should you expect when you look into the camera's viewfinder?

The finder should, of course, give you a clear, bright view of

Automatic sequence photography is easy when you combine a Minolta XD-11 or XG-7 with optional Auto Winder and Electroflash 200X.

Specifications subject to change without notice.

your subject. Not just in the center, but even along the edges and in the corners. All Minolta SLR's have extraordinarily bright finders, so that composing and focusing are effortless, even in dim light. And with a Minolta there's never a question about focusing. You'll find focusing aids in every Minolta viewfinder that make it easy to take critically sharp pictures.

Information is another thing you can expect to find in a well-designed viewfinder. Minolta believes that you should never have to look away from the finder in order to make camera adjustments. So everything you need to know for a perfect picture is right there in a Minolta finder.

The match-needle viewfinder: just align two indicators for correct exposure. Because you're doing some of the work, you can save some money.

The electronic viewfinder: light emitting diodes tell you what the camera is doing automatically to give you correct exposure.

In the Minolta XD-11 and XG-7, red light-emitting diodes tell you what lens opening or shutter speed is being set automatically and warn against under or over-exposure. In Minolta SR-T cameras, there are two pointers which come together as you adjust the lens and shutter for correct exposure.

Do you need an auto winder?

If you like the idea of sequence photography, or simply want the luxury of power assisted film advancing, an auto winder may be for you. Minolta auto winders will advance one picture at a time, or continuously at about two pictures per second. And they give you advantages not found in others, like up to 50% more pictures with a set of batteries and easy attachment to the camera without removing any caps. Optional auto winders are available for both the Minolta XD-11 and XG-7, but not for Minolta SR-T cameras.

How about electronic flash?

An automatic electronic flash can be combined with any Minolta SLR for easy, just about foolproof indoor photography without the bother of flashbulbs. For the XD-11 and XG-7, Minolta makes the Auto Electroflash 200X. It sets itself automatically for correct flash exposure, and it sets the camera automatically for use with flash. An LED in the viewfinder tells when the 200X is ready to fire. Most unusual: the Auto Electroflash 200X can fire continuously in perfect synchronization with Minolta auto winders. Imagine being able to take a sequence of 36 flash pictures without ever taking your finger off the button.

You should be comfortable with your camera.

The way a camera feels in your hands and responds to your commands can make a big difference in the way you take pictures.

The Minolta XD-11 and XG-7, for instance, are compact, but not cramped. Lightweight, but with a solid feeling of quality. Controls are oversized and positioned so that your fingers fall naturally into place. And the electronically controlled shutters in these advanced automatic cameras are incredibly smooth and quiet.

Minolta SR-T's give you the heft and weight of a slightly larger camera, but with no sacrifice in handling convenience. As in all Minolta SLR's, "human engineering" insures smooth, effortless operation.

Are extra features important?

If you're going to use them, there are a lot of extras that can make your photography more creative and convenient. Depending on the Minolta model you choose, you can select from a number of special features. For instance, some models let you take multiple exposures with pushbutton ease (even with an auto winder). Other available extras include a window to show that film is advancing properly, a handy memo holder that holds the end of a film box to remind you of what film you're using, and a self-timer that delays the release of the shutter so you can get into your own pictures.

What about the lens system?

Just about every 35mm SLR has a lens "system." But it's important to know what the system contains. It should be big enough to satisfy your needs, not only today, but five years from today.

There are almost 40 interchangeable lenses available for Minolta SLR's, ranging from 7.5mm fisheye to 1600mm super-telephoto, including macro and zoom lenses and the smallest 500mm lens in the world. And since interchangeable lenses should be easy to change, the patented Minolta bayonet mount lets you remove or attach them with less than a quarter turn.

What's next?

After you've thought about how you'll be using your camera, ask your photo dealer to let you try a Minolta. Handle the camera for yourself. Examine its features and the way Minolta has paid close attention to even the smallest details. And by all means, compare it with other cameras in its price range. You'll soon see why more Americans buy Minolta than any other brand of SLR. For literature, write Minolta Corporation, 101 Williams Dr., Ramsey, N.J. 07446.

In Canada: Minolta Camera (Canada) Inc., Ontario.

Interchangeable lenses expand your creative opportunities. There are wide angle, macro, zoom and telephoto lenses in the Minolta system. Plus more than a hundred other photographic accessories.

MINOLTA

WE WANT YOU TO HAVE THE RIGHT CAMERA.

THE AUTHORS

FRED M. KAPLAN ("Enhanced-Radiation Weapons") is a fellow of the Arms Control Project at the Center for International Studies of the Massachusetts Institute of Technology. He studied at Oberlin College, where he received his bachelor's degree with high honors in 1976. During the summers of 1975 through 1977 he did research on defense issues at the Carnegie Endowment for International Peace, the Military Audit Project and the Institute for Policy Studies. Kaplan has published articles and reviews on U.S. and Russian defense policy in several periodicals and is the author of a monograph titled *Dubious Specter: A Second Look at the Soviet Threat* (Transnational Institute, 1977).

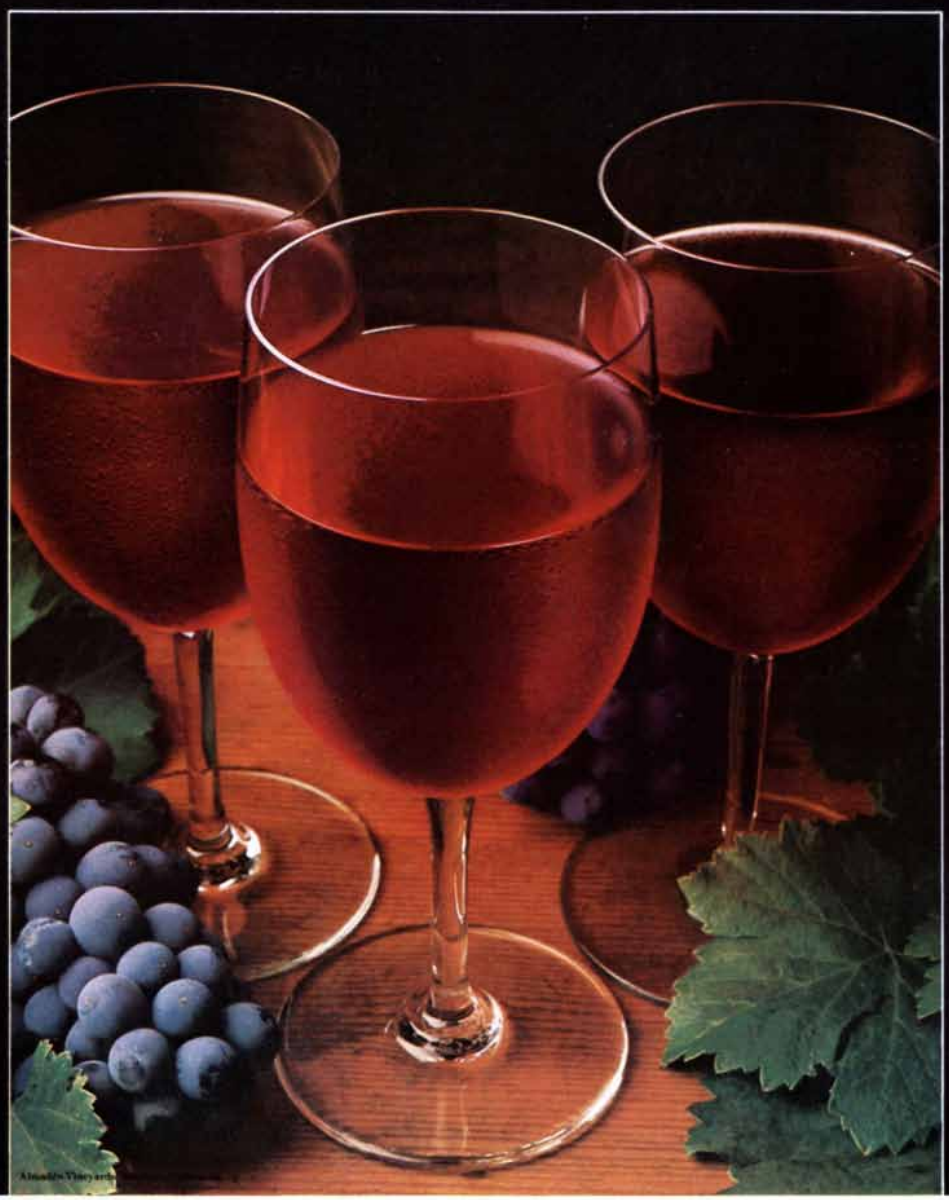
KENNETH J. HSÜ ("When the Black Sea Was Drained") is chairman of the Geological Institute at the Swiss Federal Institute of Technology in Zurich. A native of Nanking, he did his undergraduate work at the Chinese National Central University. In 1948 he came to the U.S. to continue his studies in geology at Ohio State University and at the University of California at Los Angeles, where he obtained his Ph.D. in 1954. He became a U.S. citizen in 1963. After working for the Shell Development Company and teaching at the State University of New York at Binghamton and at the University of California at Riverside he moved to the Swiss Federal Institute of Technology in 1967. Since then he has been involved primarily in the study of marine sediments. Hsü has been co–chief scientist on two cruises to the Mediterranean with the Deep Sea Drilling Project, and in 1975 he was the sedimentologist aboard the *Glomar Challenger* on an expedition to the Black Sea to obtain a continuous record of climatic history during the last ice age.

RICHARD A. MULLER ("The Cosmic Background Radiation and the New Aether Drift") is associate research physicist at the Space Sciences Laboratory of the University of California at Berkeley and at the Lawrence Berkeley Laboratory of the University of California. He was educated at Columbia University and at Berkeley, where he earned his Ph.D. in elementary-particle physics in 1969. Since then his diverse research interests have included (in addition to the measurements of the cosmic background radiation described in his article) the development of a telescope mirror that compensates automatically for atmospheric distortion, the search for quarks with unit charge and the development of a new technique for radioactive-isotope dating. Recently Muller, his wife and his sister opened a gourmet restaurant in Berkeley. "Whenever I get totally frustrated with experimental physics," he writes, "I switch gears and work on the wine list for the restaurant."

GILBERT B. DEVEY and PETER N. T. WELLS ("Ultrasound in Medical Diagnosis") share an interest in the development of medical instrumentation. Devey is head of the Middle East Section of the National Science Foundation and is responsible for managing the foundation's activities in the countries of the Arabian Peninsula. He obtained his bachelor's degree in engineering from the Massachusetts Institute of Technology in 1946 and then worked for six years as an electronics engineer at the U.S. Navy Underwater Sound Laboratory, the Bureau of Ships and the Office of Naval Research. In 1953 he moved to the Sprague Electric Company, where he spent the next 12 years developing new areas of application for advanced-technology electronic components. He joined the National Science Foundation in 1965 and served as program director in the Division of Engineering and in the Research Applied to National Needs (RANN) program. In 1973 Devey organized and managed a National Science Foundation research program in ultrasonic diagnostics. Wells is chief physicist at the Avon Area Health Authority in Bristol in England. He studied physics at the University of Aston and at the University of Bristol and did an apprenticeship with the General Electric Company. He then worked for 12 years as a research assistant on several ultrasonic projects financed by the Medical Research Council. In 1972 he was appointed to the chair of medical physics at the Welsh National School of Medicine; he moved to his present position in 1975.

R. HAVEN WILEY, JR. ("The Lek Mating System of the Sage Grouse"), is associate professor of zoology at the University of North Carolina at Chapel Hill. He studied at Harvard College and obtained his Ph.D. in animal behavior from Rockefeller University in 1970. After a postdoctoral year at Rockefeller he joined the faculty at Chapel Hill, where he currently directs the Behavioral Research Station of the North Carolina Botanical Garden. Wiley's research interests, in addition to the lek mating system of the sage grouse, are the ecological adaptations of the social structure of blackbirds and wrens, the acoustical communication systems of birds and the behavioral control of spatial relations in animal societies.

WALTER C. GOGEL ("The Adjacency Principle in Visual Perception") is professor of psychology at the Universi-



If a rosé is just a rosé, why does Almadén make three?

All rosé drinkers are not alike. Some like rosé with a hint of sweetness. Some like it dry. And others like it in between. So to satisfy all three, Almadén makes a rosé for each.

If you're one who prefers rosé with a hint of sweetness, may we suggest Almadén Mountain Nectar Vin Rosé on the left. Fresh, light and exciting. With a rich satisfying taste—like that of fresh, ripe fruit.

If you prefer a drier rosé, you'll enjoy Almadén Grenache Rosé in the middle. A fresh, fragrant wine made from the Grenache grape. The same classic grape used in the famed Tavel rosés of France. It makes our rosé bright—with an abundance of flavor and character.

And if you like a rosé that's in-between—try our new Almadén Gamay Rosé. Made from the Gamay grape—similar to the grape used in the Beaujolais wines of France—it's a distinctively different rosé. Fresh and complex—more full-bodied than our other rosés. Unlike any you've ever enjoyed.

Whichever you prefer, serve it well chilled—with your favorite food or by itself. Either way, you'll enjoy the taste of a truly fine wine. Because at Almadén, we care for our grapes as if they were our children. And you'll taste this tradition of quality in every bottle of Almadén wine.

To learn more about wine, send a postcard for a free copy of "The grapes and wines of Almadén" to: Almadén, P. O. Box 24249 SC, San Jose, CA 95154.

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Pinto. The most cargo room for the money of any small wagon.*

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*Based on comparison of EPA Cargo Volume index and sticker prices.

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HARRIS

COMMUNICATIONS AND INFORMATION HANDLING

ty of California at Santa Barbara. He did his undergraduate work in physics at Marietta College and then went on to graduate work in experimental psychology at the University of Chicago under Eckhard H. Hess. After receiving his Ph.D. in 1951 he spent the next 14 years doing research on spatial perception at the U.S. Army Medical Research Laboratory at Fort Knox and at the Civil Aeromedical Research Institute in Oklahoma City. He joined the Santa Barbara faculty in 1965. Gogel writes: "My research interests, while continuing to center on classical problems in space perception, have expanded in recent years to include the relation between cognitive and perceptual processes in responses to spatial stimuli, and the role of attention in visual perception."

L. ANDREW STAEHELIN and BARBARA E. HULL ("Junctions between Living Cells") are cell biologists interested in the structure and function of biological membranes. Staehelin is associate professor at the University of Colorado at Boulder. Born in Australia, he went to secondary school in Switzerland and obtained his Ph.D. from the Swiss Federal Institute of Technology in 1966. For the next three years he worked in the Department of Scientific and Industrial Research of New Zealand on the structure of the plant cell wall, coming to the U.S. in 1969 as a postdoctoral fellow in the laboratory of Keith R. Porter at Harvard University. The following year he moved with Porter to the newly established department of molecular, cellular and developmental biology at the University of Colorado. Staehelin's research has since focused on the junctions that coordinate the activities of cells in tissues and on the structure of photosynthetic membranes. He is currently on sabbatical leave at the University of Freiburg in West Germany. Hull is research associate in the section of cell biology at the Yale University School of Medicine. She went to Smith College and the University of Colorado, where she did research in Staehelin's laboratory, obtaining her Ph.D. in 1976.

NORMAN SMITH ("Roman Hydraulic Technology") lectures on the history of technology at the Imperial College of Science and Technology in London. Born in Southampton, he attended the University of Bristol, where he received his Ph.D. in civil engineering in 1962. He then taught engineering at the University of Canterbury in New Zealand; he moved to Imperial College in 1965. His recent research has focused on the history of dam building and the evolution of hydraulic technology, a subject about which he has written three books. When he is not writing or teaching, he combines historical fieldwork with travel and photography.

MATHEMATICAL GAMES

The Bells: versatile numbers that can count partitions of a set, primes and even rhymes

by Martin Gardner

Keeping time, time, time,
In a sort of Runic rhyme,
To the tintinnabulation that so
musically wells
From the bells, bells, bells, bells,
Bells, bells, bells—
From the jingling and the tinkling
of the bells.
EDGAR ALLAN POE, "The Bells"

Imagine that five plates labeled *a, b, c, d* and *e* are in a row on a table. Also on the table are five chessmen: a king, a queen, a bishop, a knight and a rook. In how many ways can the chessmen be arranged on the plates so that one chessman is on each plate? The answer is 5! The exclamation mark is the factorial sign, indicating that the answer is $1 \times 2 \times 3 \times 4 \times 5$, or 120. The problem is combinatorially equivalent to counting the number of ways the letters *a, b, c, d* and *e* can be permuted. In general, for n objects the number of ways is $n!$

Now alter the rules a bit to allow any number of objects, from zero to five, to be on any plate. In how many different ways can the chessmen be placed on the plates? It is obvious that one piece goes on one plate in only one way. Two pieces can go on two plates in four ways, as is shown at the left in the illustration on the opposite page. If you experiment with three plates and three objects, you will find there are 27 ways. Because 1, 4 and 27 are equal to 1^1, 2^2 and 3^3, one might guess that n objects go on n plates in n^n ways. That is indeed correct. The five chessmen can go on five plates in 5^5, or 3,125, ways.

If there are n objects and k plates, then there are k^n ways to place the objects on the plates according to the altered rules. For example, two objects go on three plates in 3^2, or nine, ways, as is shown at the right in the illustration on the opposite page. It is easy to see why the formula works. The first object can be placed on the k plates in k different ways. The second object can also go on any of the k plates, so that it too can be placed in k ways. Since there are n objects, it is clear that they can be placed on k plates in $k \times k \times k \times \ldots \times k = k^n$ ways.

Consider a more difficult problem. There are the same five chessmen and the same five plates, but now the plates are unlabeled. In other words, the plates are considered to be identical, and so their positions on the table are unimportant. For example, if the king and queen are on one plate and the other three chessmen are on another, it does not matter which plates hold the two groups. All partitions of the set that place the king and queen on one plate and the bishop, knight and rook on another, regardless of which two plates are used, will be considered identical and counted as a single way of placing the chessmen. How can all the ways of placing the five objects be counted?

Once again one object obviously goes on one plate in just one way. Two objects go on two plates in two ways: either both on one plate or one on each plate. This case models many real situations. For example, there are two essentially different ways a husband and wife can occupy unlabeled twin beds: they sleep either in separate beds or in the same bed. There are two ways a policeman can handcuff two prisoners: either each prisoner can be handcuffed separately or the two can be handcuffed to each other. The top illustration on page 26 shows the five ways three objects can be placed on three unlabeled plates. This case models the five ways three people can occupy three unlabeled beds, the five ways three nations can form alliances and so on.

As an experiment you might pause at this point and actually count the ways four objects can be placed on four unlabeled plates. In more technical terms, the problem is to determine the number of ways a set of four distinct elements can be partitioned into nonempty subsets. You will find there are exactly 15 ways. For five objects the number of ways to partition the set jumps to 52. As the number of objects n increases, a sequence of numbers is being generated: 1, 2, 5, 15, 52.... The numbers in this sequence, which are extremely useful in combinatorial theory, are called Bell numbers in honor of the Scottish-born American mathematician Eric Temple Bell, who died in 1960. They are closely related to the Catalan numbers, which were the topic of this department in June, 1976.

Although Bell numbers were recognized long before Bell wrote about them, he was the first to analyze them in depth and show their importance. In his first paper on the numbers Bell explained how his interest had been awakened. He had noticed an error in a handbook that gave what is called the Maclaurin expansion for the expression e^{e^x}, where e is the transcendental Euler number and x is any positive integer. The correct expansion is:

$$e\left(1+\frac{x}{1!}+\frac{2x^2}{2!}+\frac{5x^3}{3!}+\frac{15x^4}{4!}\cdots\right)$$

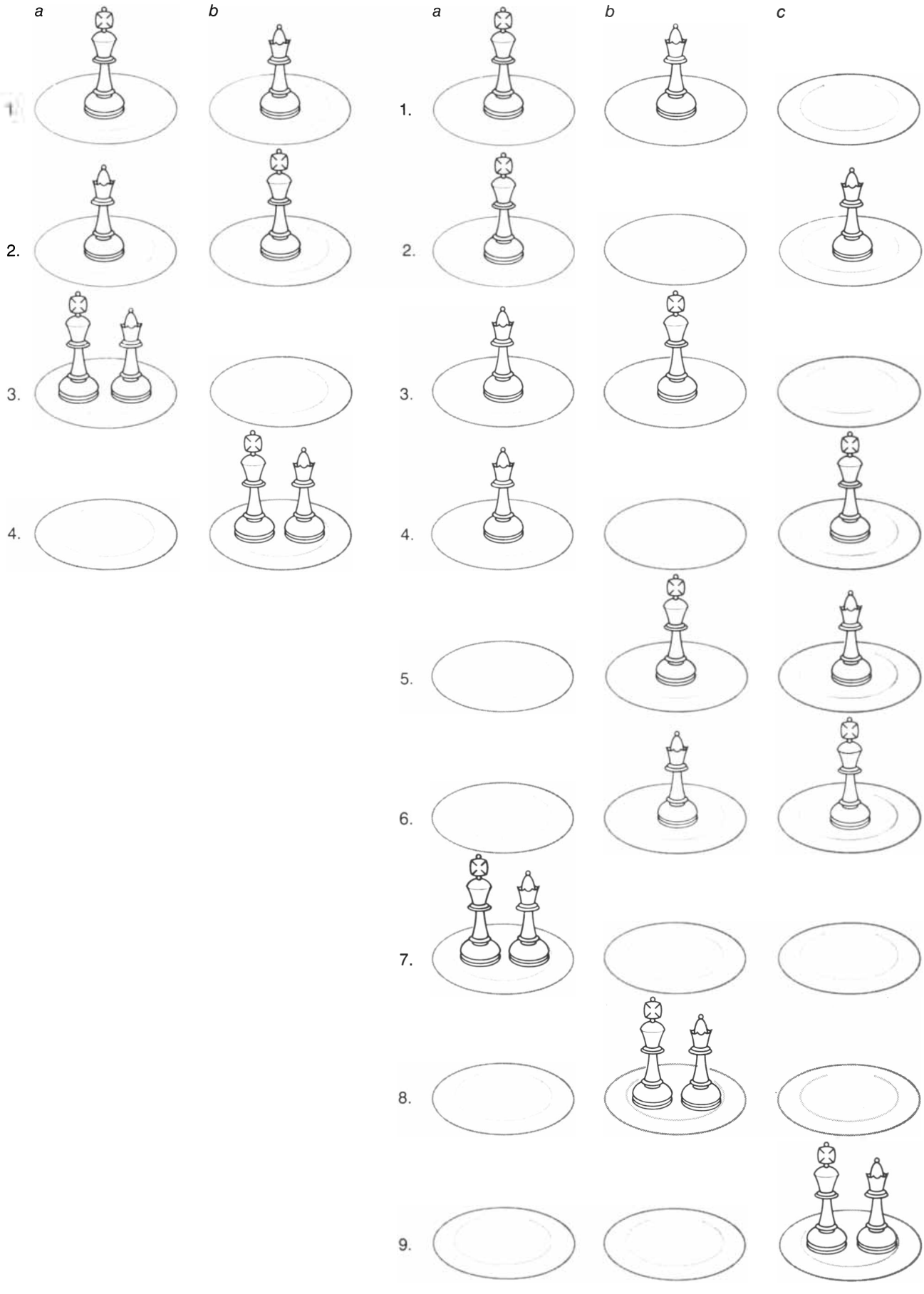
Note that the coefficients for the powers of x are precisely the Bell numbers. (Bell called the numbers exponential numbers, but after the combinatorialist John Riordan began denoting them B, to honor Bell, they quickly became known as Bell numbers.) From the Maclaurin expansion it is possible to derive what is called Dobinski's formula for the nth Bell number, B_n:

$$B_n = \frac{1}{e}\sum_{k=0}^{\infty}\frac{k^n}{k!}$$

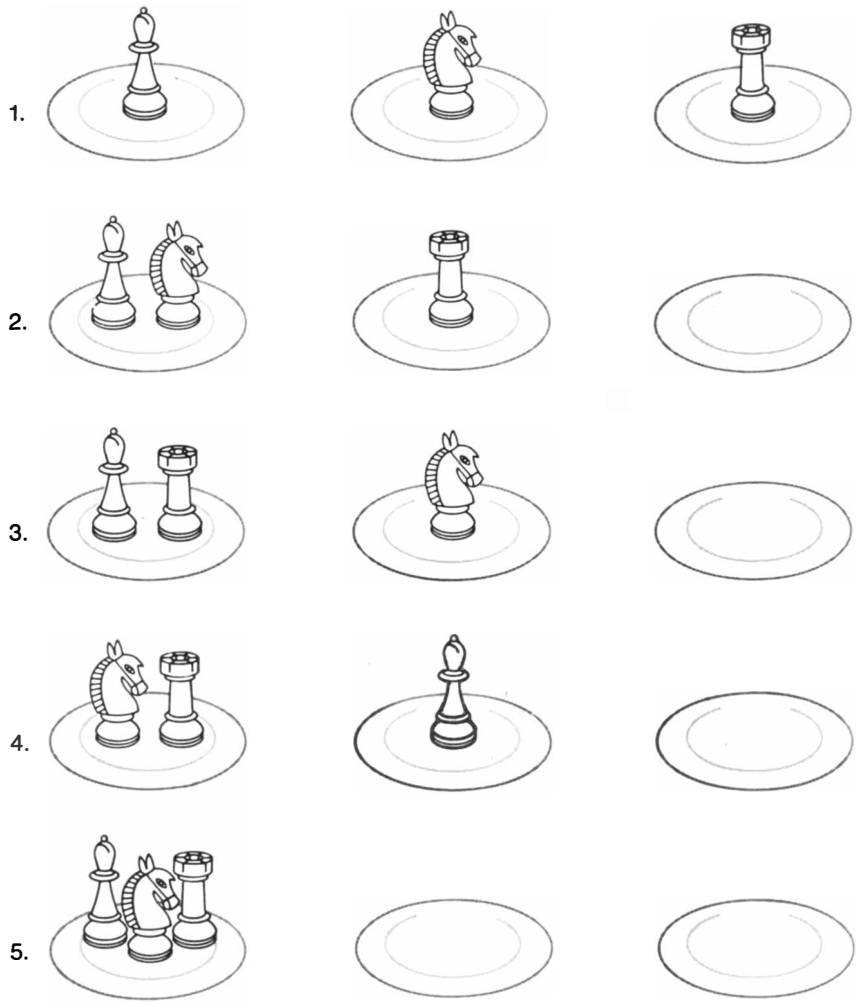
Bell was primarily a number theorist, but he is best known for his classic history *The Development of Mathematics,* his more popularly written *Men of Mathematics* and other books for the general public. Younger mathematicians may be surprised to learn that in the 1920's and 1930's Bell was a prolific writer of science fiction under the pseudonym John Taine. Five of his novels are reprinted in two Dover paperbacks: *Seeds of Life and White Lily* and *The Time Stream.* In 1951 Bell's book *Mathematics, Queen and Servant of Science* was reviewed in a Pasadena Sunday newspaper by John Taine. "The last flap of the jacket," wrote Taine, "says Bell 'is perhaps mathematics' greatest interpreter.' Knowing the author well, the reviewer agrees."

Back to the Bell numbers, which might be called Bells or even Temple Bells. The first 13 Bells are shown at the left in the bottom illustration on page 26. By convention B_0 equals 1. As you can see, the numbers grow larger at an exponential rate, or, as Poe has it in "The Bells," they rise "higher, higher, higher, with a desperate desire." The 100th Bell is a number of 126 digits.

Formulas for the nth Bell are complicated and difficult to use in calculating the series, but fortunately there is a simple recursive procedure that cranks them out rapidly. It is best understood by considering the formation of the triangle of numbers shown at the top right



Ways of placing two objects on two labeled plates **(left)** ***and on three labeled plates*** **(right)**



Third Bell number ($B_3 = 5$) *counts the ways of placing three objects on three unlabeled plates*

B_0	1
B_1	1
B_2	2
B_3	5
B_4	15
B_5	52
B_6	203
B_7	877
B_8	4,140
B_9	21,147
B_{10}	115,975
B_{11}	678,570
B_{12}	4,213,597

1							
1	2						
2	3	5					
5	7	10	15				
15	20	27	37	52			
52	67	87	114	151	203		
203	255	322	409	523	674	877	
877	. . .						
⋮							

1	2	5	15	52	203	877	. . .
1	3	10	37	151	674	. . .	
2	7	27	114	523	. . .		
5	20	87	409	. . .			
15	67	322	. . .				
52	255	. . .					
203	. . .						
⋱							

Bells (**left**) *and two forms of the Bell triangle* (**right**)

in the bottom illustration at the left. (Following a suggestion of correspondent Jeffrey Shallit, I shall call this the Bell triangle.) Start with 1 at the top and 1 below it. Since 1 plus 1 equals 2, place 2 at the end of the second row. Bring the 2 back to start the third row. The sum of 2 and the number above it is 3, and so put 3 to the right of 2. The sum of 3 and the number above it is 5, and so 5 goes to the right of 3. Continue in this manner, observing the following two rules: The last number of each row is the first number of the next row, and all other numbers are obtained by adding the desired number's left neighbor to the number above the neighbor. The sequence of Bell numbers appears on two sides of the triangle. When the triangle is rotated slightly, it becomes a difference triangle, as is shown at the bottom right in the bottom illustration at the left; each number below the top row is the difference of the two numbers above it.

Like the more familiar Pascal triangle, the Bell triangle is rich with interesting properties. In the Bell triangle shown at the top right in the illustration the sums of the horizontal rows are the numbers on the second infinite diagonal. If the sum of a row is added to the Bell number at the end of that row, the number obtained is the next Bell number. If each number is replaced by *O* for odd or *E* for even, it is easy to see that every third Bell is even. Hence the ratio of the number of odd Bells to the number of even Bells is 2 : 1, and the sum of any adjacent triplet of Bells must be even.

Dozens of curious properties of the Bell sequence have been noted, and others are still being discovered. For example, "Touchard's congruence" states: $B_{p+k} \equiv B_k + B_{k+1}$ (modulo p), where p is a prime number. In other words, if the n of B_n is expressed as the sum of a prime p and a number k, and B_n is divided by p, the remainder will equal the remainder obtained when the sum of B_k and B_{k+1} is divided by p. Let k equal zero, and the congruence becomes $B_p \equiv 2$ (modulo p). In other words, every B_n for which n is a prime number has a remainder of 2 when it is divided by that prime. For example, B_{13} is equal to 27,644,437; divide this number by 13 and the remainder is 2.

Bells play an important role in prime-number theory because they count the ways any number with distinct prime factors can be factored. For example, 30 has three different prime factors: 2, 3 and 5. B_3 equals 5. The five ways of factoring 30 are $2 \times 3 \times 5$, 5×6, 3×10, 2×15 and 30. It is not hard to see how this problem is isomorphic with the task of putting three distinct objects on three unlabeled plates. Note that three of the first 10 Bells are prime: 2, 5 and 877. Are there other prime Bells? Is there a largest prime Bell? I do not know the answer to either question.

One of the surprising applications of

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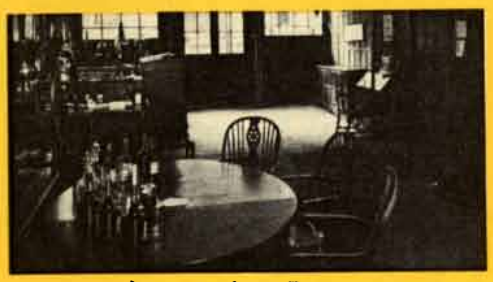

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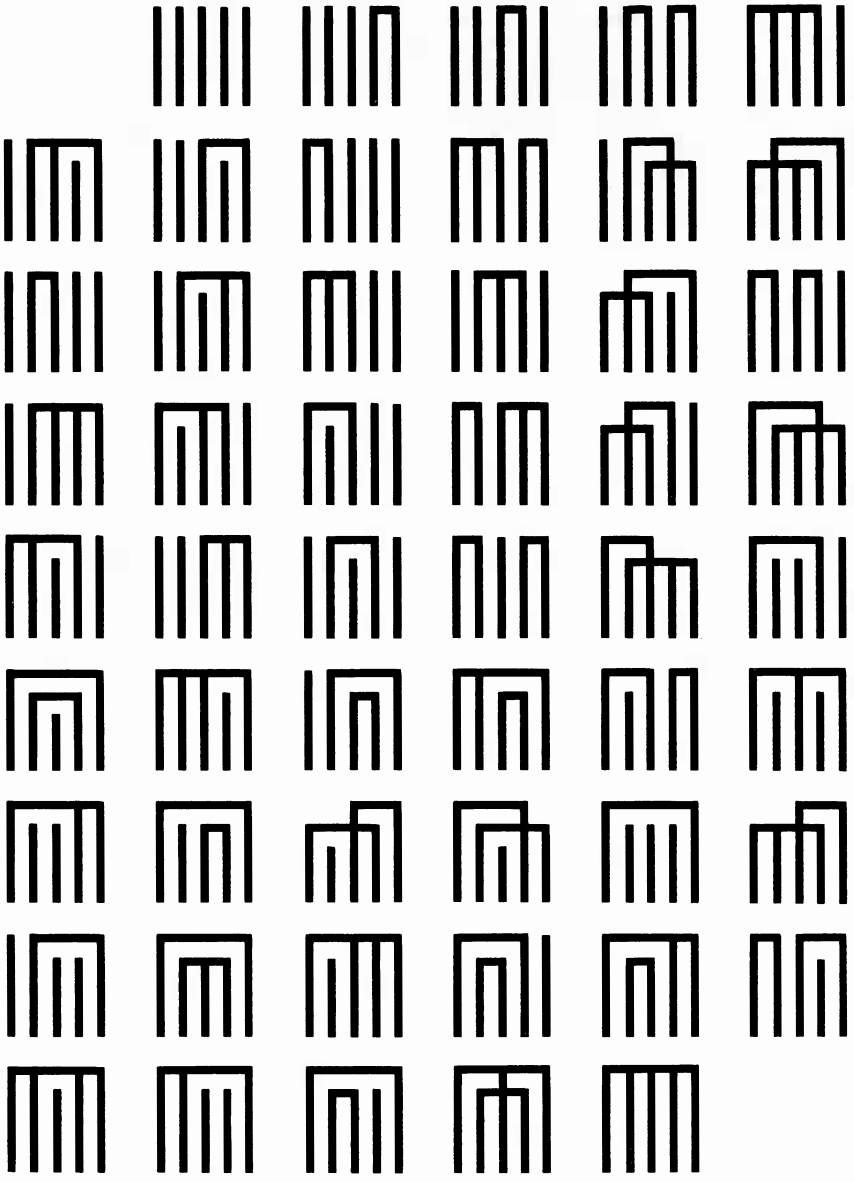
the Bells is that they count the number of possible rhyme schemes for a stanza of poetry. A one-line stanza has one rhyme scheme, a two-line stanza has two rhyme schemes (the lines either rhyme or do not), a three-line stanza has five (*aaa, aab, aba, abb* and *abc*) and so on. It is said that this "rhyming and the chiming of the bells" (Poe) was first observed by the British mathematician J. J. Sylvester, but I have not been able to find a reference to it in his little book *The Laws of Verse.* I shall be grateful to any reader who can give me the reference.

H. W. Becker, writing about the Bells in 1941, introduced what he called an "interesting theorem." Call a stanza completely rhymed if every line rhymes with at least one other and incompletely rhymed if at least one line rhymes with no other. The number of possible completely rhymed stanzas for n lines always turns out to equal the number of possible incompletely rhymed stanzas for $n - 1$ lines.

Henry W. Gould, a number theorist at West Virginia University, discovered that the Japanese had an attractive way of diagramming rhyme schemes at least as early as A.D. 1000. The illustration below shows the 52 diagrams for stanzas of five lines. Vertical lines stand for lines of the stanza, and horizontal lines join the lines that rhyme. Gould first described the diagrams in 1976 in his *Research Bibliography of Two Special Number Sequences,* a valuable listing of 175 references on Bell numbers and 445 references on Catalan numbers. Interested readers can obtain a copy postpaid by sending $3 to Gould at 1239 College Avenue, Morgantown, W.Va. 26505.

The earliest-known appearance of this method of diagramming is found in *The Tale of Genji,* a famous Japanese novel written by Lady Murasaki, who lived from about A.D. 978 to about 1031. Every chapter except the first and the last in the 54-chapter book is headed by one of the 52 diagrams for stanzas of five lines. The vertical lines are incense sticks, each of which can be any one of five different colors. Horizontal lines join sticks of the same color. The colored diagrams appear in early editions of this Japanese classic but not in English translations. As Joanne Growney observed in her 1970 doctoral dissertation, if all the diagrams with lines that intersect are omitted, the number of remaining diagrams is the fifth Catalan number, 42, and this is true in general for Murasaki diagrams of n lines. Just why Lady Murasaki chose this order for her diagrams, Gould writes, is as unknown as the basis, if indeed there is any, for the ordering of the 64 hexagrams in the *I Ching.*



***Lady Murasaki's 52 diagrams from* The Tale of Genji**

Quintets are not common in English poetry, but perhaps with diligent searching one could find notable examples of all 52 patterns. For example, Shelley's "To a Skylark" is written in quintets that correspond to the fifth diagram of row five. The fourth diagram of the second row applies to Emily Dickinson's well-known

> To make a prairie it takes a clover
> and one bee,
> One clover, and a bee,
> And revery.
> The revery alone will do,
> If bees are few.

Here is a lovely stanza from Alice Meynell's "A Dead Harvest" that corresponds to the pattern of the fourth diagram of row four:

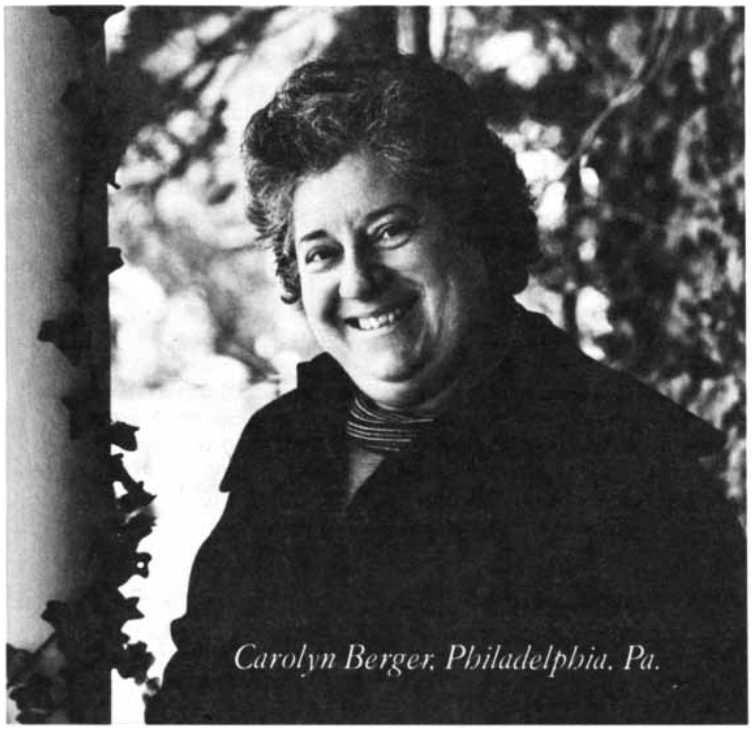
> Along the graceless grass of town
> They rake the rows of red and brown,
> Dead leaves, unlike the rows of hay
> Delicate, touched with gold and gray,
> Raked long ago and far away.

The limerick is a quintet with a rhyme scheme indicated by the fourth diagram of row six. An unconventional limerick, attributed to W. S. Gilbert, has the scheme of the first diagram:

> There was an old man of Dundee,
> Who was stung on the arm by a wasp.
> When asked "Does it hurt?"
> He replied "No it doesn't.
> I'm so glad that it wasn't a hornet."

There are several applications of the Bells to graph theory. Consider the following problem. Place six dots in a circle as if to mark the corners of an invisible hexagon and label the dots *a* through *f.* Regard an isolated dot as a degenerate convex polygon of one corner and two dots joined by a straight line as a degenerate convex polygon of two corners.

"I thought seeing Italy would teach me more about my father. Instead it taught me more about myself."



"My maiden name is Aquino. A very common name in the town of Monte Fredane, where my father was born. He left there almost 100 years ago, in the steerage section of a boat, to start a new life in America.

"Recently, I went to Italy to visit his hometown. My father's house is still standing. (It's home now to another family.) I visited the church where my father was baptized and was able to see the record of his birth in the Town Hall. You see, the Monte Fredane I saw is very much the same as the one my father left so many years ago.

"Even with a background of hardship and coming to a strange new land, my father and mother managed to raise 12 children. Sometimes with an iron hand. But always with love.

"There were many times that my father and I didn't agree. And many times that I didn't understand his ways. But now I do.

"What formed his personality was the land he left. And through him, the memory of that same land formed mine."

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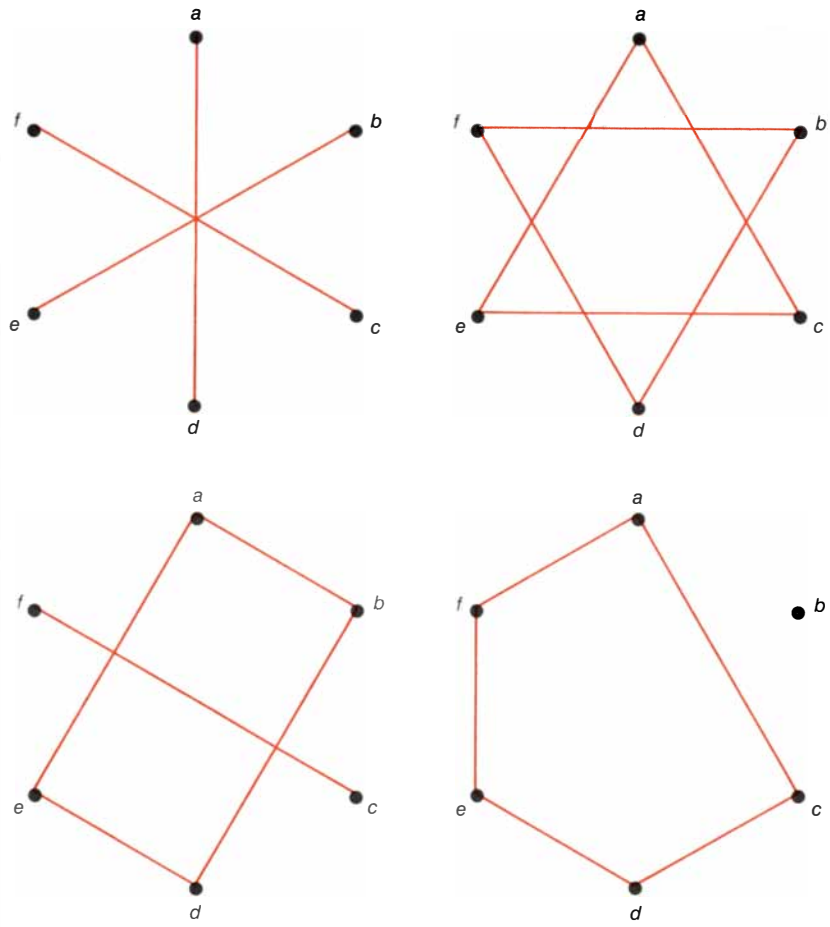
With a pencil connect the dots in any way to form disjoint convex polygons of one, two, three, four, five or six corners. (Disjoint means that no two polygons may have a dot in common.) The lines of the same polygon may not cross one another, because if they did, the polygon would not be convex; lines of distinct polygons may, however, intersect. If you like, you may draw nothing, so that the pattern will consist of six one-corner polygons. Or you may connect all six dots to make a single hexagon. Or you may produce any mixture of polygons provided they are convex and disjoint.

The illustration below shows four possible patterns. How many different patterns are there? If you have followed the discussion of the Bells, the question should present no difficulty. I shall answer it next month in a general way that applies to n dots connected by disjoint convex polygons of one corner through n corners.

In my February column I incorrectly described the bottom illustration on page 24 as a projection of a four-dimensional simplex. Several readers wrote to point out that the figure shown is not a simplex but a section of a complex polyhedron called a Hessian polyhedron. A description of Hessian polyhedrons can be found in H. S. M. Coxeter's marvelous book *Regular Complex Polytopes* (Cambridge University Press, 1974, pages 119–124).

William Funkenbusch wrote to say that Sicherman dice could be used at the craps table of a casino only for the game itself, not for the allowed side bets such as the ones that involve making certain sums the "hard way." Two hard-way bets, 4 and 10, obviously cannot be made with Sicherman dice at all.

Many readers misinterpreted the problem of the 27 dice. When I spoke of 54 pairs of "facing" numbers, I meant not the 54 single numbers on the faces of the 3-by-3-by-3 cube but the 108 interior face-to-face numbers on the 54 pairs of adjacent dice. The numbers on each pair are multiplied and the 54 products are added. The problem is to find arrangements of 27 dice that minimize and maximize this sum. It is a difficult problem to solve without a computer. I do not yet have either answer, but I do know the minimum is less than 300 and the maximum is greater than 1,000. I shall report on the best answers I receive.



A Bell problem

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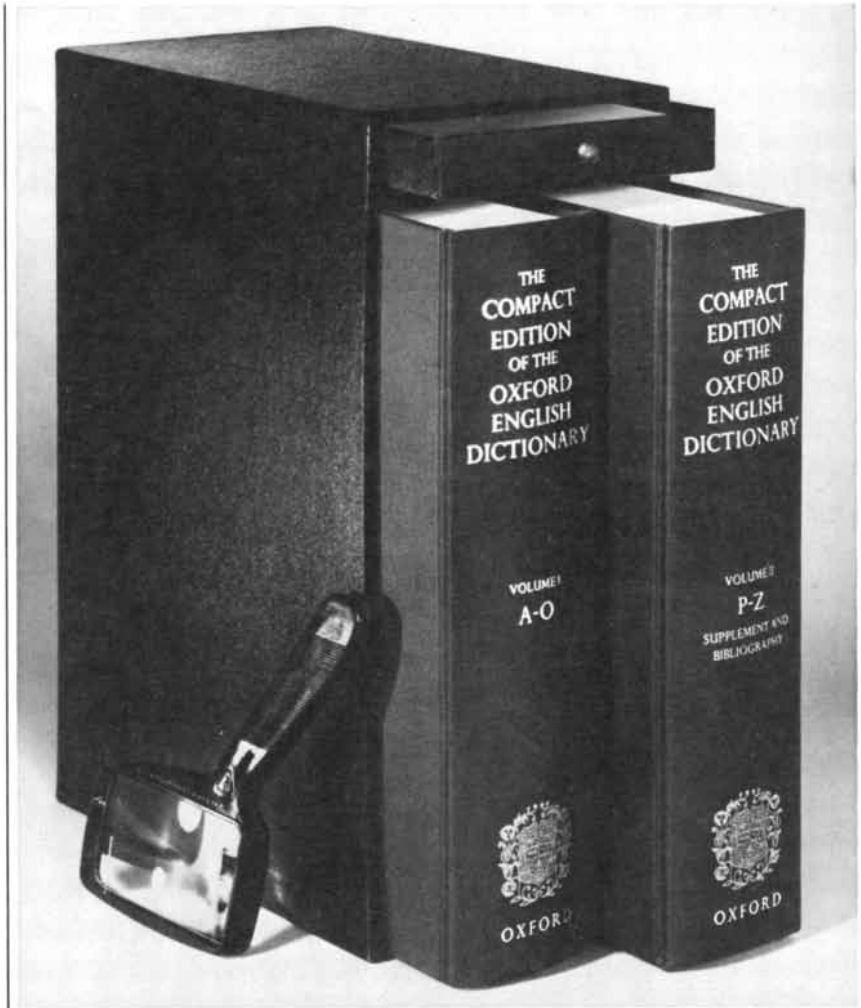

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BOOKS

Physicists in Hitler's Germany, the Viking exploration of Mars and Newcomen's engine

by Philip Morrison

SCIENTISTS UNDER HITLER: POLITICS AND THE PHYSICS COMMUNITY IN THE THIRD REICH, by Alan D. Beyerchen. Yale University Press ($18.50). It was the best of times. From 1925 to the early 1930's a flood of penetrating papers had filled the *Zeitschrift* and the *Annalen*. From Born, Pauli and Heisenberg in Göttingen, from Einstein and Schrödinger in Berlin, from Sommerfeld in Munich and his students ("in 1928 nearly one-third of all full professors of theoretical physics in the German-speaking world were Sommerfeld pupils") had come the most profound of all steps to our knowledge of matter and radiation. Quantum mechanics reached its full powers, still unchallenged after half a century. Of course, the Weimar Republic physicists were not alone: Dirac and Bohr and de Broglie are hardly German names. But the big German universities and institutes, notably the powerful mathematical center in Göttingen around Hilbert, Courant and Weyl, guarded the core of the subject. The reviews and the indispensable texts in their bright yellow covers told it to all, in German.

It was the worst of times. In a year or two the Reichsminister of education, sitting beside Hilbert at a dinner, asked: "And how is mathematics in Göttingen now that it has been freed of the Jewish influence?" Hilbert never temporized. "Mathematics in Göttingen? There is really none any more."

In a cool, meticulous volume, which draws not only on the printed word but also on many oral interviews with participants in the events, Professor Beyerchen, a University of Florida historian, tells how it was done, how the physicists encountered the hooked cross. Nobel prizewinners and bemedaled war veterans, canny university politicos with grant money flowing in and isolated, unworldly specialists—all were swept away under the law (the Law for the Restoration of the Career Civil Service, April 7, 1933, and many supplements), in spite of active public protest, dogged passive protest, quiet protest behind the scenes and the use of legal channels.

In quantitative terms at least a fourth

PHILIPP LENARD, who elaborated an "Aryan" physics, receives an honorary doctorate at Heidelberg in 1942. The man in the Nazi uniform to right of Lenard is Wilhelm Ohnesorge, Reich Post Minister, who had been a student of Lenard's at the University of Kiel.

of the physicists were made to go, or took the powerful hints. Qualitatively, many more of the best left. It is to be recalled that atomic physics was not then the discipline it is today, a proverbial source of worldly power by way of thermonuclear weapons, lasers and transistors. It was still abstract, unfamiliar, akin more to academic philosophy or even to science fiction. Bright young scientists whose Jewish background would have barred them from more lucrative and more conspicuous careers in medicine or in chemistry sought this intriguing intellectual refuge, where upright men like Planck and Sommerfeld never hesitated "to promote a Jew when the candidate was highly talented." But the content or quality of the research was never an issue in the years of dismissal. Anti-Semitism came first.

There were lines drawn around matters of substance as well. The tale includes the wretched figures of two able physicists (Johannes Stark and Philipp Lenard), men long alienated by envy and disappointment, who elaborated an Aryan neoclassical physics, the subject freed not only from the infamous Jews and part-Jews but also from the inordinate influence of theory, as from the materialism they could brand as Marxist. Surely it was inconsistent to return physics to Newton as a base: mechanical materialism had always stemmed from Newton's particles, and the new relativity and quantum mechanics are even today widely seen as the negation of strict determinism. But the personal careers of the two leaders and the public ideology of the Third Reich alike demanded this difficult stance. "Aryan physics was a microcosm of National Socialism, a coalition of views just as irrational in form and nihilistic in content. It is a dangerous form of intellectual arrogance to believe that a movement must be rationally consistent in order to achieve political power," writes the historian dryly.

The high point of the Aryan theorizers was the conflict over succession once Sommerfeld reached the age of retirement in 1935. Heisenberg was the obvious man, and he was the choice of the faculty even after the ministry had once rejected his name. In the summer of 1937 the matter, still unsettled, took an alarming turn. The SS journal itself published a piece on the dispute, alluding to "white Jews" and comparing Heisenberg's Nobel prize to the one given the pacifist Carl von Ossietzky during his imprisonment in a concentration camp. The matter was plainly grave.

The first step Heisenberg and his family took to deal with it was extraordinary, a revelation of a lunatic and arbitrary regime. The physicist's mother had known Himmler's parents in old days in Munich. Mrs. Heisenberg went to Mrs. Himmler to seek some redress. "My heavens, if my Heinrich only knew of this.... He is such a nice boy—always congratulates me on my birthday.... So if I say just a single word to him, he will set the matter back in order." (We owe this remarkable account to Heisenberg himself!) Finally the aerodynamicist Ludwig Prandtl intervened, presuming on a dinner conversation with Himmler. It worked, and Himmler agreed that in spite of the attacks Heisenberg seemed a decent young man, whom the SS might make use of in their world-ice research. Munich circles, however, held enough allies of "Giovanni Fortissimo and Leonardo da Heidelberg," as Sommerfeld called Stark and Lenard, for Heisenberg not to succeed to his old teacher's chair, although Himmler held out hope in writing of an important exonerating appointment at some later time.

Came fission and the war. The professors' demand for academic autonomy and for the exemption of younger men from service at the front was now bolstered by their claim of the new relevance of their work for the war effort. The Aryan ideologues had no way to match the promise of the uranium project. The academics won the fight in that they maintained the old standards of peer judgment, which they themselves consistently pointed out did not at all mean opposition to the Nazis.

The choice had once been to fly or to stay. If one stayed (Jews had of course simple survival to consider), it meant self-alignment with the party, or perhaps "prudential acquiescence." "For many others it was inner emigration away from political involvement. For a very few it was a form of resistance."

This tragicomedy, with its careful letters and agreed statements, its little encounters, influential friends and strong rejoinders, is played very quietly. Offstage a continent burns and shudders. Only once do we see the red glow itself, when on a February night in 1944 the Royal Air Force attacked Berlin and a high-explosive bomb exploded "right in the director's room" of Otto Hahn's Institute for Chemistry.

It was too late for military atoms. Max von Laue wrote: "Absolutely everything conducted in science was 'decisive for the war effort.'... Many, many young people owe to this designation the activity which... kept them alive. This is the only meaning which the ominous

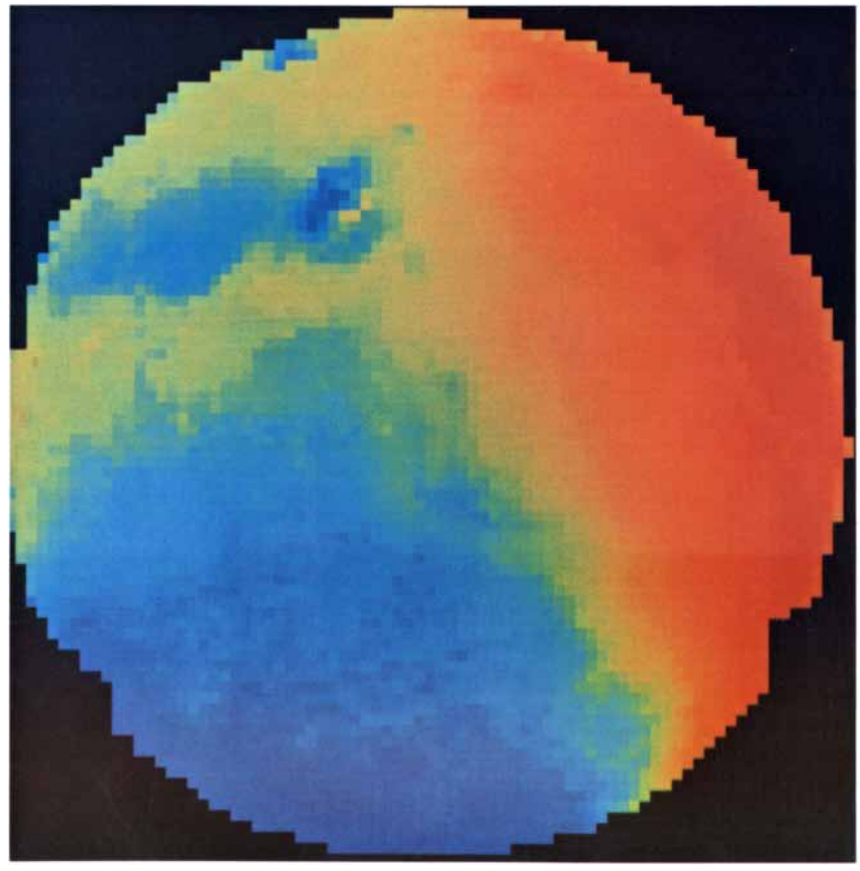

IMAGE OF MARS made from observations at a wavelength of 20 micrometers shows cool (*blue*) and warm (*red*) areas. The planet is illuminated by the sun from the right. The south pole is near the bottom. The cool spot at the top left is associated with the volcano Arsia Mons. The image appears in a paper by Hugh H. Kieffer, T. Z. Martin, Alan R. Peterfreund, Bruce M. Jakosky, Ellis D. Miner and Frank Don Palluconi in *Scientific Results of the Viking Project.*

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word 'kriegsentscheidend' had in the years 1942–45."

The irony of history has it otherwise. The German physicists, even in the face of published warnings of the truth by such a sharp observer as Carl Ramsauer, president of the German Physical Society after 1940, remained complacent in their evident superiority. Actually the Americans had long since overtaken them. In nuclear and quantum physics particularly the greening of American physics had begun long before the years of forced exile from Germany. There were young Europeans who had sought opportunity in the uneasy years before 1932, for example Samuel Goudsmit. There were bright Americans with postdoctoral years at Göttingen, for example Robert Oppenheimer. There were the energetic experimenters and brilliant planners, with and without European experience, for example Ernest Lawrence and I. I. Rabi. All of them, led and urged on by the illustrious and justly fearful emigrants after 1933, were convinced that "German science was the best in the world, and that if a bomb could be built, the Germans could—and would—build it."

So did our epoch of the bomb arrive. The just cause was pursued to extremity in the fear that our German counterparts—disaffected, complacent, under a regime that had bet everything on the short run, carrying the suppressed guilt of a bloody and unreasoning tyranny, yet so talented—would beat us to it. If you want to examine the fine structure, this book will disclose it to you. It is impossible to close without tribute to the noble few who remained outspoken in their moral opposition to the Reich. Einstein said it well in 1944: "If [the scientists] are different, it is not attributable to intellectual capability but human stature, as in the case of Laue.... [He] tore himself loose step by step from the traditions of the herd under the effect of a strong feeling of justice." Not many followed him. To be sure, most were not secure enough, and indeed "their goal of professional autonomy did not demand it."

SCIENTIFIC RESULTS OF THE VIKING PROJECT, reprinted from *Journal of Geophysical Research,* September 30, 1977. American Geophysical Union, Washington, D.C. ($30). Ten years ago planners began their work. Now we hold a bulky volume, color gatefolds, stereoscopic pairs and all, that presents more than 50 scientific papers on Mars firsthand by 100 authors, as they appeared in the most appropriate journal last year. They stand as a rich and meticulous technical report of the first year's results from a complex four-site field station 400 million kilometers out, with some of the story of getting there.

Two summary articles are followed by 200 pages of photointerpretation from close orbit, then a look at the atmospheric water vapor, thermal mapping of the surface and radio and radar studies. Next the atmosphere is sampled from top to bottom; a closer look sets in. The two lander sites are meticulously reported: landscape, rock-by-rock geology, motions (very few), minerals, magnetism, winds, fogs, chemistry and biology. Tiny pockmarked Phobos and Deimos are not neglected.

Nearly every report is both well illustrated and accompanied by a quantitative interpretation of some kind, whether it is the shear strength of lava, judged from the width of a lava-channel levee, or the simulation of an elementary analysis of Martian surface materials by a computer mixture of plausible minerals. This expertise is of course fully justified by the cost of the long link that is needed to bring us the data; it makes less for easy general reading than for careful study by readers who want to learn how to do field science, no holds barred. Dreamers and browsers will nonetheless find plenty to catch the eye; students and colleagues are sure to consult the work time and time again for methods as well as results.

Let us salute Viking with a brief list of some Mars realities we now know or surmise; the volume arrays the evidence in full.

Mars is no red planet. It is mostly a "moderate yellowish brown," and its sky in clear weather is a paler version of the same color. The surface is quite still. There are no forms suggesting life, no pigmented colors suggesting plants, no artifacts to be seen. (There is an upright capital *B* on one large rock, not very well drawn.)

A long time ago giant flash floods carved the landscape in a number of places; a volume of water equal to that of Lake Erie poured past in a few days' time, scouring great channels.

A magnet holds a few percent of the fine-grained particles of Martian soil. The magnetic material is maghemite, the gamma phase of Fe_2O_3, a minor but widely occurring mineral on the earth. The same material catalyzes the oxidation of organic compounds in water (supplied from the earth) by superoxides in the soil (supplied locally by the ultraviolet decomposition of the carbon dioxide atmosphere).

There are not only gigantic shield volcanoes on Mars, rising 25 kilometers above the plains, but also flattish saucer volcanoes, a type unknown on the earth; one of them is nearly 1,500 kilometers in diameter but less than three kilometers high, all the product emerging from one central vent.

There is no evidence to support the concept of a seasonal wave of soil darkening once thought certain by earth-based observers. There are windblown streaks, and some volatiles deposit and resublime, even snow. But if anything dark is systematically seasonal, it has to be in the dusty atmosphere.

That dusty world has a hazy sky, with a morning ground fog of water ice, suspended soil particles and in the fall a high ice cloud (a mixture of dry ice and water ice).

The predicted range to Mars was short by 20 meters. We should do a good deal better next time.

Dust there is but no allergens! The organic content of the soil itself, over a wide range of molecules from methanol to naphthalene, is in general below some parts per billion. Any trace compounds from meteorites or photochemistry or other such paths, let alone any from life forms, must be oxidized away so soon that their steady abundance is negligible. Antarctic soil gave peaks orders of magnitude higher for two dozen compounds sampled.

Do not forget that the time it took the experimenters to respond to a new piece of data was normally two weeks. That was the delay for software preparation and checking. (The wrong computer command could be disastrous.) The Viking spacecraft accepted queries only once a day. At one crucial point a most urgent look was taken by camera at a jammed sampling arm. Those pictures were back and in the hands of the analysts in "a little over thirty hours," a heroic effort. All four Viking substations (two in orbit, two on the ground) are robust and well; they should work the Martian year round, perhaps until early 1979, when once again our radio link will be blocked by the sun and the lonely Vikings will sleep.

Pan for nuggets on your own. The book is a 725-page bargain and a sober celebration; like Mars, it is pretty dry but full of interest.

THE STEAM ENGINE OF THOMAS NEWCOMEN, by L. T. C. Rolt and J. S. Allen. Science History Publications/USA, Neale Watson Academic Publications, Inc. ($15). Everyone vaguely knows the name of Newcomen, whose early steam engines, with the big walking beam protruding from the tall brick engine house, are seen so often in reproductions of old engravings. The engines seem quaint, whimsical precursors of the real steam engine, the one James Watt derived from the little lecture-model Newcomen engine that once came for repair to his instrument shop in the physics department at Glasgow.

This well-illustrated and knowing monograph, a reworking of a version published in 1963 by the late senior author on the 300th anniversary of Newcomen's birth, sets the vulgar opinion straight. The Newcomen engines were in no way oddities; they were in fact the first effective industrial heat engines.

practical forerunners of all fuel-fed prime movers, a mushrooming commercial success throughout the 18th century. The first known engine of the kind was built 10 miles west of Birmingham in 1712, "an Extraordinary Fire Engine" pumping water up 50 yards from a mine cut into the famous Dudley Ten Yard coal seam. The engine cost 450 pounds, worked at above five horsepower and drew the Spanish ambassador to see it. Newcomen and his partner, concerned about commercial security, would not admit their fashionable visitors to the enginehouse. The location of this engine is now well established by a number of corroborative records and some industrial archaeology. There are hints of an earlier Newcomen engine in Cornwall.

It was a fine piece of engineering. All the working parts were of clear brass; in "its purposeful and ordered complexity" (a detailed engraving of 1719 is reproduced on a full page) it had almost every one of the features that persist today, differing only in details, size, cost and the change from brass to iron. The design continued through the entire 18th century and beyond, in steady success.

The cycle was simple. A "haystack" boiler raised steam from a coal fire. The steam, at atmospheric pressure, entered a big cylinder. The load of the pump rods pulled the piston up as the cylinder filled with steam, driving out the air. Then a jet of cold water was sprayed into the steam volume. The steam condensed to a partial vacuum and the excess atmospheric pressure pushed the piston down and raised the heavy pump rods. A well-functioning engine had a mean internal pressure of only a third of an atmosphere on its power stroke. The valving was automatic from a very early stage. Snifting, snoring, hissing and knocking, the big engines made a dozen strokes a minute; the power they developed grew finally to 40 or 50 horsepower, from a cylinder six feet across with a stroke even bigger.

Thermal efficiency stayed low; after all, the steam was cooled by a jet of water, and there was a layer of water at the top of the piston to seal the leather gasket. The thermal yield was maybe 1 percent, but the deep Cornish tin and lead mines and the big Tyneside collieries could afford the fuel and the investment; there was no other practical way to pump out water. Long wood rods drove force pumps lifting water 40 yards or so at a stage. In deep mines one pump would feed an open wood cistern built on a stage higher up the shaft, which would in turn be drawn on by the next pump above, all powered by the same engine. Millwrights could handle the power output of some tens of horsepower; big waterwheels, the Dutch windmills and the Boulton and Watt steam engines were all in the same range. Higher power came in gradually with high-pressure steam in the Victorian epoch.

Thomas Newcomen died in 1729. We have no likeness of him; his financial condition is unknown; his grave is unmarked. He was an inspired but practical provincial tradesman, an ironmonger at Dartmouth in Devon. The "Proprietors of the Invention for raising water by fire" collected high royalties on about the first 100 Newcomen engines, all those built in England and on the Continent up to the expiration of the Savery patent in 1733. Newcomen apparently became inventor-engineer for that joint stock company, which held the very broad patent given Captain Thomas Savery, another Devon inventor, in 1698. Savery's "fire engine" (he called it "the miner's friend") was a steam-jet pump without heavy moving parts, never practical. The use of hot, high-pressure steam such as it would need to work at the usual mine depths was premature for the state of the engine builder's art by a century.

Growth continued apace under a line of successors, after 1733 freed of royalties. One would buy a cylinder and piston casting from the right ironfounder, and clever local millwrights did the rest, under one or another experienced engineer right on the site. There was no Boulton and Watt factory for the Newcomens. Yet by the year 1800, when the Watt patent on the new steam engine expired, there were some 1,500 Newcomen engines in use (a small fraction of which were adapted to crankshaft gear for rotary motion), and only 500 or 600 engines of the Watt type or any other kind. One big Newcomen pumped the water out of Peter the Great's drydocks at Kronstadt, others pumped water for Paris and London, and one drained a copper mine in New Jersey.

They were done in by historical feedback. Deep mines, more coal and cheaper iron; more iron, better tools and machines; better machines, high-pressure steam and the Victorian rise of engineering sophistication. At a colliery near Bristol the longest-lived Newcomen of them all worked regularly from the decades around 1750 until it was dismantled in 1900, still producing a measured 52 horsepower.

With this book anyone can understand why the famous sponsoring British Society for the study of the history of science and technology is named after the modest Thomas Newcomen, "the first great mechanical engineer."

HEALTH AND DISEASE IN TRIBAL SOCIETIES. Ciba Foundation Symposium 49 (new series). Elsevier North-Holland Inc./Excerpta Medica ($28). No man is an island, but many small societies are still islands, away from the currents of ideas, goods and genes. Most but not all of the societies under discussion here are hunter-gatherer groups, from Australia to the Amazon or Africa. Two dozen anthropologists, epidemiologists, human geneticists and nutritionists from half a dozen countries took part in London late in 1976 in this symposium on the "island" societies, reported in fascinating primary papers, along with remarkably candid and pleasingly digressive discussion.

The central topics are infectious disease within isolated communities and the medical responses indigenous to them. Two or three case histories are given in some detail; there are chapters on nutrition and on the responsibilities of well-meant intervention into another way of life. We, the powerful (if transient) society, gain from the diversity of those peoples, as instructive for their antibodies as for their theories of disease. But do they gain a reciprocal benefit? The historical answer is surely no; they stand, rather, to be destroyed.

The instances are melancholy and eloquent, yet some observers see hope. The moral issue is not a simple one: Can we really leave them alone, preserved like "rare orchids"? Dependency and poverty result from a contact as thin as the airplane overhead or the slow leakage of trade iron. Then comes a real shove, after a new road or some suggestion of mineral wealth. The Australian aborigines ("sitting on the uranium") have already "told us they don't want further studies made"; they want some benefits of past study. What they have mainly got in the government settlements so far is obesity, alcoholism, glue sniffing, gambling, venereal disease and sloth. ("But then they have little else to do.") A week's family diet is listed: Sydney-side junk food plus one wombat.

Aidan Cockburn, a paleopathologist from Detroit, takes a longer view of disease. Continental drift opened the Atlantic a couple of hundred million years back. Parasites such as the trypanosomes, one of which induces sleeping sickness, are so varied and numerous in both Africa and South America that they must have been on the ancestral continent before the ocean came. The tsetse fly, vector of the disease, is now only in Africa, but once it was on the other side of the Atlantic too. (Four excellent fossil specimens have been found in the Florissant shales near Denver.) Worms and intestinal protozoa follow the radiation of the primates; 11 protozoan species are shared by Old World monkeys and New World ones.

Herpes, yellow fever, malaria and yaws are similarly shared. Once man left Africa for the entire world he shed those parasites whose special vectors or intermediate hosts could not withstand the new climates. Malaria could not have been carried through Siberia to the New World. Lice, mites and other

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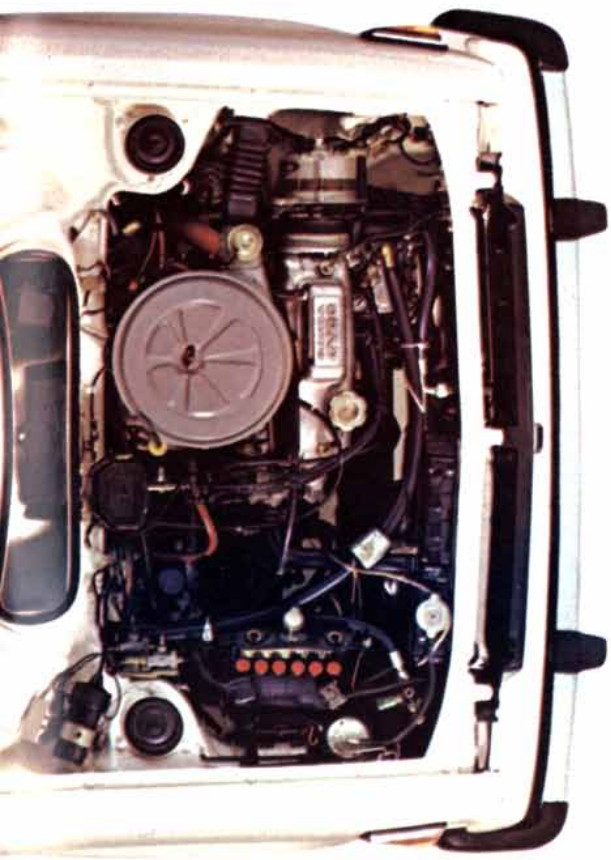

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dwellers on man could come along, and new ones could establish themselves. Domestication and settlement on the land brought new intimates, directly the dog and the goat, say, indirectly the sparrow and the mosquito. All their pathogens would soon be shared. A few infections would find themselves changeling invaders: new, specifically human pathogens.

In general parasites need a threshold host population. In small populations only persistent chronic infections will survive; the swift, acute disease demands large numbers. There is plenty of experience to support this conclusion, and more is given here. The doctors have seen "virgin soil" visitations of measles in a number of Amazon tribes in the past decade. That acute but benign disease killed nearly 30 percent of the cases in one group, where susceptibility was near 100 percent. Village life collapsed; there was no one able to bring water to the sick mother or infant in the heat of the day. The high rate of complicating bronchopneumonia was "in part explained by the jack-knife position the ill Indian assumed in his hammock, there to await the death some very malevolent spirit was arranging." There is still no clear evidence for a genetic susceptibility different from our own, but the matter is open. (One fatality in 5,000 cases of measles is recent British experience.)

Greenland is much too small to support endemic measles; that takes a million people. Even Australia was not populous enough to support rubella ("German measles"). That epidemic has come there and gone several times, although now the cities are bigger and are linked by air, and even London is not far off in time. The inference is clear: pests such as measles, mumps, smallpox and influenza depend on the large populations of agricultural man. They came from modified parasites of our domesticates and in man must be less than 6,000 or 8,000 years old. Fertilized fields brought hookworm; irrigation brought schistosomiasis; slash-and-burn agriculture favored malaria.

Remarkable reports as usual come from that patchwork of tongues and peoples, the highlands of New Guinea. There penicillin cures yaws after one injection, in two dramatic weeks. Nothing else ever helped much. No New Guineans refuse injections; none contend that their traditional healers are still needed for the disease. Now the "injection doctors" operate in many places as syringe entrepreneurs and rather haphazardly stick anyone who pays. (In Thailand these healers often refer patients to modern clinics; the house of Aesculapius too has many mansions.)

In 1974 two Indonesian physicians were astonished to find among the Ekari people of West New Guinea an epidemic of severe burns of the feet! It turned out that the burns occurred when sleeping people rolled into the house fires customarily kept burning all the cold mountain night. Healthy people can quickly withdraw, and they rarely incur serious burns. These new cases were convulsive: during seizures of grand mal epilepsy the patient was in a coma, unable to withdraw from the fire until help came. The epilepsy had followed a tapeworm infection from newly imported gift pigs. The people had already noticed the cysts in the flesh of the pigs. The larvae sometimes infest the human brain; now the hygiene of the village has changed, and the slow baking of succulent underdone pork is giving way to a less subtle cuisine.

Kuru, the chronic degenerative disease spread by a new rise of cannibalism mainly among the ceremony-conscious women of the Fore people of New Guinea, is soon to be gone. No one born after the cannibal mourning fashion ceased has ever got kuru. It is down to zero in those under 19; only the older people still show the slow progress of the agent ingested many years back. In 1971 an epidemic cretinism and goiter appeared in the Jimi River valley of Papua. Cheap, uniodized trade salt had replaced the scarce salt from the traditional mineral springs, the only source of iodine for the "severely depleted but still asymptomatic populace," a people utterly ignorant of the sea. D. Carleton Gajdusek, whose extraordinary experiences with transient medical wonders these are, holds a minority view of acculturation: the faster the better.

If the hunter-gatherer life is so adaptive (a million years of steady state, we think), why are its people generally small? (Exceptional men reach five feet nine inches.) Why are they apparently short-lived? If the population size is balanced, what controls population growth? These questions are asked by a medical ethnographer of Case Western Reserve University, Betsy Lozoff. She has taken a portable laboratory and a data-recording computer into the field to seek answers in swift, rich, unobtrusive studies of social events, nutrition and blood. Answers were offered by many but with little agreement so far; there is much to learn, if we can somehow manage to do less harm.

READING DISABILITIES: AN INTERNATIONAL PERSPECTIVE, edited by Lester Tarnopol and Muriel Tarnopol. University Park Press, Baltimore ($14.50). Take the crudest measure, the difference between the grade in arithmetic and that in the Czech language, and some 2 percent of all the schoolchildren in Prague show a specific disability in reading, "below the standards which their abilities in other spheres would lead one to expect." So it runs for the 18 countries here reporting, each in a chapter by a concerned specialist in the problem. The idea of dyslexia, or word blindness, still by no means sharply or convincingly defined, goes back at least to the 1880's. Putting aside children with general mental retardation, it appears that one child in about 30 quite universally is in real reading trouble. In the U.S., heterogeneous in every way, with strong class differentiation and areas of shameful discrimination, this number is easy to augment by adding the emotionally disturbed and the children with a desperate environment, 10 percent or more. The various countries that report a lower incidence see some connection with the languages themselves; phonetic Czech, with its unique diacritical marks, and ideographic Chinese seem less likely to induce trouble than ambiguous and disorderly English. English-speaking countries do seem to be more affected, but there is no doubt a strong influence of the rich American studies in the area, studies accompanied by impressive psychometric test scores and statistical treatment.

It is interesting to read the experiences of Argentina, Canada, China, Denmark, Germany, Norway and a dozen more, including the U.S. (particularly California). Everywhere the problem is multiple, everywhere no panacea works, everywhere there is need for insightful, improvisatory, hopeful teachers. (A "specific teaching disability" is no rare disorder either.) One comes away with a feeling of honest and sympathetic groping, with some empirical success but little clarity.

The notion that a perceptual difficulty is at the bottom is strong; the inverted letters and the trouble with copying and a dozen little exercises suggest it strongly. But it is not yet clearly made out, any more than the effect of nonphonetic languages is clear. The special phonetic alphabet used for initial teaching in a well-known British program proved no significant help for the weakest 10 percent of readers and spellers. The Czechoslovak psychologist Zdaněk Matějček "after many years of experience" concludes that the "single most difficult task is to create a general psychotherapeutic atmosphere of understanding." He is optimistic still.

The problems of bright nonreaders show something in common with the reading problems of the retarded. This fact has been used, perhaps even abused, to imply that a kind of marginal deficiency is involved. Perhaps, rather, the joint problem will help to unravel the reading task itself, a subtle, widely mastered perceptual and interpretative quasi-linguistic skill for which we were certainly not evolved. This is a book with many more questions than answers, good background for those who would move ahead.

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Enhanced-Radiation Weapons

Although President Carter has deferred production of "the neutron bomb," it is still an alternative of U.S. policy. It remains a weapon of doubtful utility that could result in an all-out nuclear exchange

by Fred M. Kaplan

The enhanced-radiation warhead (or, as it is widely and somewhat misleadingly known, the neutron bomb) is the latest development in the U.S. military's search for a "cleaner," more usable nuclear weapon. This new type of warhead, which could be available in some versions by 1979, is designed to kill more enemy soldiers per kiloton of explosive yield detonated over the battlefield than the types of nuclear weapon currently deployed for that purpose, while minimizing collateral, or unintended, damage to buildings, the countryside, friendly soldiers and nearby noncombatants.

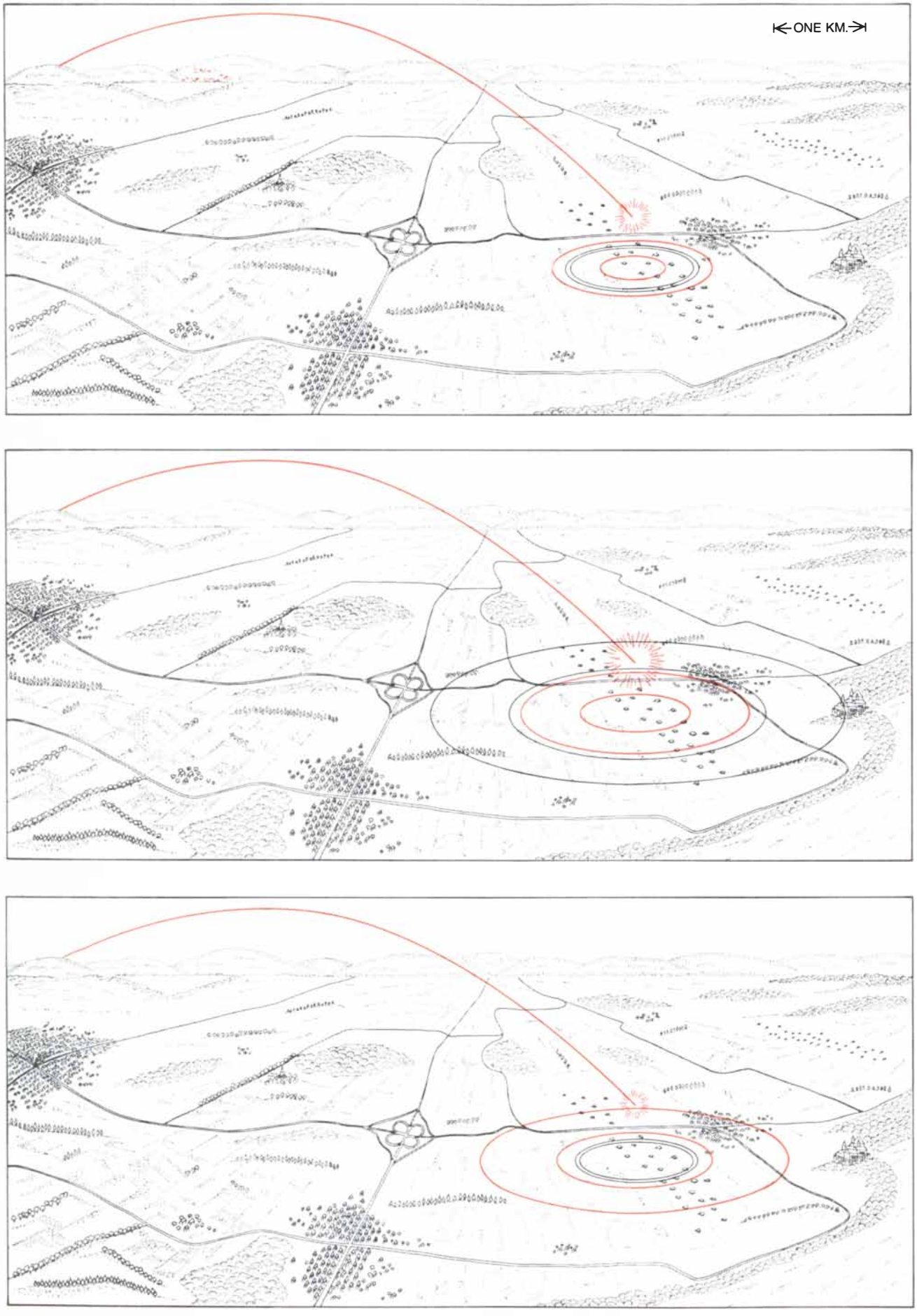
Many military officers contend that by using these more precise and refined enhanced-radiation warheads a "limited nuclear war" could be kept limited, its damage virtually confined to the battlefield. The enhanced-radiation warhead, like the generation of tactical nuclear weapons that preceded it, is intended for use in a European ground war between the nations of the North Atlantic Treaty Organization (NATO), including the U.S., and the nations of the Warsaw Pact, including the U.S.S.R. The Carter Administration's military budget for the fiscal year 1979 allocates unprecedentedly high expenditures for U.S. forces committed to the European-war contingency. The new tactical nuclear weapon therefore merits detailed discussion, particularly in view of the extraordinary notice given the weapon and the various misunderstandings that have arisen as a result. How did the weapon come into being? How does it work? What are its effects? What is its military utility? Should it be produced and deployed?

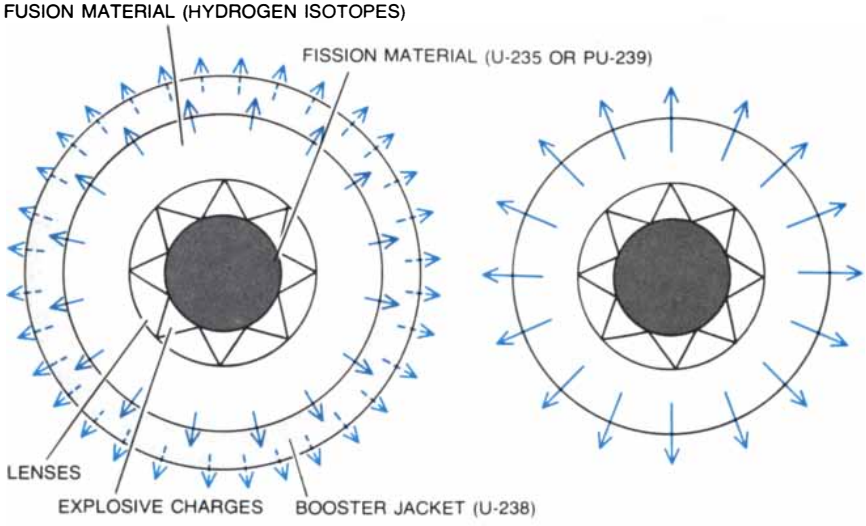
It is important to emphasize at the outset that there is nothing new about the notion of a neutron bomb. The possibility of developing a tactical nuclear weapon of this type was recognized soon after the invention of the hydrogen, or fusion, bomb in the late 1940's. A few scientists engaged in nuclear-weapons development, principally at the Lawrence Livermore Laboratory, worked on the concept of an enhanced-radiation warhead throughout the 1950's and 1960's, and they and others were politically active on behalf of its further development and deployment.

It was not until the early 1960's, however, that Secretary of Defense Robert S. McNamara ordered a general study of the prospects of tactical nuclear weapons. On the basis of that study and various simulated war games he concluded that a European-theater nuclear war would be a losing battle for both sides. Millions of civilians would die, and the use of such weapons would not necessarily turn a European war to NATO's advantage. Far from serving as substitutes for manpower and conventional firepower, tactical nuclear weapons would necessitate higher manpower levels, so that the NATO soldiers who would be killed as a result of the U.S.S.R.'s nuclear retaliation could be readily replaced. In fact, it was decided that since the Warsaw Pact forces plan to reinforce front-line troops in echelon style, whereas the NATO forces plan for individual replacements within existing division structures, a European-theater nuclear war would probably favor the U.S.S.R. and its allies, even if NATO possessed more or "better" nuclear weapons.

Moreover, the risk of escalation to an all-out strategic nuclear war between the U.S. and the U.S.S.R. as a result of such a strategy was held to be too great, primarily for two reasons. First, the "firebreak" between conventional and

SOME EFFECTS of three different types of tactical nuclear weapon are indicated in the idealized scenes on the opposite page. The setting in all three cases is a semirural area in West Germany, where military officials of the North Atlantic Treaty Organization anticipate an invasion by the forces of the Warsaw Pact nations. Each salient of such an offensive would presumably be led by an attacking force of hundreds of Russian tanks, which in such situations are expected to move in two or three echelons with the tanks in the first echelon spaced approximately 75 to 100 meters apart. An echelon of this kind is shown just to the right of center in each scene; a second echelon follows three kilometers behind the first at the upper right. In all three cases a Lance missile bearing a tactical nuclear warhead has been launched against the first echelon of Russian tanks by NATO forces located some 130 kilometers away. The scene at the top shows the estimated blast and thermal effects (*black*) and prompt-radiation effects (*color*) of a nuclear-fission warhead with a one-kiloton explosive yield detonated on target at an altitude of 500 meters. The middle and bottom scenes respectively show the corresponding effects for a 10-kiloton fission warhead and a one-kiloton enhanced-radiation fission-fusion warhead (the neutron bomb). In all three cases the inner black circle delineates the extent of the blast damage resulting from a shock wave with an overpressure of five pounds per square inch, enough to destroy most buildings. The outer black circle corresponds to a thermal-radiation exposure sufficient to cause second-degree burns to unprotected people in the open. The inner colored circle shows the limit of the area exposed to at least 8,000 rads of prompt radiation (mostly neutrons), enough to cause "immediate permanent incapacitation" of soldiers or, given current tank-protection factors, "immediate transient incapacitation" of tankmen. Outer colored circle corresponds to a prompt-radiation dose of 150 rads, enough to kill about 10 percent of the exposed individuals and cause a high incidence of cancer in survivors. Distance scale is given at top right in first panel. Effects of residual radiation (radioactive fallout) are not shown.





TWO TYPES OF FISSION-FUSION WEAPON are compared in these highly schematic diagrams. In both cases a set of chemical explosive charges detonates the weapon, causing fission reactions in its core that in turn trigger fusion reactions in a surrounding layer. The standard fission-fusion device (*left*) is enclosed in an additional jacket of uranium 238, a nonfissionable isotope that boosts the weapon's explosive yield considerably by capturing many of the fast neutrons (*solid colored arrows*) released by the fusion process. The U-238 nuclei then fission, emitting large numbers of much slower "thermal" neutrons (*broken colored arrows*). Most strategic nuclear weapons are based on this concept. The enhanced-radiation warhead (*right*) omits the U-238 jacket. In effect a greater proportion of fast neutrons are released by the enhanced-radiation weapon at the expense of explosive yield. Slow neutrons are captured by atomic nuclei in the air much more readily than fast neutrons. Hence beyond a short range the enhanced-radiation warhead produces many more neutrons than a standard fission-fusion warhead.

nuclear warfare was at that time clear; trying to blur the distinction between tactical and strategic nuclear war would create considerable ambiguity, leading to mutual suspicion, tension and possibly to preemptive strategic nuclear strikes. Second, the U.S.S.R. had many nuclear-armed intermediate-range ballistic missiles (IRBM's) deployed in its territory, some of them in the same areas occupied by intercontinental ballistic missiles (ICBM's); the temptation would be great in the early stages of such a European-theater nuclear war for NATO to preemptively knock out those IRBM's inside the U.S.S.R., possibly triggering a strategic nuclear exchange between the two superpowers.

After weighing these considerations McNamara turned to a policy of building up conventional, or non-nuclear, war-fighting capabilities, and he put off spending money on a new generation of tactical nuclear weapons. (He did accept the nuclear-armed Lance missile, however, because of its longer range and consequent reduced vulnerability.) During Melvin R. Laird's term as Secretary of Defense more money was allocated to develop a new generation of tactical nuclear weapons, but the negative attitude toward the modernization of tactical nuclear weapons essentially prevailed until James R. Schlesinger became Secretary in 1973.

During Schlesinger's earlier tenure as Chairman of the Atomic Energy Commission he had shown considerable enthusiasm for tactical nuclear weapons. By the time he was appointed Secretary of Defense, however, his interest appeared to have lessened. Still, Schlesinger apparently felt compelled to make some concessions to the advocates of tactical nuclear weapons, an assortment of converging interests that included the Atomic Energy Commission, the Congressional Joint Committee on Atomic Energy, the weapons laboratories, certain military departments and the Atomic Energy Division of the Office of the Secretary of Defense. Schlesinger, who had little bargaining power in the White House during the Nixon and Ford administrations, had to manage his own complex coalition. To gain support from these disparate interests for his plans to further build up conventional forces for NATO, he gave them money for the modernization of tactical nuclear weapons.

The coalition in favor of a modernization program for tactical nuclear weapons was actively aided by Schlesinger's own emphasis on enlarging the range of U.S. "options" in nuclear-force planning. Thanks in part to new technologies, such as highly accurate inertial-guidance systems for missiles, Schlesinger reprogrammed strategic nuclear weapons to have "selective strike" capabilities and greater "flexibility," creating new "target packages" that were far more diversified than those available to the defense planners of the preceding decade. Along with the expansion of strategic options, he ordered an increase in the available options for fighting a European-theater nuclear war. This new emphasis gave what appeared to be official support to those military officers who were beginning to think seriously about the possibility of fighting and winning a limited nuclear war and about the necessity, under such circumstances, of limiting collateral damage.

Meanwhile the development of the Sprint anti-ballistic-missile (ABM) system at the Los Alamos Scientific Laboratory in the mid-1960's and the subsequent ban on further ABM production imposed by the SALT I treaty of 1972 led some weapons-laboratory scientists to think about reducing the yield of the Sprint warheads to adapt them for use as tactical nuclear weapons. (Sprints were short-range nuclear-armed antimissile missiles designed to be detonated in the atmosphere, depending primarily on neutrons rather than X rays for their effectiveness.) All these various interests—of the armed services, the weapons laboratories, the Congressional committees and the Department of Defense—have converged to create the present situation.

Today enhanced-radiation nuclear warheads are being developed for the Lance missile and for the eight-inch artillery shell. An enhanced-radiation warhead for the 155-millimeter artillery shell is also in prospect, although it still appears to be in the early stages of development. (At least one of these warheads, probably the one for the Lance, has already been tested at an underground site near Las Vegas.) Currently deployed Lance warheads have explosive yields ranging from one kiloton to 100 kilotons; the charges of the eight-inch nuclear shells range from five to 10 kilotons. The new enhanced-radiation version of the Lance warhead will have two yields, which can be preset simply by pushing a few buttons; one yield is considerably smaller than a kiloton and the other is slightly larger than a kiloton. The eight-inch enhanced-radiation shell will have three yields, ranging from substantially under a kiloton to roughly two kilotons.

The effects of a nuclear explosion consist of blast (a shock wave of overpressure), thermal radiation (heat), prompt radiation (mostly neutrons and gamma rays) and residual radiation (radioactive fallout resulting from decaying fission products). The energy released from a fission explosion is divided into several fractions: typically 50 percent blast, 35 percent thermal radiation, 5 percent prompt radiation and 10 percent residual radiation. In a hypothetical pure-fusion weapon the effects would be 20 percent blast and thermal radiation, 80 percent prompt radiation (mostly neutrons) and comparatively little residual radiation (the precise amount depending on the characteristics of the soil under the explosion).

The fusion reaction that takes place between ions of deuterium and tritium (two heavy hydrogen isotopes) is accompanied by the liberation of very-high-energy, or fast, neutrons. The energy of these neutrons is about 14 million electron volts (MeV), which is substantially more than the still quite fast 2-MeV neutrons released by a typical fission reaction. Neutrons are slowed down and eventually captured by debris from the weapon itself, by objects in their path and by the air. The faster the neutrons are, the more collisions they experience before being completely captured. Moreover, fusion produces 10 times more neutrons per kiloton of explosive yield than fission does. Thus neutrons released from a fusion weapon are higher in radiation intensity, and penetrate greater distances before being completely absorbed, than those released from a fission weapon.

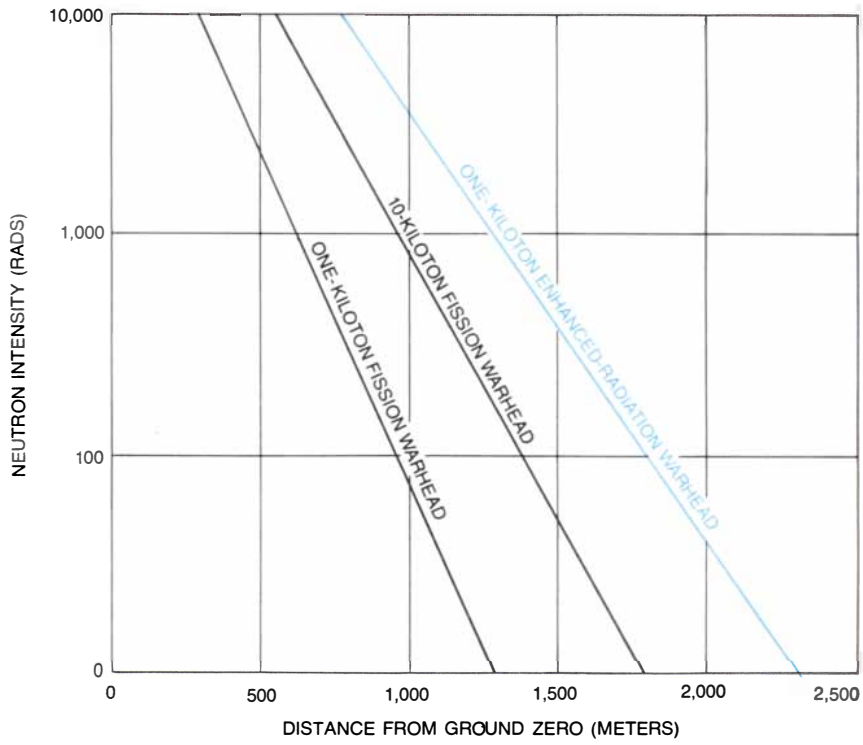
The present incarnation of the enhanced-radiation warhead is a fission-fusion weapon. The fission-fusion mix differs slightly between the Lance device and the eight-inch device, but the detonating process is the same in both of them. When the weapon is detonated, the fission reaction triggers a fusion reaction, which in turn releases many fast neutrons. That is why the enhanced-radiation warhead is often called a neutron bomb. The term is correct in the sense that the enhanced-radiation warhead releases many more neutrons than other weapons of equivalent yield. It is misleading, however, in that the warhead's detonation also releases a great deal of energy in forms other than neutrons. (In fact, any nuclear weapon smaller than about two kilotons could be called a neutron bomb in the sense that at ranges corresponding to the lethal radius of the weapon, even if it were completely a fission one, the energy released in the form of prompt radiation would be greater than the fraction that goes into blast and thermal radiation, and prompt radiation in the form of neutrons would dominate prompt radiation in the form of gamma rays. If such a weapon were exploded in the air at a height of several hundred meters, it would cause only slight blast and thermal effects on the ground, even though the damage from neutrons would still be substantial.)

The enhanced-radiation warhead is not close to being a pure fusion weapon. In terms of explosive yield the subkiloton and one-kiloton enhanced-radiation warheads for the eight-inch artillery shell are roughly 50–50 fission-fusion devices. The enhanced-radiation version of the Lance warhead is about 60 percent fusion and 40 percent fission. The two-kiloton eight-inch enhanced-radiation shell is between 70 and 75 percent fusion. The energy released from the Lance and the lower-yield eight-inch enhanced-radiation weapons is divided approximately into 40 percent blast, 25 percent thermal radiation, 30 percent prompt radiation and 5 percent fallout. The highest-yield eight-inch enhanced-radiation shell produces about 10 percent more prompt radiation and slightly less blast, thermal radiation and residual radiation. In other words, the enhanced-radiation warhead promises to be neither the collateral-damage-free weapon that its supporters see nor the "ultimate capitalist weapon" (destroying only people, not property) that many people in peace groups fear.

The fundamental distinction between the enhanced-radiation warhead and other, more fission-dominated nuclear weapons of very low yield is that the former releases many more and much faster neutrons. Of the energy released by the Lance and the lower-yield eight-inch enhanced-radiation weapons, six times as much is in the form of prompt radiation than is the case in a fission warhead of equivalent yield; in the highest-yield eight-inch enhanced-radiation shell the energy available for prompt radiation (particularly neutrons) is reported to exceed that of fission weapons by as much as 10 times.

There is also a distinction, apart from the number of kilotons, between the enhanced-radiation warhead and fission-fusion weapons of higher yields. Standard fission-fusion weapons (including most strategic nuclear weapons) are surrounded by a "jacket" of uranium 238 that boosts the weapon's explosive yield; the jacket captures or considerably attenuates the fast neutrons released by the fusion process. Since enhanced-radiation weapons by definition call for very low thermal yields and the release of many fast neutrons, an enhanced-radiation warhead has no U-238 jacket.

What, then, is the military mission of the enhanced-radiation warheads supposed to be? The chief concern among many NATO military officials is the possibility of a Russian-led Warsaw Pact blitzkrieg across the northern plains of West Germany. Russian military doctrine and the deployment of Russian forces suggest that such an attack, if it were launched, would involve the onslaught of thousands of tanks as the prime mover of the offensive. Some military planners believe that an attack of this type, particularly if it were mobilized with little warning time, could not be met by NATO without the use of nuclear weapons. (This contention is vigorously disputed.) For several years some U.S. military officers have criticized the "impracticality" of most of the tactical nuclear weapons currently deployed in Western Europe, drawing attention in particular to their comparatively high yields, some of them much higher than the yield of the 20-kiloton bomb that destroyed much of Nagasaki at the end of World War II. Such



NEUTRONS EMITTED by three different types of tactical nuclear weapon are represented as a function of distance from the point at which the weapon is detonated. Two black curves give the neutron intensity for a one-kiloton fission weapon and a 10-kiloton fission weapon. The colored curve gives intensity for a one-kiloton enhanced-radiation fission-fusion weapon.

high-yield weapons would be effective for stopping Russian tanks, but they would also kill or severely injure many NATO soldiers and German civilians and would devastate much West German territory. Moreover, the effects of induced and residual radiation could make the occupation and recovery of the affected territory a lethal prospect for some time.

With the enhanced-radiation weapon the military has hit on a different tactic: to kill the Warsaw Pact soldiers inside the tanks instead of destroying the tanks themselves. This result, they say, is possible with the high neutron flux generated by the enhanced-radiation weapons.

Radiation doses are measured in rads, one rad being the absorbed dose of any nuclear radiation accompanying the liberation of 100 ergs of energy per gram of irradiated material. If tactical nuclear weapons are to be useful in a war, they must kill their intended victims as quickly as possible. "Immediate permanent incapacitation," according to recent U.S. Government tests conducted with rhesus monkeys, requires 8,000 rads. Since modern tanks have a radiation-protection factor of roughly .5, tanks must be exposed to 16,000 rads instantaneously if NATO's aims are to be optimally achieved. Recently, however, the NATO military doctrine has been revised to read that "immediate transient incapacitation," which requires only 2,500 to 3,500 rads (or, given tank protection, 5,000 to 7,000 rads), may be sufficient to neutralize invaders for military purposes.

Within five minutes a person exposed to 8,000 rads is incapacitated, and he remains incapable of performing physically demanding tasks until his death, which occurs within a day or two. A dose of 3,000 rads also incapacitates within five minutes, but the victim may partially recover within 30 minutes; still he remains a doomed man until his death four to six days later. He may also remain a helpless man, but maybe not. (It turns out that this uncertainty has significant military implications.) Exposure to 650 rads functionally impairs a human being within two hours, and he may respond to medical treatment; more likely a painful, lingering physical deterioration ends in death within a couple of weeks, a gruesome prospect, to be sure, but perhaps enough of a respite for the victim to fight on for some time.

These results are due to the ionizing effects of neutrons colliding with protons inside living cells. Ionization breaks down chromosomes, swells cell nuclei, increases the viscosity of the cell fluid, enhances cell-membrane permeability and destroys cells of all kinds, particularly those of the central nervous system. Moreover, exposure to ionizing radiation delays or destroys the process of mitosis, a long-term genetic effect that inhibits normal cell replacement.

In effect, enhanced-radiation weapons distribute given rad doses over larger areas, compared with fission weapons of an equivalent or even somewhat higher yield. For example, anyone within a 375-meter radius of a one-kiloton fission explosion (and anyone within a 630-meter radius of a 10-kiloton fission explosion) would be exposed to at least 8,000 rads. If a one-kiloton enhanced-radiation warhead were exploded instead, the 8,000-rad circle would widen to a radius of 850 meters. Thus a one-kiloton enhanced-radiation warhead could potentially kill about twice as many tankmen as a 10-kiloton fission weapon, but the blast damage to an area would be only about a fifth as large.

This feature is of course the main selling point for the enhanced-radiation warhead from the perspective of NATO military officers. The key is that the new weapon can substantially reduce the collateral damage of a nuclear explosion, meaning that blast, thermal radiation and fallout effects will be less dominant. This sounds all to the good at first. Nevertheless, it is misleading to assume, as some of the weapon's advocates seem to have done, that with this new generation of tactical nuclear weapons a European-theater nuclear war can now be safer and more easily managed than was once thought possible.

For one thing, it takes two sides to fight a "limited nuclear war," and the Russians seem to have neither the ability nor the disposition to join in. Of the 3,500 tactical nuclear weapons they have deployed to strike targets in the European theater (compared with NATO's 7,000) the majority are thought to have a yield in excess of 20 kilotons, and about 600 of the Russian missiles have a yield of between 500 kilotons and three megatons. The Warsaw Pact nations' tactical nuclear missiles are far less accurate than NATO's, making the selective-strike tactics necessary for effective damage-limiting war-fighting strategies difficult if not impossible for them to accomplish. Russian military doctrine does not seem to recognize any fine distinction between different types of tactical nuclear war, as U.S. military planning often does. Indeed, most of the

	NAME OF DELIVERY SYSTEM	NUMBER OF WARHEADS IN EUROPE	EXPLOSIVE YIELD (KILOTONS)	MAXIMUM RANGE (MILES)
NATO	HONEST JOHN MISSILE	196	20	25
	PERSHING MISSILE	180	60–400	450
	LANCE MISSILE	80	1–100	70
	SERGEANT MISSILE	56	LOW	85
	PLUTON MISSILE	24	15–25	75
	SSBS-2 MISSILE	18	150	1,875
	M-110 EIGHT-INCH HOWITZER SHELL	360	5–10	10
	M-115 EIGHT-INCH HOWITZER SHELL	27	5–10	10
	M-109 155-MILLIMETER HOWITZER SHELL	691	LOW	10
	LANCE MISSILE WITH ERW	?	ABOUT 1	85
	EIGHT-INCH HOWITZER SHELL WITH ERW	?	1–2	>10
	155-MM. HOWITZER SHELL WITH ERW	?	?	?
WARSAW PACT	SS-4 SANDAL MISSILE	500	1,000	1,200
	SS-5 SKEAN MISSILE	100	1,000	2,300
	SS-20 MISSILE	20(X3)	?	3,000
	SS-1b SCUD A MISSILE	880	?	50
	SS-1c SCUD B MISSILE		?	180
	SS-12 SCALEBOARD MISSILE		>1,000	500
	FROG 3-7 MISSILE	650	?	45
	M-55 203-MILLIMETER HOWITZER SHELL	?	?	18

TACTICAL NUCLEAR WEAPONS currently deployed in Europe by the NATO countries (including the U.S.) and the Warsaw Pact countries (including the U.S.S.R.) are listed in black type in this table. The new enhanced-radiation weapons proposed by the U.S. for the NATO arsenal are listed in colored type. The enhanced-radiation version of the Lance missile would have two possible yields, one somewhat less than a kiloton and the other slightly more. The enhanced-radiation version of the eight-inch shell would have three yields available, ranging from substantially less than one kiloton to roughly two kilotons. The Russian SS-20 intermediate-range ballistic missile (IRBM) carries three independently targetable nuclear warheads.

RUSSIAN MAIN-BATTLE TANK, designated the T-62, was photographed during a military parade in Red Square in Moscow. The Warsaw Pact forces are estimated to have 20,000 heavy tanks (mostly T-62's but also older models) deployed in the European theater.

Russian writings on the subject assume the inevitability of escalation, drawing no distinction between tactical nuclear war and all-out strategic nuclear war. In discussing a European-theater nuclear war such writings make virtually no mention of pinpoint accuracy and selective targeting except occasionally to hold them up to ridicule. A mass barrage punching wide holes in NATO's defenses, followed by a breakthrough with heavy tanks (whose structure and surface materials provide some protection against nuclear effects), seems to be the kind of mission envisioned for tactical nuclear weapons from the viewpoint of the U.S.S.R.

If NATO were to use enhanced-radiation weapons against Warsaw Pact tanks, the Russians would almost certainly strike back with nuclear weapons of their own. As a U.S. Army intelligence study of Russian military operations notes: "Should the first echelon [of tanks in an offensive] collapse, a series of counterattacks will be instituted, coordinated with all combat units to include ... nuclear strikes." The Russians would probably not be very concerned about collateral damage to the West German civilian population; even if they were, the high yield and poor accuracy of their weapons would keep them from doing much about the unavoidable consequences.

Even before the virtually certain Russian nuclear retaliation the damage caused by NATO's use of enhanced-radiation warheads would be substantial, regardless of the presumed limitations of the blast, thermal and fallout effects of individual weapons. The posture statement of the U.S. Department of Defense for the fiscal year 1977 states that if nuclear weapons were used in Europe, such action "should ... induce the Soviet Union to terminate the conflict quickly.... It should be done with decisiveness and shock effect to cause the Soviets to reconsider their activities." To achieve such a shock effect NATO would have to do more than stop a small number of tanks; much more damage would certainly be needed to make a dramatic impression on the Russian leaders.

How much more damage might that be? When Russian tanks are beginning an offensive, they move in two echelons (three under some circumstances). Tanks in the first echelon are spaced 75 meters apart in non-nuclear situations and 100 meters apart in nuclear situations. The second echelon moves up about three kilometers behind the first. The Warsaw Pact has some 20,000 tanks deployed for the central region of Europe, where the first battle of a NATO/Warsaw Pact war would probably be fought. Assertions by U.S. Army officers that the enhanced-radiation warhead causes little collateral damage are contingent on the weapon's being used in highly selective, even individual, strikes. Yet if NATO wanted to stop an impressive fraction of the first-echelon tanks, that is, if the enhanced-radiation weapons are to be at all useful militarily, the action would call for a barrage of many hundreds or even thousands of nuclear weapons. They would most likely include not only low-yield enhanced-radiation weapons but also low-yield and medium-yield fission weapons. Under such circumstances much radioactivity could be induced in the soil, particularly if some of the weapons were accidentally to detonate on or near the ground. In any event the number of fatalities and irradiated "walking ghost" casualties would be very high even if the nuclear war could be kept quite limited.

The enhanced-radiation warheads might reduce the collateral damage caused by blast and thermal radiation, but they would increase the damage caused by prompt radiation. Exposure even to comparatively small doses of radiation can have grave consequences for human beings, and enhanced-radiation warheads would extend the distance within which people are exposed to dangerous doses. For example, 10 percent of the people exposed to 150 rads will die from radiation sickness, and Hiroshima and Nagasaki survivors exposed to 150 rads showed a disproportionately high incidence of breast cancer. Exposure to only 30 rads doubles the mutation rate in progeny, and defective genes can be expected to appear for 10 generations. The inhabitants of the Marshall Islands who were exposed to a mere 14 rads as a result of U.S. nuclear testing in 1954 later developed thyroid nodules, cancers and leukemia.

A one-kiloton enhanced-radiation warhead releases 150 rads out to a distance of 1.7 kilometers, 30 rads out to 2.1 kilometers and 14 rads out to 2.3 kilometers. These effects can be compared respectively with 900, 1,170 and 1,300 meters for a one-kiloton fission weapon and 1,285, 1,570 and 1,700 meters for a 10-kiloton fission weapon.

With the enhanced-radiation warhead the collateral damage caused by prompt radiation would be even more extended. For radiation damage caused by gamma rays there is thought to be a threshold rad level below which no biological damage is caused. No such threshold is believed to exist for neutron radiation. Furthermore, in terms of genetic damage, leukemia and cataract of the eye, the biological effects from neu-

trons are about six times greater than those from gamma rays. Thus as few as one or two rads of neutron radiation could cause leukemia and cancers. Exposure to a mere five rads could double the mutation rate in the progeny of those exposed. If a single neutron collides with a strand of DNA in a sperm or egg cell, the probability of irreparable long-term genetic damage is high.

In other words, the notion that enhanced-radiation weapons are fairly benign to people on "our side" is highly questionable. Both NATO combatants and friendly noncombatants are likely to suffer much harm. The hazard to the noncombatants is increased by the fact that the eastern lands of West Germany have become highly urbanized.

The military utility of the enhanced-radiation warhead is questionable on an even more elementary level. Except for the tankmen who were fairly close to the actual detonation the exposed enemy personnel would remain alive for hours, days or even weeks; many of them could fight on, perhaps even more aggressively than before because of their knowledge that death from radiation was certain. Of course, NATO could accommodate to this problem by setting off a much larger number of enhanced-radiation weapons. Since the alleged virtues of the enhanced-radiation warhead stem mainly from its capability for precise, selective, limited strikes, however, this kind of massive barrage would undercut the entire rationale of the weapon. Besides, armor-penetrating neutrons would not make a tank so radioactive as to exclude the possibility of other tank crews' replacing those exposed to radiation. The tanks could drive on.

The effective use of these weapons also assumes a massive concentration of tanks. Yet it is a safe assumption that the NATO nations would not order the firing of any nuclear weapons unless the Warsaw Pact nations had first exhausted and overrun NATO's non-nuclear defenses. Even if the Russians had concentrated their tanks in the initial phases of the offensive, they would almost certainly disperse their armored forces after breaking through the NATO front-line defenses. (In fact, their writings on tactical operations suggest that this is exactly what they would do.) Under such conditions many thousands of enhanced-radiation warheads would have to be employed to immediately incapacitate the occupants of a significant number of Warsaw Pact tanks, again nullifying the alleged virtues of the enhanced-radiation weapon.

In spite of the apparently minimal military utility of enhanced-radiation weapons, the U.S. Department of Defense justifies them on the grounds that "if NATO arsenals contained the neutron warhead, opposing countries would be aware of NATO's ability to defend itself with less damage; this *could be* a deterrence to attack." Although the Department of Defense does not explicitly state that this weapon would enhance deterrence, the implication is that the Russians might think NATO would be more likely to use the enhanced-radiation weapons than the older, more fission-dominated weapons.

Here three comments should be made. (1) Even without the threat of enhanced-radiation weapons the Russians would be taking a big risk in attacking, since the U.S. has consistently refused to adopt a policy of not being the first to fire nuclear weapons. (2) Enormous damage would result from NATO's use of enhanced-radiation weapons, to say nothing of the damage that would be caused by a virtually certain Russian nuclear retaliation. (3) Although the topic is much too complex to treat in detail here, there is no reason to believe that NATO is incapable of defending Western Europe without resorting to nuclear weapons. Conventional firepower ratios between NATO and the Warsaw Pact nations are virtually even, and it is a well-known maxim that an attacker requires substantial superiority. The often-mentioned superiority of the Warsaw Pact nations in number of tanks is offset by the advantage NATO holds in superior antitank weapons, particularly with the recent advances in precision-guided munitions and remotely piloted vehicles. Weapons of both new types have greater ranges than the guns on Russian tanks, and both can, in the words of a U.S. Army field manual, "hit what they see, kill what they hit."

Military training in the U.S.S.R. and the other countries of Eastern Europe is notoriously poor and extremely rigid. The political reliability of the Czechoslovak and Polish divisions, at least for offensive warfare, is doubtful. Tactics and strategy in the Warsaw Pact armies rely heavily on the tank, which is becoming an increasingly vulnerable and obsolete weapons system. Moreover, the numerous surprise-attack scenarios circulating these days do not take into account the low readiness levels of the Warsaw Pact armies, the hundreds of ways intelligence agencies can observe and track signs of mobilization, the deficient Russian logistics network and many other weaknesses in the Russian war machine.

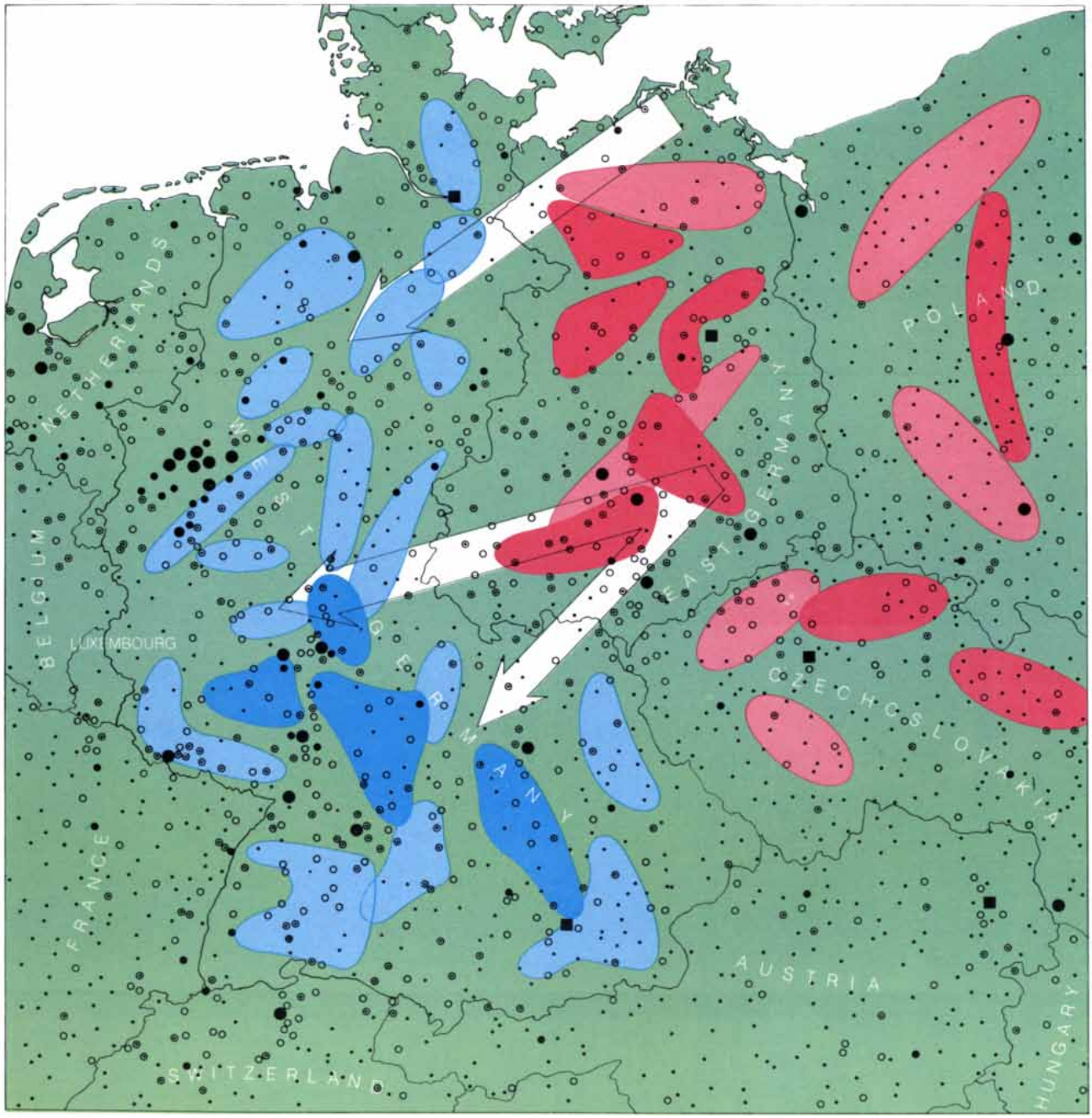
This is not to say that there is no room for improvement in NATO. Various maldeployments of forces could be corrected; lines of communication could be moved farther back, away from the forward edge of the battle area; more conventional antitank weapons could be deployed; airfields could be more widely dispersed; more aircraft could be deployed at "hardened" sites. The present U.S. Administration appears to be addressing itself to these problems. Since some of these tasks call for very substantial expenditures, it seems wasteful to spend large sums on such weapons as the enhanced-radiation warhead.

The costs of producing enhanced-radiation warheads would be enormous. The eight-inch enhanced-radiation artillery weapon will cost about $900,000 per shell (including the costs of the projectile, the casing and so forth). The enhanced-radiation version of the Lance missile is expected to cost only slightly less. Instead of buying two rounds of eight-inch enhanced-radiation shells the U.S. could obtain, say, three M-60 main-battle tanks, 50 or so advanced non-nuclear antitank weapons or more than 5,500 rounds of conventional artillery shells. In other words, if the U.S. decides to invest in enhanced-radiation devices, NATO will be acquiring an extraordinarily costly weapon that will probably never be used at the expense of comparatively cheap weapons that would markedly improve NATO's defense posture. Assuming that the Russians dispersed their tanks widely and that they adopted certain measures against neutron radiation, then conventional antitank weaponry would probably be both cheaper and militarily more effective.

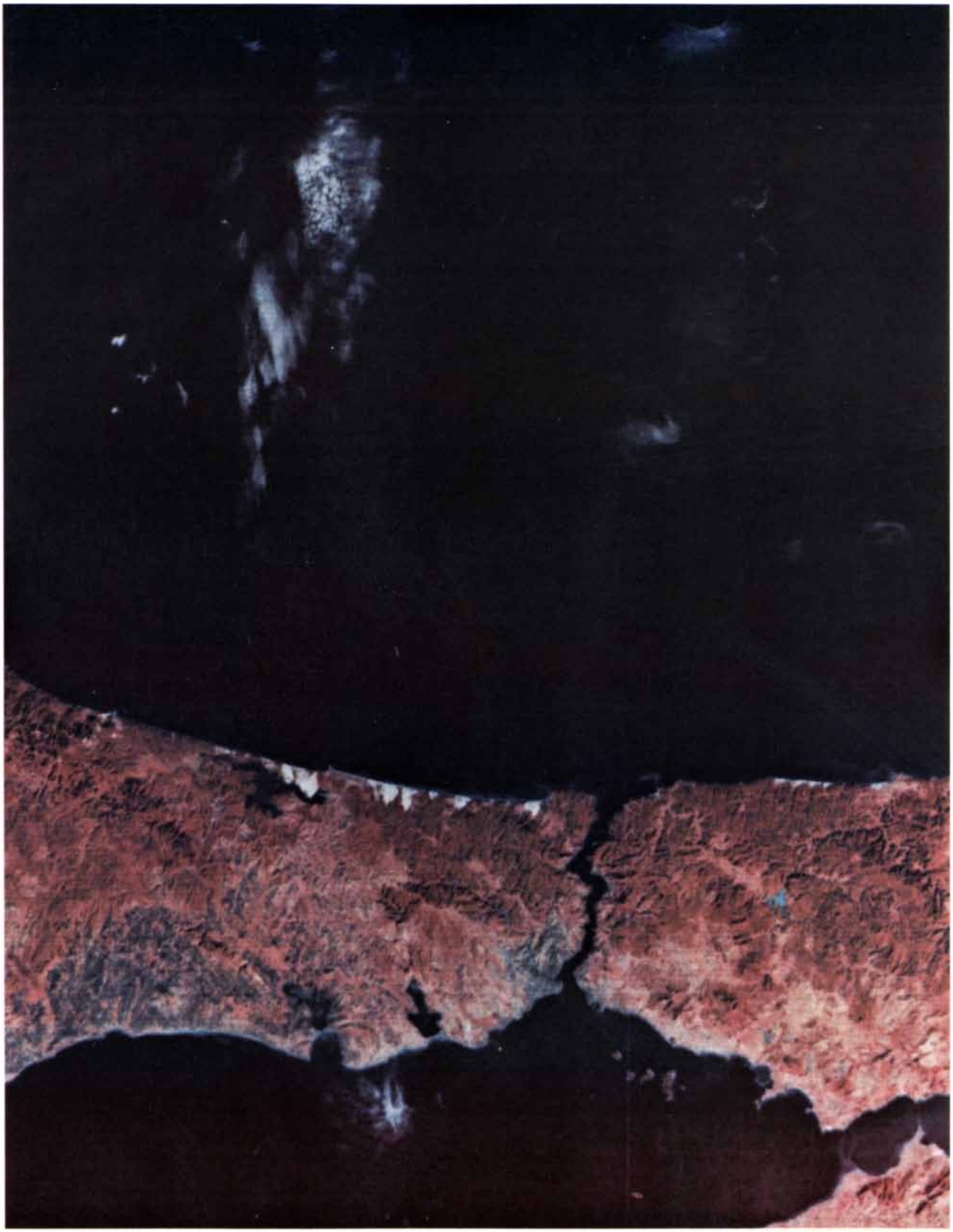
It remains true that the enhanced-radiation warhead could do as much damage to an attacking force as higher-yield weapons without causing as much collateral damage. Against this clear advantage, however, one must take into account the enormous damage that would ultimately result from any introduction of nuclear weapons into a conventional war. It might also be said in favor of enhanced-radiation devices that, as the systems of this new generation of tactical nuclear weapons are currently planned, they incorporate features other than enhanced radiation. They will have a longer range (about 130 kilometers for the enhanced-radiation version of the Lance), improved command-control communication systems and securer lock mechanisms. These added features would probably have a stabilizing effect in that they would make tactical nuclear weapons less likely to be overrun by a conventional Warsaw Pact attack and less susceptible to accidental firing. Nevertheless, these features could easily be incorporated in the present generation of tactical nuclear weapons; the enhanced-radiation feature is not necessary for such purposes.

The enhanced-radiation warhead is a particularly dangerous weapon insofar as it might mislead anyone into believing that its deployment would make it possible for nuclear warfare to be safely limited and tightly controlled; in this sense its very deployment could lower the threshold separating conventional warfare from nuclear warfare. Enhanced-radiation weapons are no

more (and perhaps they are less) "humane" than chemical weapons, whose first use has long been outlawed by international treaty. Moreover, the enhanced-radiation warhead has little more military utility than any other type of low-yield nuclear weapon. Finally, to the extent that the U.S.S.R. believes the U.S. will use enhanced-radiation weapons in a European ground war, their deployment invites a preemptive Russian nuclear attack in any extremely tense situation, perhaps as the first move in a European war. In any event there is no reason to believe the enhanced-radiation warhead would in any way diminish the likelihood that a European-theater nuclear war would escalate to an all-out nuclear war, or that its introduction would somehow moderate the probable response of the U.S.S.R.



HYPOTHETICAL INVASION of Western Europe by the forces of the Warsaw Pact countries is depicted on this map. Irregularly shaped colored areas show the approximate deployment of NATO and Warsaw Pact forces on mobilization day (*see key for color coding of the deployment areas*). The forces would be redeployed between mobilization day and D day (the first day of the war). The arrows show what are considered to be the most likely major invasion routes. The three most likely axes of attack are along the main autobahns. An attempt by the NATO forces to stop the Russian armored divisions leading any one of these major attacks by resorting to enhanced-radiation nuclear weapons would require a barrage of hundreds of such warheads well within the borders of West Germany. Because of the growing urbanization of the region a counterattack of this kind could kill several hundred thousand, and conceivably several million, civilians and NATO combatants (not including the deaths that would be caused by probable Russian nuclear retaliation). Population distribution is indicated by keyed symbols.



NARROW STRAIT at the Bosporus provides the only present connection between the Black Sea and the Mediterranean. The Black Sea is at the top; the body of water at the bottom is the Sea of Marmara, which communicates with the Mediterranean through the Dardanelles, some 500 kilometers to the southwest. The Bosporus is some 30 kilometers long and for most of its length is one or two kilometers wide. It is also quite shallow. In earlier times, when the global sea level was lower, the Bosporus was a river draining a freshwater lake in the Black Sea basin. The dark region at the southern end of the Bosporus is the city of Istanbul. The picture was made from an altitude of 915 kilometers by the *Landsat 2* satellite. It is a false-color image in which the areas covered by vegetation appear bright red.

When the Black Sea Was Drained

Less than six million years ago rivers feeding the Black Sea were diverted into the dry basin of the Mediterranean. After a period of desiccation the Black Sea was until recently a freshwater lake

by Kenneth J. Hsü

Not even the largest and most prominent features of the earth's surface can be regarded as permanent. Because the rigid plates that make up the surface are in motion continents and oceans are constantly being reshaped and rearranged. Mountain building associated with the movement of the plates alters patterns of drainage and climate, and the plant life and animal life of a region necessarily respond in turn. Examples of such changes have been found in the historical record; others can be observed in progress today, and plate tectonics, the theory formulated to explain them, is now well established. Even so, it comes as a surprise to learn that a familiar feature of the globe, which has had the same form since the first maps were drawn, has been subject to sudden transformations.

An extraordinary episode of this kind was discovered in 1970. Sediment cores extracted from the floor of the Mediterranean Sea revealed that the entire Mediterranean dried up some six million years ago. For almost a million years the sea floor remained a desert basin two kilometers below the surrounding continental plateaus. Then the basin was flooded again by water from the Atlantic; the refilling took several centuries, and during that time the Strait of Gibraltar must have been the most spectacular of all waterfalls.

It has now been learned that the Black Sea has a history quite as eventful as that of the Mediterranean. The Black Sea was initially an arm of a great ocean, then a part of a large inland sea that covered much of eastern Europe. In a brief crisis it became almost dry, then after being refilled it became a deep freshwater lake. The brackish and largely stagnant sea that occupies the basin now has evolved only since the end of the ice age and is not a great deal older than the civilizations that grew up nearby in the Levant.

The Black Sea today is about 1,200 kilometers long and has a maximum depth of some 2,200 meters. It is the catchment basin for a major portion of the European continent, and it receives several important rivers, including the Danube, the Dniester, the Dnieper and the Don. It communicates with the Mediterranean through a narrow waterway made up of the Bosporus, the Sea of Marmara and the Dardanelles.

Both the Mediterranean and the Black seas are remnants of an ancient equatorial ocean that separated Africa from Europe and connected the Atlantic with the Indian Ocean. In 1900 Eduard Suess, a Viennese geologist, named this sea Tethys for the Titan of Greek mythology, daughter of Gaea and wife of Oceanus. Some 20 million years ago the northward movement of the African plate began to close off the Tethys Sea. The collision with Asia severed the eastern connection with the Indian Ocean. The collision with Europe gave rise to a long chain of mountains that includes the Alps, the Dinaric and Hellenic mountains of Yugoslavia, Albania and Greece, and the Taurus Mountains of southern Turkey. The result of this mountain building was to divide the Tethys into two inland seas. One was the ancestral Mediterranean, which occupied the same basin it does today. The other sea, to the north and east, has been called the Paratethys.

The Paratethys extended from the Hungarian basin in the west across southeastern Europe and the present Black Sea and Caspian Sea to beyond the Aral Sea in the Asian territory of the U.S.S.R. Communication between the Paratethys and the Mediterranean was cut off about 15 million years ago. After that the Paratethys became a brackish sea much like the Baltic of today. Maurice I. M. Gignoux, a French geologist, suggested in 1920 that it be named Lac Mer, or literally "Lake Sea," to emphasize that it was intermediate between a lake and an open ocean.

The only large bodies of water from Lac Mer that survive today are the Black Sea, the Caspian Sea and the Aral Sea. It is now apparent that the disintegration of the great inland waterway was closely associated with the sudden drying up of the Mediterranean. A detailed record of at least some events in this story has been read in the sediments deposited on the floor of the Black Sea.

The catastrophic desiccation of the Mediterranean was discovered by drilling hundreds of meters into the sedimentary rocks and oozes of the sea floor and extracting the sediments as cores. The drilling was done by the research vessel *Glomar Challenger,* which was built specially for deep-sea drilling. Erected over the deck of the ship is a large derrick, and there are facilities for storing and handling more than seven kilometers of drill pipe. Equally important, navigational aids and a special propulsion system maintain the ship's position precisely over the borehole even in stormy seas. Launched in 1968, the *Glomar Challenger* is operated by the Scripps Institution of Oceanography under the guidance of an international group of investigators, the Joint Oceanographic Institutions for Deep Earth Sampling committee (JOIDES).

Earlier seismic studies of the Mediterranean had revealed a layer of material some 100 meters below the sea floor that acts as a strong reflector of sound waves. The voyage of the *Glomar Challenger* in 1970, in which I participated, revealed the nature of this reflective layer. It is made up of carbonate and sulfate rocks, which are typically laid down in shallow water, and salts, which are deposited by the complete evaporation of brines. A possible explanation for the presence of such a layer was immediately obvious, but it was also extreme: the layer could have been formed if the Mediterranean was evaporated dry. After the voyage my colleagues and I were able to reconstruct how that might have happened [see "When the Mediterranean Dried Up," by Kenneth J. Hsü; SCIENTIFIC AMERICAN, December, 1972].

The Mediterranean has a large hydrographic deficit: more water evaporates from its surface than flows into it from the surrounding watershed. Its level is maintained only because a large volume of water flows in through the Strait of

Gibraltar. About six million years ago the continued northward movement of the African plate gave rise to mountain building on the Iberian Peninsula and in the northwest corner of Africa, creating an isthmus that sealed off the Mediterranean. Over the next 1,000 years or so the enormous volume of the Mediterranean—some four million cubic kilometers—evaporated away and salts and other residues were deposited in the desiccated basin. A little more than five million years ago the Atlantic broke through at Gibraltar and the basin again became a sea. The refilling of the basin is a datum that marks the division between two epochs of geologic time; the Miocene (less recent) and the Pliocene (more recent). These epochs were followed about 1.8 million years ago by the Pleistocene (most recent). The present epoch is the Holocene (wholly recent), which began some 10,000 years ago.

This interpretation of the Mediterranean's history was not accepted entirely without objection, and one item of seemingly contrary evidence was particularly bothersome. In a sample of late Miocene age from an eastern Mediterranean drill site we found fossils of small crustaceans belonging to the ostracod genus *Cyprideis*. The *Cyprideis* species were native to fresh water or brackish water and could not have survived in brines, much less on a desert plain. Evidently the isolated Mediterranean was not always dry; at times the sunken salt flats must have been covered by great lakes. Where did the fresh water to fill those lakes come from?

Certain species living in the Mediterranean and in nearby waters today had also presented a puzzle. In many submarine caves along the Adriatic coast of Yugoslavia, for example, there are inbred species that seem to represent "living fossils," relics of an ancient fauna that has not survived except in such isolated habitats. Other inbred populations are known in coastal regions of southern France, Spain and North Africa, and a particularly notable collection of relic species was discovered in 1891 in Lake Ohrid, a mountain lake on the border between Yugoslavia and Albania.

By definition the inbred populations are not related to those in the waters that surround them, but species in each of these pockets are related to species in other pockets. What is more remarkable, many of the species have relatives in the distant and completely isolated Caspian Sea. All these species have a common ancestry, which can be traced in the fossil record of the Paratethys rather than in that of the Mediterranean.

There were now several enigmatic observations to be accounted for, but this was one instance where the multiplication of mysteries gave as a product one simple hypothesis. The disintegration of Lac Mer, the presence of freshwater lakes in the Mediterranean basin and the dispersal of Paratethys species could all be explained if the Paratethys was drained into the Mediterranean sometime later in the Miocene. The hypothesis could most readily be tested by examining the sedimentary record from one of the surviving Paratethys basins.

In 1973 I served as chairman of an advisory panel set up by JOIDES to evaluate proposals to drill in the Black Sea. It was decided that the drilling might well clarify the relation between the Mediterranean and the Paratethys, and plans were made for another voyage of the *Glomar Challenger*.

Another reason for drilling in the Black Sea was to study the origin of petroleum. At depths below about 200 meters the water of the Black Sea is stagnant; it contains no oxygen and is rich in the toxic gas hydrogen sulfide, so that the deep bottom can support no life other than anaerobic bacteria. Under such conditions organic material tends to be preserved. It is thought petroleum is formed when such preserved organic sediments are buried and converted into hydrocarbons at elevated temperature and pressure.

Still another goal of the drilling project was to help clarify the existing record of climatic history during the ice age. Four stages of European glaciation are generally recognized; they are named Günz, Mindel, Riss and Würm after the places in southern Germany where characteristic formations were first described. There are also four recognized stages of glaciation in North America, named Kansan, Nebraskan, Illinoian and Wisconsin. The question of whether the two chronologies correspond has never been resolved, mainly because there is no continuous record of the entire ice age in any sedimentary se-

MODERN SEAS in southeastern Europe and southwestern Asia are remnants of an ancient equatorial sea, called Tethys, that connected the Atlantic with the Indian Ocean. The main surviving bodies of water are the Mediterranean, which still communicates with the Atlantic

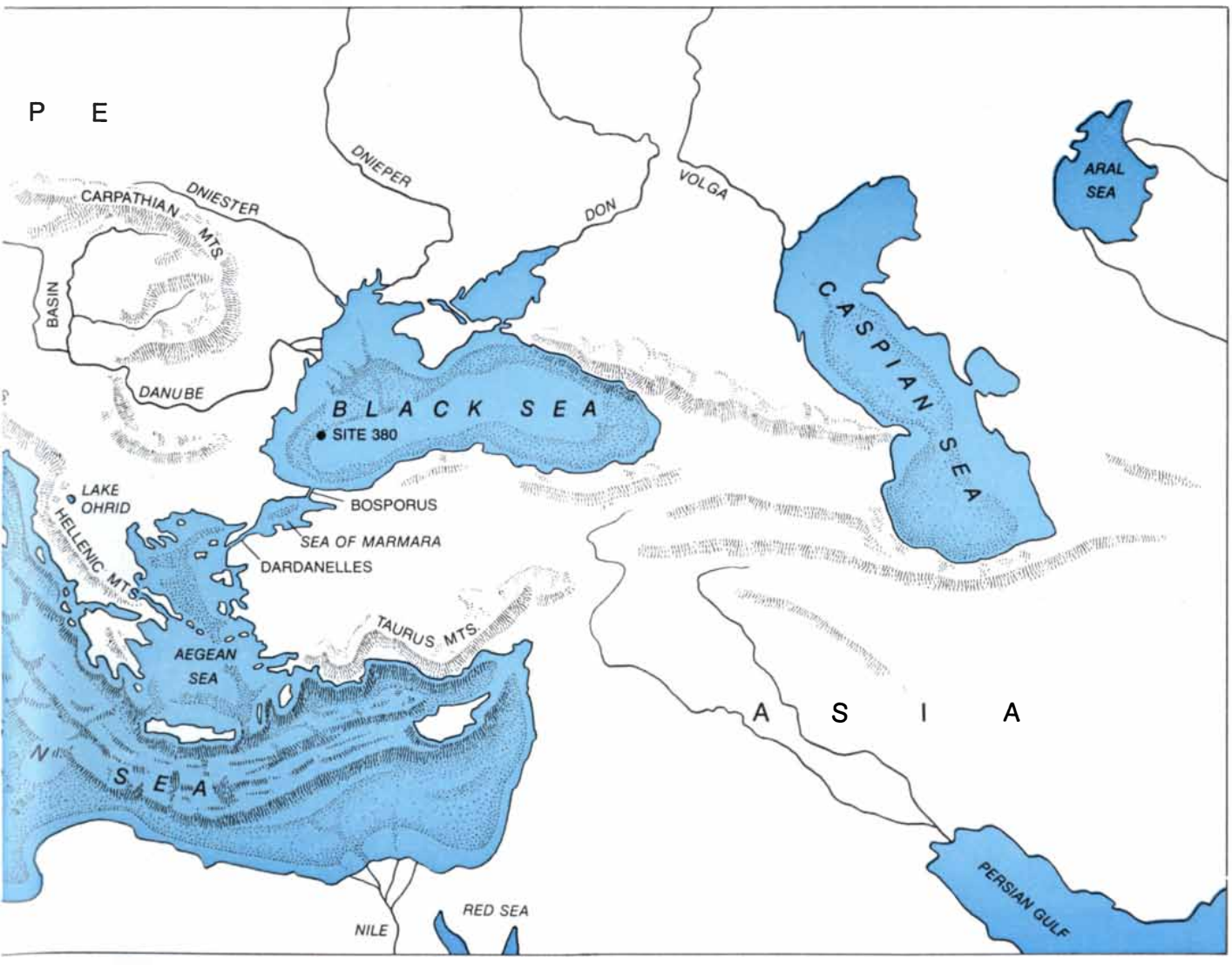
ries found on land. Marine sediments do provide a complete record, but their interpretation is ambiguous. Some geologists recognize four major glacial stages comparable to those on land, but other workers have detected a pattern of many glacial advances with an average period of 100,000 years or less. Even the onset of the ice age has not been precisely dated; it may coincide with the beginning of the Pleistocene some 1.8 million years ago, but it could also be much earlier or much later.

The *Glomar Challenger* entered the Bosporus on May 19, 1975, with a crew of 50 and a scientific staff of 20, headed by David A. Ross of the Woods Hole Oceanographic Institution and Yuri Neprochnov of the Moscow Institute of Oceanology. In a voyage of just three weeks holes were drilled at three sites. The deepest penetration was achieved at the base of the western continental slope off the coast of Bulgaria, at a location designated Site 380. There, in water 2,000 meters deep, the drill brought up cores 1,073 meters long.

From the first examination of the cores it became apparent that marine waters have not always flowed through the Bosporus. Indeed, even before the expedition began there had been hints that the Black Sea was not always brackish. In 1969 the Woods Hole Oceanographic Institution had obtained shallow sediment cores (about 10 meters long) from the Black Sea. Ross and Egon T. Degens of Woods Hole found evidence in these cores that the Black Sea was a freshwater lake during a 12,000-year period of the last ice age. They were able to explain the fresh-water episode as a consequence of a change in the worldwide sea level. The Bosporus is not only a narrow strait but also a quite shallow one, with a sill less than 35 meters below the present sea level. During the colder stages of the ice age, when much of the world's water was locked up in continental glaciers, the sea level was depressed by as much as 100 meters. During those periods the Bosporus was not a strait but a meandering river draining a freshwater lake in the Black Sea basin.

It had been assumed that the fresh-water episode discovered in 1969 was one of a few rare incidents attributable to unusual climatic conditions. The much deeper sediments brought up by the *Glomar Challenger* proved otherwise. It is the present, marine condition in the Black Sea that should probably be regarded as exceptional; during most of the period represented in the sediments fresh-water conditions prevailed.

One consequence of this discovery is that the Black Sea is a poor place

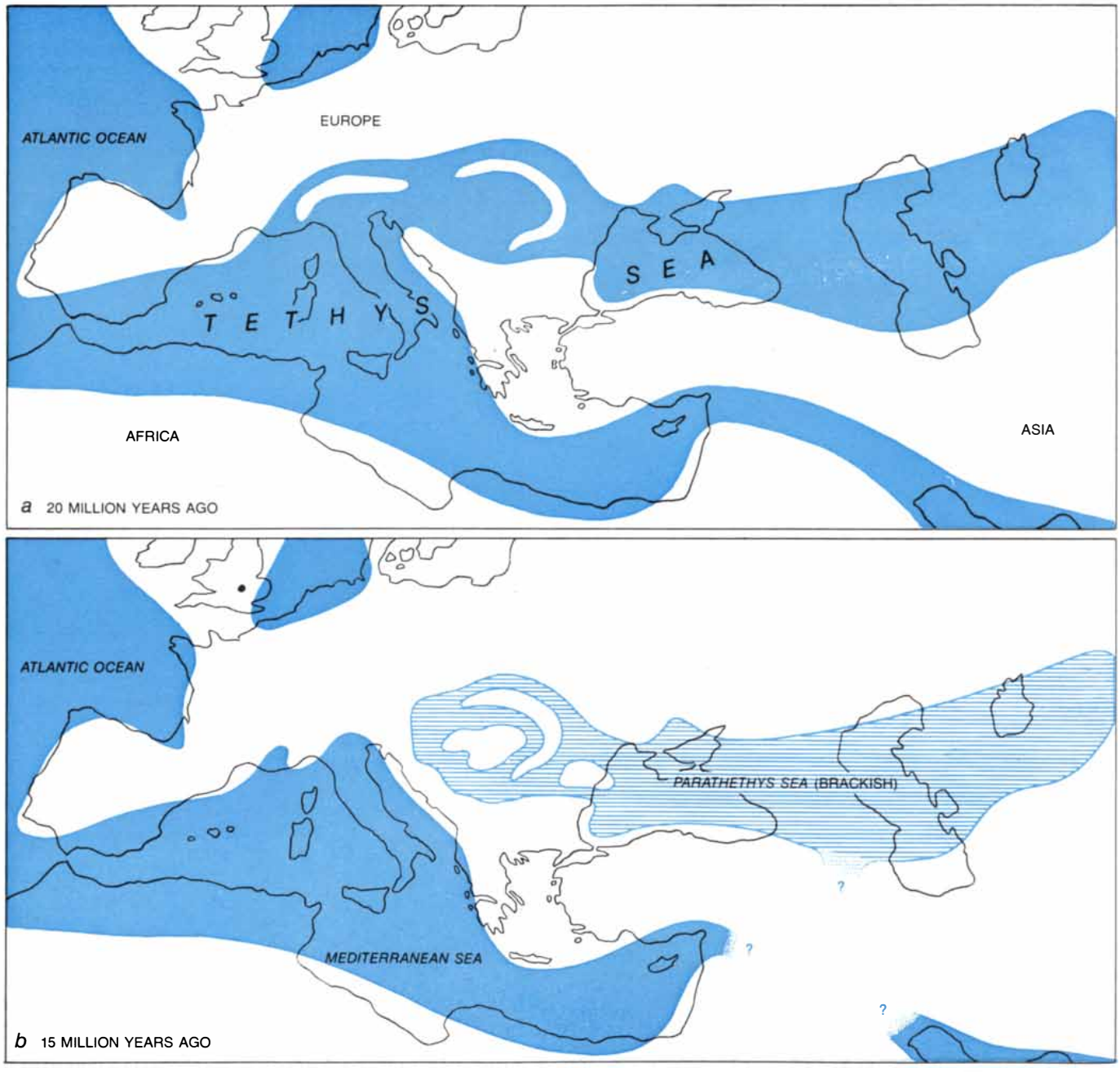


through the Strait of Gibraltar; the Black Sea, which has a tenuous connection with the Mediterranean through the Bosporus, and the Caspian and Aral seas, both of which are now isolated. The history of the seas has been investigated by drilling cores in the bottom sediments, most recently in the Black Sea. The longest Black Sea cores were extracted from Site 380, near the western continental slope.

for studying the genesis of petroleum. Except for one layer near the surface none of the sediments recovered were particularly rich in organic carbon. The anoxic condition that prevails today in the deeper waters of the Black Sea is largely a result of the interaction at the Bosporus between the brackish surface waters of the Black Sea and the more saline water of the Mediterranean. There is a system of stratified, opposed currents in the strait: the Black Sea water flows south at the surface as the Mediterranean water, which is about twice as salty, flows north along the bottom. The more saline water is denser and so it sinks into the basin, where it remains trapped by the density gradient and is isolated from the circulation pattern of the sea. Since the bottom water has no access to the surface, it can absorb no oxygen, and all higher forms of life are excluded from the abyssal plain.

This mechanism depends on a continuing influx of marine water, and it could not have operated when the Black Sea was a freshwater lake. Fossil evidence of bottom-dwelling animals found at several levels in the sediments indicates that the bottom waters were often aerated in earlier periods. Organic detritus reaching the bottom then would have been consumed by scavenging organisms. At other times the bottom was apparently lifeless, since finely laminated sediments were not disturbed by bottom-dwelling organisms, but even then little organic material was deposited.

The predominance of freshwater sedi-

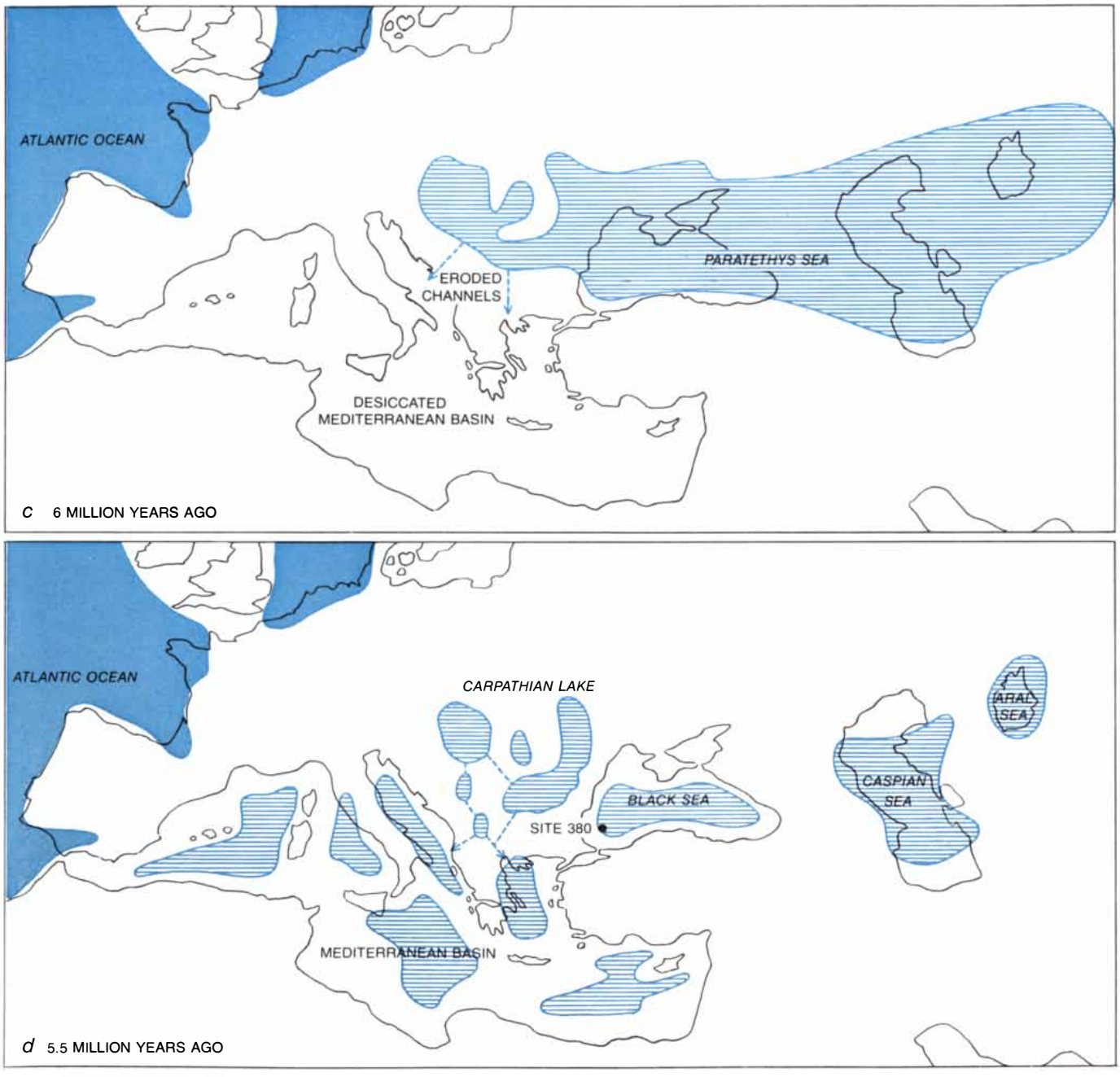


CLOSING OF THE TETHYS SEA was brought about by the collision of Africa with Europe and Asia. The approximate positions of the ancient waterways are shown here superposed on a map of the modern coastlines. Some 20 million years ago (*a*) the Tethys was still open to both the east and the west, although it was divided into two great arms. The southern arm was ancestral to the modern Mediterranean; the northern arm has been given the name Paratethys. Mountain building eventually isolated the Paratethys (*b*), which then became a brackish inland sea. About six million years ago the continued northward progress of the African continental plate gave rise to

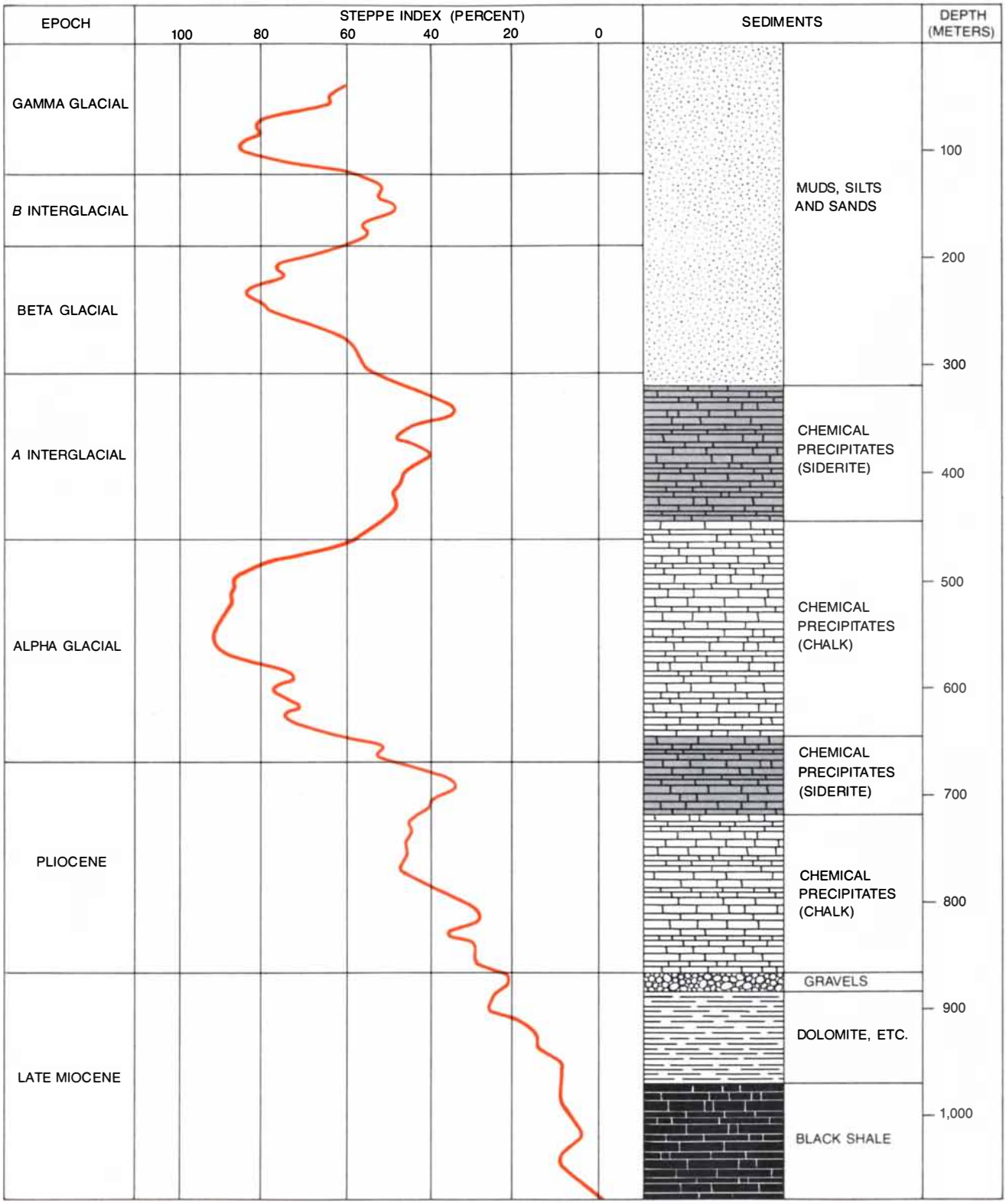
ments also raised a serious obstacle to the interpretation of the Black Sea's history. The standard method for dating sediment series is by looking for fossil species known to be characteristic of each interval of geologic time; indeed, the standard divisions of geologic time are defined mainly by the emergence or disappearance of certain species that are conspicuous in the fossil record. These landmark species were chosen for their wide geographic distribution and their limited temporal duration. Almost all of them are marine species, and so it was not immediately obvious how the Black Sea sediments, with their largely freshwater fossils, could be dated. Even the total duration of the sequence was not known; the kilometer-long cores might represent the accumulated sediments of 10 million years or of only two or three million.

The Black Sea sediments do contain fossils. They include free-floating diatoms and dinoflagellates, bottom-dwelling foraminifera, certain larger bottom-dwelling animals such as ostracods and mollusks, and the pollen and spores of land plants washed into the sea. Almost all the fossils belong to species that remained unchanged for long periods, and they are therefore of little use in dating the sediments. They do reveal a great deal, however, about changing conditions in the Black Sea, including the climate of the surrounding region.

In plants speciation and evolutionary change are generally rather slow processes, but the growth of plants is very



an extraordinary episode in the history of the Mediterranean (*c*). Mountain building severed the connection with the Atlantic and the entire sea evaporated, becoming a desert basin. The catastrophic drying up of the Mediterranean was ultimately to have an influence on the Paratethys as well. As the water level fell streams were rejuvenated and their headwaters were eroded, eventually breaching the divide between the basins. As a result the Paratethys drained into the Mediterranean and both seas were reduced to a network of lakes (*d*). Because drainage pattern was reorganized even deep basins of Paratethys, which could not be drained directly, lost water to evaporation.



SEDIMENTARY RECORD from the Black Sea was obtained in 1975 by the *Glomar Challenger,* a research vessel designed explicitly for drilling in the sea floor. The record shown is from Site 380, where cores totaling more than a kilometer were extracted. The deepest sediments are black shales, produced by the compaction of mud. Above this layer are sediments containing dolomite and gravel, both of which indicate a shallow-water environment. There then followed a long period of chemical sedimentation, in which calcium carbonate (chalk) and the iron carbonate siderite were alternately precipitated. At 332 meters below the surface the sediments become predominantly muds, silts and sands, which are still being deposited today. At first the sediment series could not be dated, but fossil pollen gave a correlation with climate. A "steppe index" developed by Alfred Traverse of Pennsylvania State University indicates the percent of the pollen derived from the steppelike vegetation characteristic of cooler climates. In the steppe index it is possible to recognize three periods of glaciation, which Traverse designated Alpha, Beta and Gamma. These cold episodes were preceded by a long period of semitropical conditions.

sensitive to climate. Fossilized plant material is therefore a good indicator of ancient temperature. Fossils from dozens of plant genera are found in the Black Sea sediments, mainly in the form of pollen grains, which are distinctive and readily identified. The plants represent a wide range of habitats, which can be grouped in two general categories. In some strata the pollen is mainly from shrubs that are characteristic of steppe vegetation, and in others it is from trees, such as pines, oaks and beeches, which indicates the presence of forests. Alfred Traverse of Pennsylvania State University, who accompanied the Black Sea expedition, developed a "steppe index" to express quantitatively the nature of the land flora. The index is simply the percent of the pollen found at a given level that comes from steppe vegetation. A value of 100 suggests that the Black Sea watershed was covered almost entirely by steppes, and a value of zero paints a landscape of mixed pine and deciduous forests.

Through most of the sedimentary record forests and steppe vegetation alternate. The pattern is easily interpreted in terms of climate. The forests predominated during warm interglacial periods; with the advance of continental glaciers they were replaced by steppes. The curve tracing the steppe index has many short-term fluctuations, but by applying an averaging procedure that smooths the curve Traverse was able to recognize three major stages of glaciation, which he designated Alpha, Beta and Gamma.

The climatic oscillations suggested by the pollen analysis do not continue into the earliest sediments drilled. In the cores from Site 380 pollen from steppe vegetation is rare or absent at depths greater than about 650 meters below the sea floor. In the lowest strata the pollen is derived mainly from semitropical plants. Therefore it would appear that the sedimentary record extends to before the onset of the ice age. Unfortunately the pollen samples give no information on the date of onset or on the dates of the three subsequent periods of glaciation. With the dates unknown the entire sediment series remained a tantalizing text that could not be read. It was two years before an international team of investigators decoded its message.

One dramatic feature of the Black Sea cores is an abrupt transition between two quite different types of sediments. For a long interval the material deposited on the bottom consisted mainly of chemical precipitates; then, at a time marked by a boundary 332 meters below the sea floor, the dominant sediment type changed to silts and muds, which are still being formed today.

The chemical sediments are carbonate minerals: calcite ($CaCO_3$), aragonite ($CaCO_3$), dolomite ($CaMg(CO_3)_2$) and siderite ($FeCO_3$). That a freshwater lake could have been saturated with carbonates is not surprising. Chalk made up almost entirely of calcite is now deposited every summer on the bottom of the Lake of Zurich. Rising temperatures drive carbon dioxide out of solution and that in turn decreases the solubility of the carbonate minerals, which are therefore precipitated. A lake in the Black Sea basin during the ice age would have had an environment similar to that of the Lake of Zurich today: glaciers were some distance away and the annual variation in temperature was large enough to alter the solubility of carbonates. The formation of carbonates other than calcite can be explained by changes in the chemistry of the lake water. The iron carbonate siderite, for example, was deposited mainly in warm, humid interludes, when meandering rivers carried much dissolved iron into the basin.

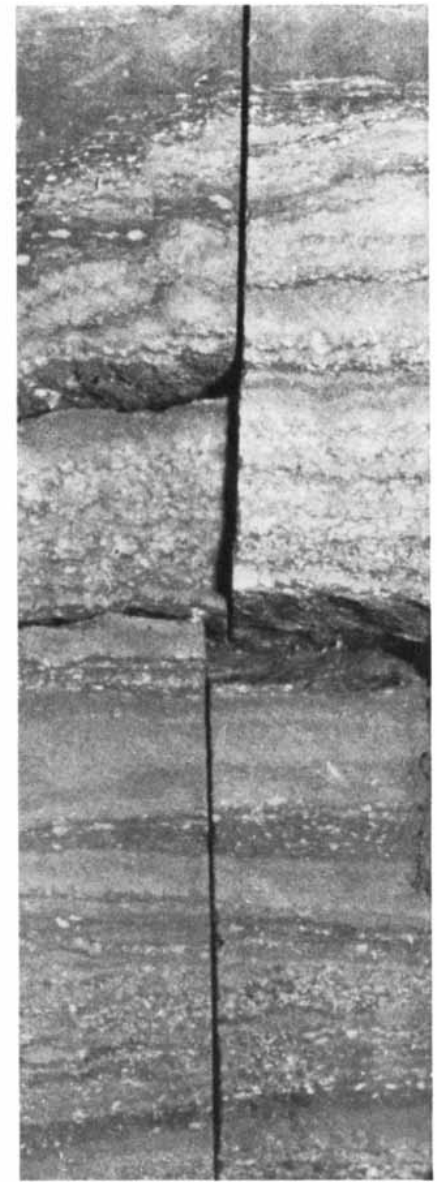
Pure minerals can be deposited in a lake only if clays, silts and other products of weathering in the surrounding landscape (collectively called clastics) are excluded. At the Lake of Zurich the clastics are trapped in other lakes upstream. The Black Sea, on the other hand, now receives a heavy burden of clastics, much of it contributed by the Danube. In earlier times some barrier must have prevented the Danube clastics from reaching the Black Sea basin.

The nature of that barrier became apparent in 1976, when Dan Jipa, a Romanian geologist, pointed out to me a thick section of clastics in the foothills of the eastern Carpathians. The material is now exposed at the surface, but it was deposited as sediment in a lake of Pliocene and Pleistocene age. During a subsequent tour of the Danube delta I was told that boreholes there reach bedrock under a thin cover of Pleistocene sediments. Apparently the Danube once passed through the Carpathian lake, where most of the suspended solids had time to settle out. At some time during the Pleistocene the lake became filled with silt and the Danube was forced to change course. Deprived of the "settling tank" upstream, the Black Sea was flooded with clastics and the period of chemical sedimentation came to an end.

The Carpathian sediment bed provided the first information on the age of the Black Sea sediments, although the date implied was very approximate. The top of the Carpathian series was estimated to be between .5 and 1.5 million years old. If the transition from chalk to mud at a depth of 332 meters corresponds to the change in the Danube's course, then that layer must have been laid down during the same interval.

A more precise dating of the Pleistocene Black Sea deposits was ultimately obtained by studying the remnant magnetism of the sedimentary rocks. A number of minerals, chiefly those containing iron, are weakly magnetic, and their fields tend to line up with the earth's magnetic field at the time they are deposited. The earth's field has occasionally reversed its polarity, and these events have been catalogued and dated from extensive studies of sedimentary rocks from the Atlantic and Pacific sea floors. If reversals of magnetic orientation could be found in the Black Sea cores, then they could be dated by reference to the chronology elsewhere.

Detecting the field reversals was not easy because many of the iron-containing minerals in the Black Sea sediments



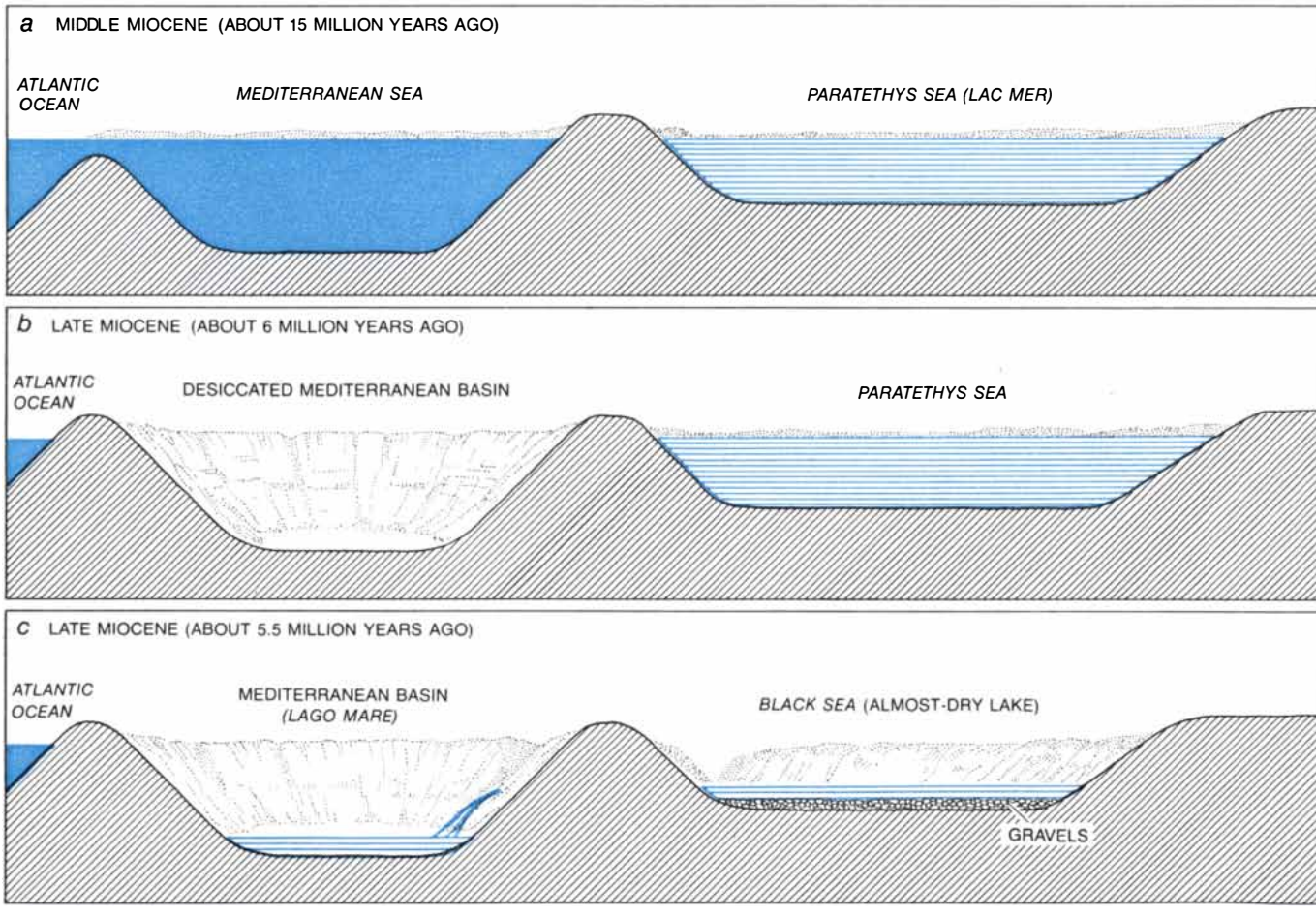
LAMINATED DOLOMITE from deep in a core extracted at Site 380 provides evidence that the Black Sea was once a shallow lake. The dolomite includes features called stromatolites, from the Greek for "flat stone." The stromatolites are derived from the growth of blue-green algae in thin mats. Since the algae are photosynthetic, they can grow only in shallow water, and they are found today mainly on tidal flats. The gravels above the stromatolites are also typical shallow-water deposits.

are not chemically stable; the magnetic orientation they exhibit today might reflect the direction of the earth's field not when the minerals were first deposited but at the time of some later chemical transformation. Nevertheless, my assistant Federico Giovanoli and I were able to recognize two reversals, which we believe correspond to the events designated Jaramillo and Olduvai in chronologies compiled elsewhere in the world. They represent two brief episodes, respectively one million and 1.7 million years ago, when the earth's field returned temporarily to normal polarity during a prolonged epoch in which the field was mainly reversed.

The discovery of the magnetic anomalies provided two fixed dates for the history of climatic variation revealed by the pollen studies. Our interpretation of the chronology suggests that continental glaciation began in the regions surrounding the Black Sea at or near the beginning of the Pleistocene some 1.8 million years ago. The data also suggest that there were three major stages of glaciation, together with a great many short periods of cold weather. The correlation of the Black Sea stages labeled Alpha, Beta and Gamma with those known from other regions is not certain. Almost no correlation can be perceived with the classical European ice ages. The three major stages and the numerous short episodes of cold climate do, however, seem to run parallel to the climatic variations recorded in the marine sediments of the Atlantic. For example, there is fairly good correlation with a climatic record reconstructed by M. Briskin and William A. Berggren of the Woods Hole Oceanographic Institution from fossils in sediments from the Atlantic. The interpretation of the magnetic reversals also supplied a date for the boundary at 332 meters where the Danube detritus first reached the Black Sea: the change in the Danube's course appears to have taken place some 600,000 years ago.

The studies of fossil pollen and remnant magnetism ultimately yielded a chronology for the Black Sea throughout the Pleistocene, or in other words for roughly the past two million years. A first glimpse into the more remote past was obtained by Musat Gheorghian of the Romanian Academy of Sciences, who found in the oldest samples from the Black Sea cores a fossil fauna typical of the Paratethys. The fossils were of several inbred species of bottom-dwelling foraminifera native to a brackish sea, and their evolutionary development suggested that the oldest sediments recovered from Site 380 were between eight and 10 million years old. The paleobotanical evidence supported this conclusion: in the same oldest layers Traverse had found abundant pollen characteristic of plant life from a warm, upland habitat; the plants in question disappeared in Europe some six to eight million years ago, when the climate began to cool appreciably. If this dating of the sediments is correct, then the record should extend through the late Miocene interval, some five to six million years ago, when the Mediterranean dried up. What happened to the Black Sea when its neighbor was reduced to a desert?

Before the 1975 expedition of the *Glo-*



RELATED HISTORIES of the Mediterranean and the Black Sea are presented schematically in a cross section of the Mediterranean and the Black Sea basins. When the two seas were separated by the rise of various Alpine mountain ranges (*a*), the Paratethys received ample runoff from the central European plains, so that it remained filled. Its salinity, however, declined. During the subsequent desiccation of the Mediterranean (*b*) the Paratethys retained its character until the reorganization of the European drainage system diverted much of its water to the Mediterranean. It was during this era (*c*) that shallow-water sediments such as gravels were deposited. When the Strait of Gibraltar was cut open, refilling the Mediterranean, the Black Sea (and possibly other parts of the Paratethys) briefly resumed a marine

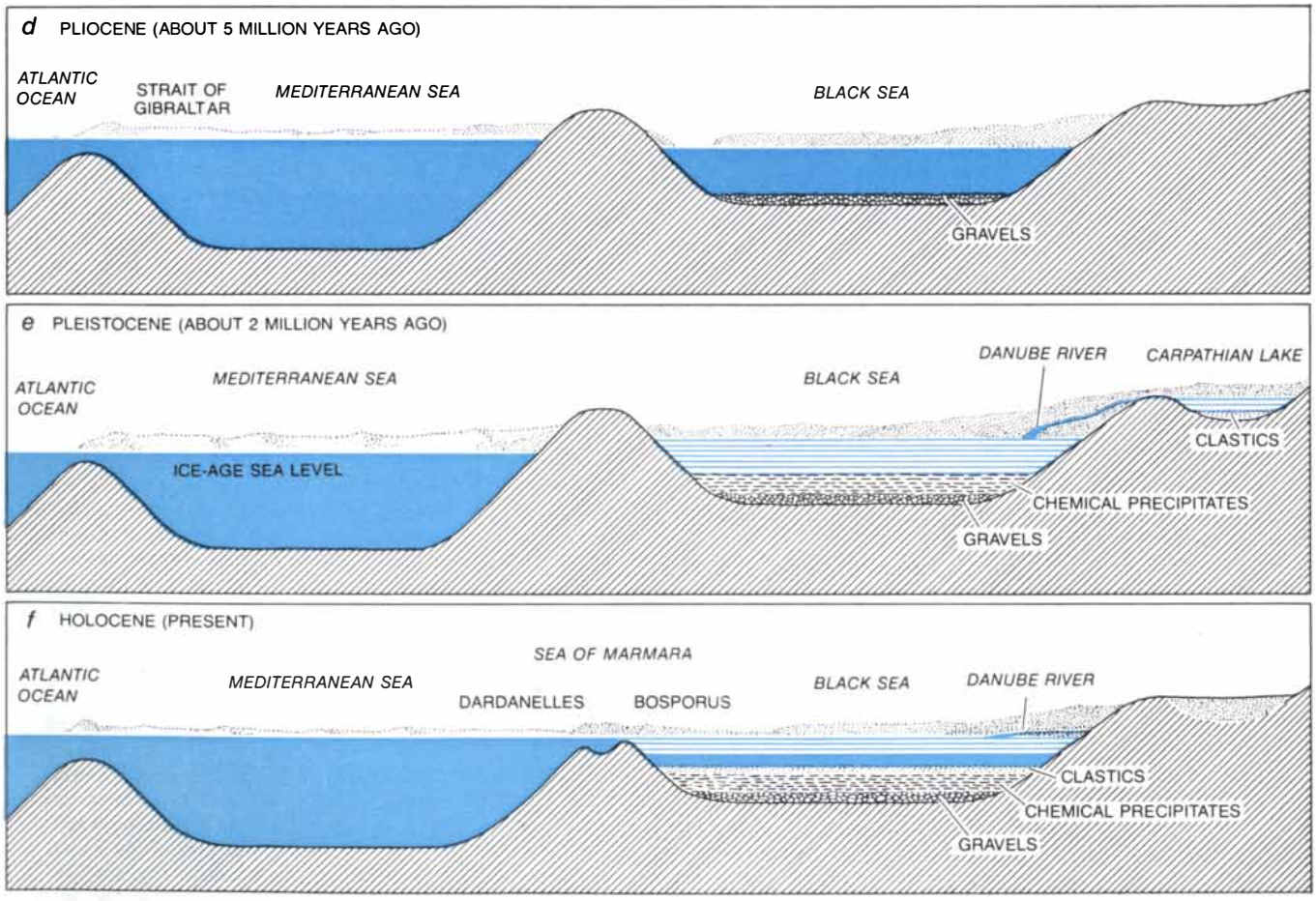
mar Challenger a French oceanographic cruise in the Black Sea had identified a strong acoustic reflecting layer 1,000 meters or more below the sea floor. Deeply buried structures that resembled salt formations were also found. It was the discovery of such a reflecting layer, of course, that had provided the first clue to the desiccation of the Mediterranean. The *Glomar Challenger* did drill through a reflecting layer, but it is still not certain that this reflector is the one the French expedition identified. In any case no salt was encountered in the sediments; the reflecting layer that was penetrated, 865 meters below the sea floor at Site 380, was found to consist of cemented gravels.

Gravel is a deposit of shallow water. It is occasionally transported from a coastal zone to a deep-sea plain by submarine turbidity currents, but the Black Sea gravels showed none of the features that result from such transport. It therefore began to appear that when the gravels were laid down the Black Sea was a shallow lake within a deep basin.

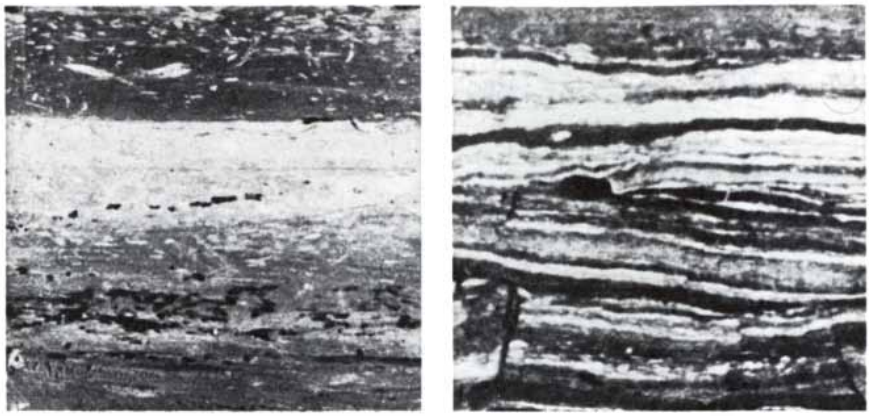
Examination of the fossils incorporated in the cemented gravels and in adjacent layers soon provided support for this hypothesis. Peter Stoffers of the University of Heidelberg found dolomite between the gravel layers. The dolomite included features called stromatolites, which are formed by the growth of blue-green algae in flat mats, giving the stone a characteristic laminated structure. Similar algal mats grow in coastal regions today; because the algae require sunlight for photosynthesis they can grow only in shallow water. Stoffers also found oolite, a sandy deposit that typically is formed in tidal channels near coastlines. Hans Schrader of the University of Kiel identified in sediments from just below the gravels a species of diatom that is known to have a shallow-water habitat.

Having shared the responsibilities of chief scientist on two drilling expeditions in the Mediterranean, I was enthusiastic about the prospect of demonstrating a late Miocene episode of desiccation in the Black Sea. Important evidence needed to be established, however. First, none of the fossils from the gravels and the associated sediments could readily be dated. What was even more troubling, there was little reason to believe the Black Sea could have dried up. Unlike the Mediterranean, the Black Sea today has no hydrographic deficit: the influx of several major rivers more than compensates for losses by evaporation. In addition, the Black Sea was one of the deeper basins of the Paratethys. If it lost most of its water, the entire sea must have gone dry. Could any evidence be found for such a general and widespread desiccation?

In 1976, while I was traveling in Eastern Europe as an exchange scholar, a coherent model began to emerge. Sediments from regions of the Paratethys basin that were not always submerged include layers of volcanic ash that can be dated by measuring the extent to which radioactive isotopes have decayed since the material was molten. By this method it was established that salt beds found in some parts of the Paratethys basin are more than 15 million years old, much older than

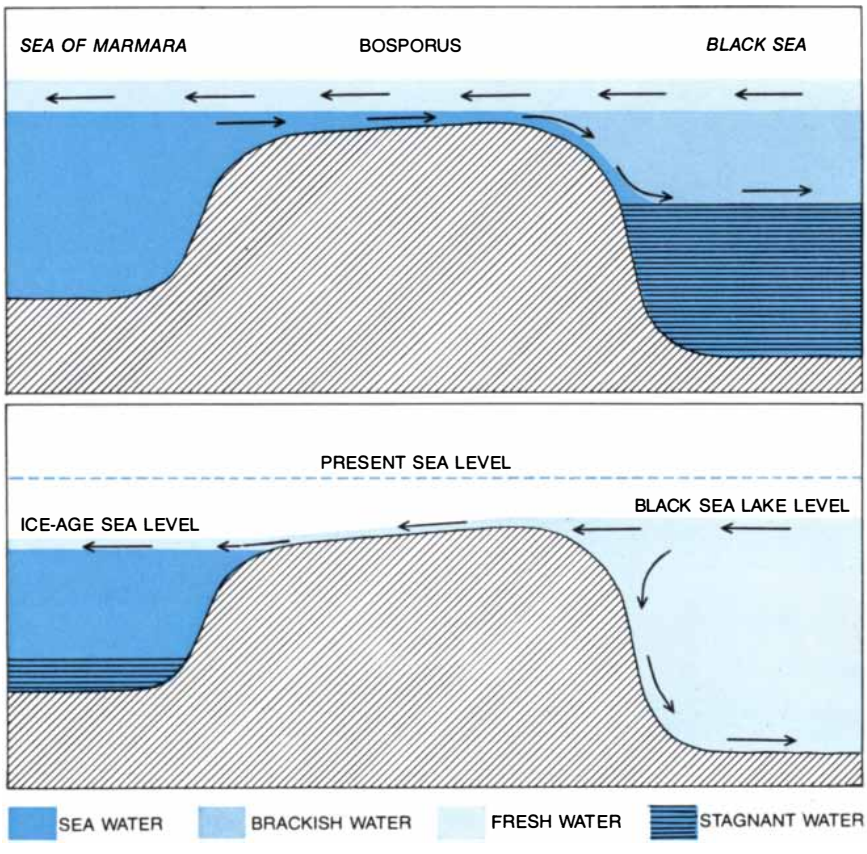


environment (*d*). The connection with the Mediterranean was soon severed again, however, and the Black Sea began a long interval as a freshwater lake (*e*). Silt and other products of weathering that are collectively called clastics were dammed up in a lake in the eastern Carpathians, so that carbonate minerals could be precipitated in the Black Sea. About 600,000 years ago the lake in the Carpathians silted up and the clastics, carried mainly by the Danube, began to reach the Black Sea. At that time the era of mud and silt deposits began, an event that is marked in the sedimentary record by the horizon at a depth of 332 meters. Then about 10,000 years ago the Bosporus was cut open and marine waters again entered the Black Sea (*f*), giving rise to an anoxic stratum of stagnant brackish water below surface.



CHALK DEPOSITS from Site 380 bear evidence of alternating periods when the deep waters of the Black Sea were fresh and inhabited, and other periods when they were brackish and virtually lifeless. The irregular dark markings in the sediments at the left are the trails of small bottom-dwelling worms. The sediments at the right consist of fine, alternating layers of chalk and clastics carried into the sea by rivers. If there had been any bottom-dwelling animals at the time these sediments were deposited, the finely laminated structure would have been disturbed.

the salt beds of the Mediterranean. In the late Miocene epoch no salt was deposited in what are now the Balkan countries, and so it does not appear that the Paratethys was evaporated dry. On the other hand, R. Jiříček of the Czechoslovakian Academy of Sciences was able to show that the Paratethys of the Balkans did undergo a crisis when the Mediterranean dried up. At that time the brackish Lac Mer disintegrated, leaving only scattered freshwater lakes. Since no salt was deposited, the lake basins could not have been evaporated dry; the only plausible alternative is that much of the water of the Paratethys went down a drain.



CURRENTS IN THE BOSPORUS have had a major influence on the environment within the Black Sea. Today (*top*) the sill of the Bosporus is about 35 meters below sea level and there is a system of stratified countercurrents. Comparatively fresh water from the Black Sea flows out along the surface as saltier marine water enters at the bottom. Because the saline water is denser it sinks and becomes stagnant. During periods of glaciation the global sea level was as much as 100 meters below its present level. In those glacial periods (*bottom*) the Bosporus was not a strait but a river, and the freshwater lake in the Black Sea basin was aerated at all depths.

Jiříček's report provided the information needed to reconstruct the closely entangled histories of the Mediterranean and the Black Sea. In the late Miocene the Mediterranean was a salt plain at the bottom of a deep depression, like an enormous Death Valley. Then it was flooded by brackish water, creating a series of lakes on the floor of the basin. The lake system has been given the name Lago Mare, the Italian equivalent of Lac Mer. In the lakes brackish-water animals flourished. They included the ostracods of the genus *Cyprideis,* whose fossils, found above the salt deposits but below the marine sediments laid down after the opening of Gibraltar, had created such a puzzle during the Mediterranean exploration.

The water needed to fill Lago Mare came from the Paratethys, which was thereby partially drained. With the drying up of the Mediterranean, rejuvenated streams had cut deep canyons into the continental slope; although the slopes are now again submerged, some of those canyons can still be seen in sea-floor profiles. At the same time erosion of the headwaters lengthened the rivers, with the effect that the watershed between the Mediterranean basin and the Paratethys basin was pushed northward. Finally the divide was breached and Lac Mer was emptied, probably by way of deep ravines that ran through Hungary and Yugoslavia to the Adriatic.

With the formation of Lago Mare the drainage system of Europe was reorganized. Whereas the Paratethys had been receiving much of the runoff from the humid regions of central Europe, that water was now pirated by the Mediterranean basin. As a result the Black Sea no longer received enough water to compensate for evaporation. Since salt deposits were not found in the cores, it cannot be determined with certainty whether the Black Sea was ever completely dry, but there is no doubt that for a time it was a shallow brine lake. Gravel and fossils of shallow-water species were deposited; moreover, Frank T. Manheim of Southern Florida State University has determined by studying the water in pores of the sediments that the shallow lake was at least three times as salty as normal seawater.

The draining of the Paratethys would have carried animal species typical of that sea into the Mediterranean basin. Those animals may well have been the ancestors of the inbred and isolated species now found in the caves of the Yugoslavian coast and in coastal regions elsewhere in the Mediterranean. In the Miocene epoch they occupied the Lago Mare system of lakes; when the Strait of Gibraltar was cut open, a marine fauna invaded and most of the resident species were exterminated. Only those that re-

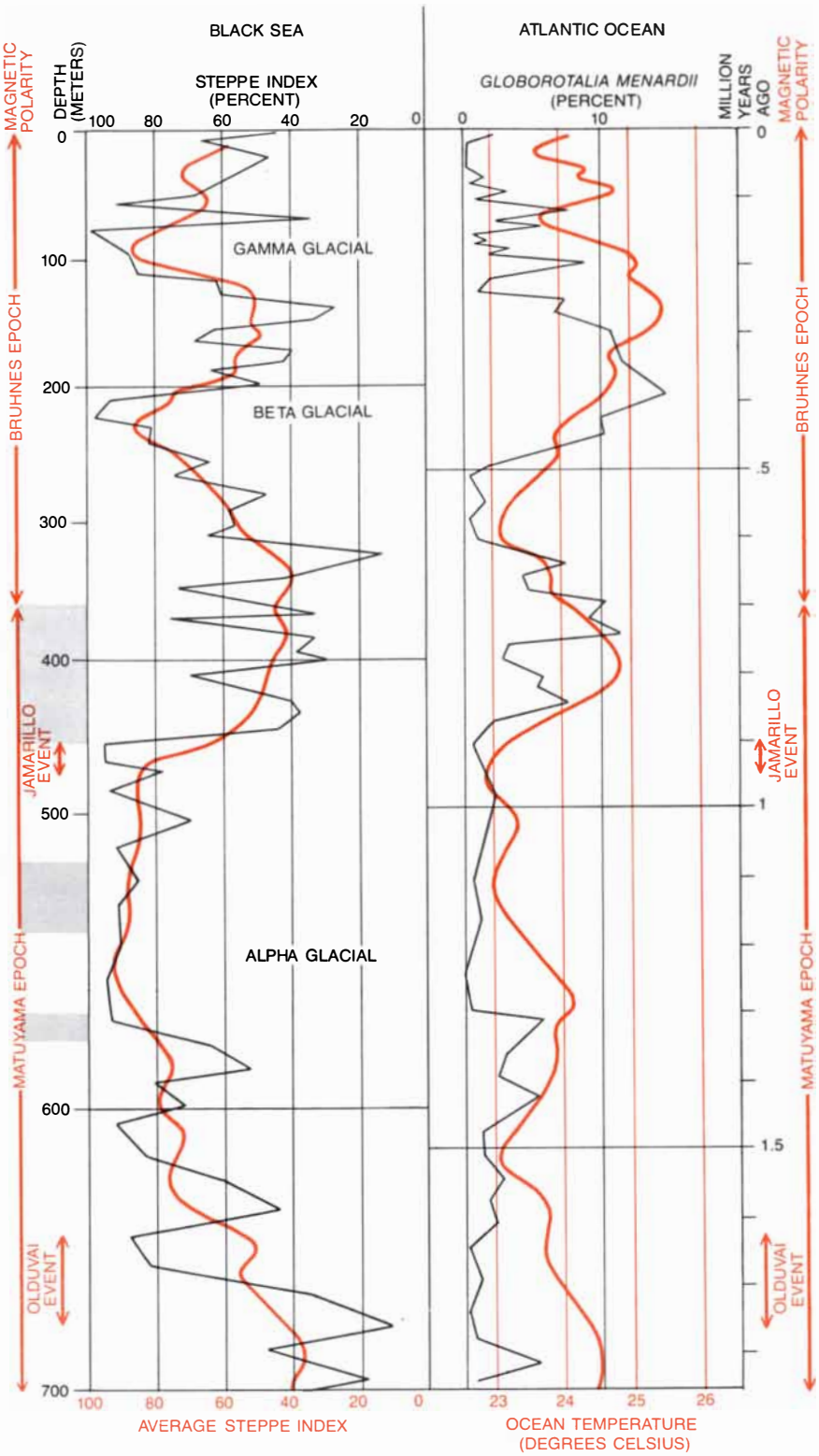
treated to isolated freshwater habitats survived. The "living fossils" of Lake Ohrid on the border between Yugoslavia and Albania may have a similar origin; the lake is probably a remnant of an ancient channel connecting the Paratethys with the Mediterranean, and the species could have been stranded there when the channel was closed off.

The evidence needed to confirm this hypothesis was some direct indication that the Black Sea gravels were deposited during the period when the Mediterranean was desiccated. It was obtained in late 1976, when Schrader discovered a diatom flora in sediments a little below the gravels that could be dated to the late Miocene.

Lago Mare was short-lived; it was inundated when seawater entered the Mediterranean at the end of the Miocene or at the beginning of the Pliocene, some 5.2 million years ago. In the Black Sea brackish or marine muds directly above the gravel beds indicate that the marine influence extended briefly to at least parts of the Paratethys basin. The seawater may have entered through the same channels that had earlier drained the Paratethys into the Mediterranean basin, although there are other possibilities. Whatever the route, the weak connection with the Mediterranean was soon broken, the drainage system was again reorganized and the Black Sea began once again to receive more water than was needed to balance evaporative loss. The Black Sea basin was refilled, but the Paratethys as a whole never recovered, and much of the area that was once the floor of that ancient sea is now intensively farmed agricultural land.

With an excess input of fresh water the Black Sea gradually lost its salinity, and for most of the next five million years it was a freshwater lake. At the beginning of the Pleistocene 1.8 million years ago the global climate turned significantly cooler, and glaciers formed in eastern Europe. This was the epoch dominated by chemical sedimentation, with the clastics carried by the Danube dammed up in a lake in the eastern Carpathians. A little more than half a million years ago the lake silted up, the Danube took its present course and muds became the dominant Black Sea sediments.

Only in recent times did the sea assume its present characteristics, as erosion gradually cut open the Bosporus. During warm interludes, when the global sea level was unusually high, marine water spilled through the Bosporus to make the Black Sea brackish, but each time the glaciers returned, fresh water was restored. Finally, at the beginning of the Holocene epoch some 10,000 years ago, the oceans rose to their present level and salt water again entered the Bosporus. The lifeless abyss of the modern Black Sea was created.



CHRONOLOGY of the Black Sea sediments was eventually constructed by identifying reversals in the magnetic orientation of rocks from the cores. The magnetic anomalies were caused by reversals in the polarity of the earth's magnetic field, which can also be detected in other sedimentary rocks, including some that are reliably dated. During the Jamarillo and Olduvai events and the Bruhnes epoch the field had the same orientation it has now; during the Matuyama epoch it was reversed. In some sediment levels (*gray*) the field direction is not stably indicated. With at least two dates fixed by magnetic anomalies it is possible to compare the Black Sea climatic record, represented by the steppe index, with other indicators of ancient climate. One of these indicators is the percent of the foraminifer assemblage *Globorotalia menardii* in marine sediments, which is correlated with the mean ocean temperature. Individual measurements of both indicators are shown in black and smoothed curves in color. The colored curve at the right gives estimated temperatures based on several fossil species in addition to *G. menardii*. In many periods the two temperature curves coincide, although the first glacial advance in the steppe index (designated Alpha) is split into two shorter periods in the Atlantic record.

The Cosmic Background Radiation and the New Aether Drift

Sensitive instruments have found slight departures from uniformity in the radiation left by the primordial "big bang." The experiment reveals the earth's motion with respect to the universe as a whole

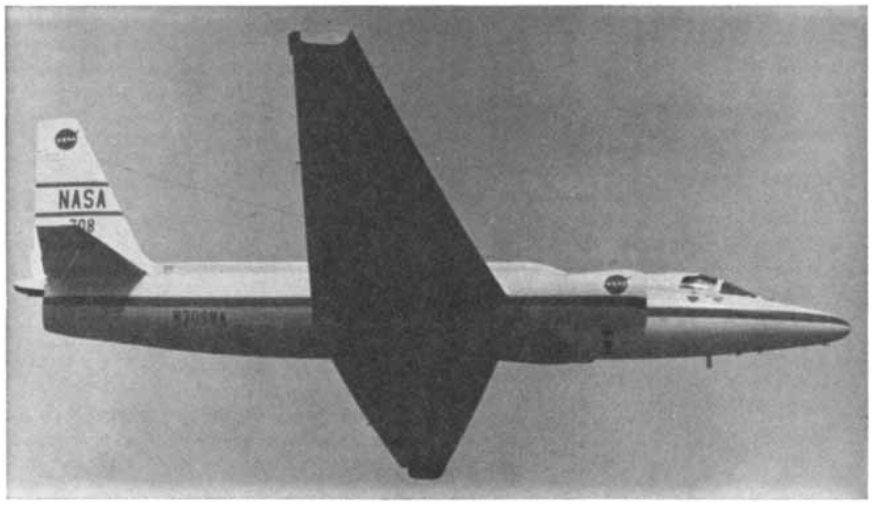
by Richard A. Muller

A curious radiation that bathes the earth almost uniformly from every direction has turned out to be a unique source of information about the nature and history of the universe. The faint radiation was identified 13 years ago during a search for noise sources capable of interfering with satellite communications systems. The "noise" proved to be of cosmic origin and soon became known as the three-degree cosmic black-body radiation because it has the spectral characteristics of a black body, or perfect emitter of radiation, whose temperature is about three degrees Kelvin (three degrees Celsius above absolute zero). Most astrophysicists now believe this microwave radiation was emitted shortly after the "big bang," the cataclysmic explosion in which the universe was created some 15 billion years ago. Not only is it the most ancient signal ever detected; it is also the most distant, coming from well beyond the quasars, the most remote luminous sources known. The three-degree radiation is a background in front of which all astrophysical objects lie.

The observation of the cosmic background radiation is the closest we have come to a direct study of the primordial explosion itself. The very existence of the radiation is the strongest evidence in favor of the big-bang theory. The isotropy of the radiation, that is, the uniformity of the radiation from different directions in space, tells us that the big bang, although it was unimaginably violent, also went quite smoothly. The slight departure from isotropy that has recently been discovered indicates that our galaxy is hurtling through the universe with the surprisingly high velocity of 600 kilometers per second. It is this cosmological velocity that has been called "the new aether drift," in reference to the "aether drift" that A. A. Michelson and E. W. Morley sought unsuccessfully to discover nearly a century ago by measuring the velocity of light over paths rotated at different angles with respect to the earth's motion in space. The three-degree cosmic background radiation provides an all-pervasive radiation "aether" for performing an analogous experiment.

The cosmic background radiation was discovered in 1965 by Arno A. Penzias and Robert W. Wilson of Bell Laboratories; its significance was immediately recognized by Robert H. Dicke and his group at Princeton University. Since then much has been learned about the spectrum of the radiation. Its intensity has now been studied at wavelengths ranging from 30 centimeters down to half a millimeter, confirming the initial conjecture that its spectral curve conforms to that of a black body at a temperature of three degrees K.

One of the most important observations reported by Penzias and Wilson was the constancy of the temperature of the radiation from different directions in space. Their measurements indicated that the temperature varies by less than 10 percent in any direction. Subsequent experiments set even lower limits on the departure from isotropy. Two independent groups have recently carried out measurements sensitive enough to show, however, that the temperature of the radiation is not precisely the same in all directions. One set of experiments was performed at Princeton by David T. Wilkinson and Brian E. Corey, the other set at the Lawrence Berkeley Laboratory of the University of California by a group that included George F. Smoot, Marc V. Gorenstein and me. It is now known that the temperature of the three-degree back-



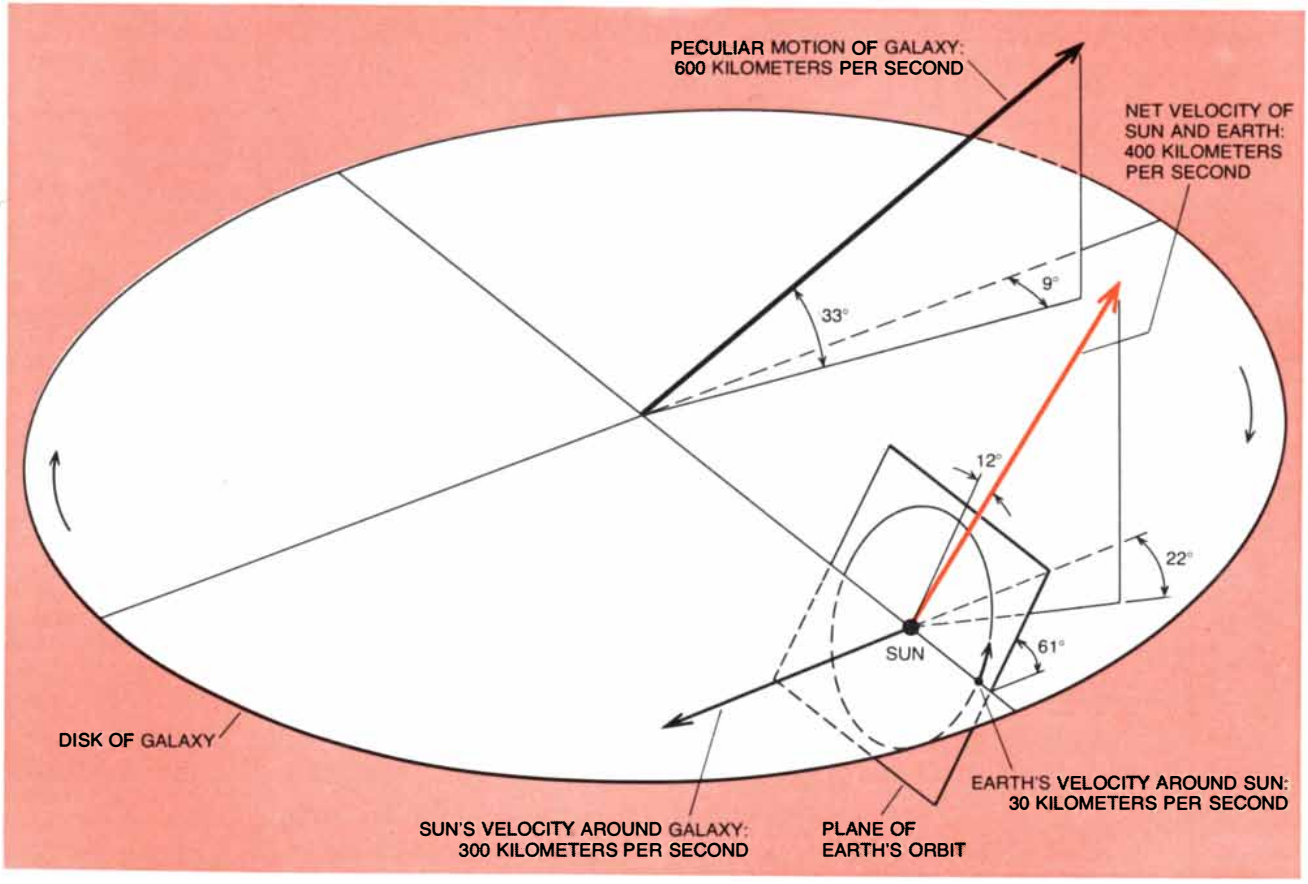
INSTRUMENT PLATFORM in the new aether-drift experiment was a U-2 aircraft operated by the National Aeronautics and Space Administration. Like the original aether-drift experiment performed nearly a century ago by A. A. Michelson and E. W. Morley, the new experiment was designed to measure the earth's motion with respect to a universal frame of reference, in this case the cosmic background radiation. That radiation, which is equivalent to the radiation emitted by a black body (a perfect radiator) with a temperature of about three degrees Kelvin (three degrees Celsius above absolute zero), is radiation left over from the fireball in which universe was created 15 billion years ago. U-2 has made 10 flights carrying an ultrasensitive microwave receiver designed by the author, George F. Smoot and Marc V. Gorenstein.

ground radiation varies by about a tenth of a percent across the sky, with the hottest region being in the direction of the constellation Leo and the coolest in the direction of Aquarius. The temperature varies smoothly between these two regions, following a simple cosine curve. This distinctive pattern ("the great cosine in the sky") leads us to identify the velocity of the solar system as the cause of the anisotropy. In order to explain how this conclusion has been drawn and what its significance is it is necessary to review the big-bang theory, the origin of the cosmic background radiation and just what it is that has been learned from the existence of the anisotropy.

The big bang was not simply an explosion of a clump of matter into an otherwise vast and empty space. Although such a picture would account for Hubble's law (the observation that distant galaxies are receding from us at a velocity proportional to their distance), it seems incapable of accounting for the uniformity with which matter and radiation fill space. The known universe appears to be so uniformly populated that astronomers accept the "cosmological principle": the belief that the universe is essentially the same everywhere. In addition, the idea of an exploding clump of matter sitting somewhere in space offers no natural way to account for the existence of the cosmic background radiation. Any radiation emitted at the time of the explosion would have left the vicinity of the original mass even faster than the matter would have left it, and the radiation would no longer be around to be observed.

In the big-bang theory there is no primordial clump of matter and no center to the explosion. Space is uniformly occupied; there is no outer edge to the distribution of matter. The big bang was not an explosion of matter within space but an explosion of space itself. According to Einstein's general theory of relativity, the "amount" of space between objects is not fixed, even if the objects retain their respective coordinate positions. In the calculations done in the big-bang theory the galaxies are usually assumed to be at rest as the amount of space between them increases. Any motion that leads to a change in a galaxy's coordinate position in this theory is referred to as a peculiar velocity, not because it is strange but because it is peculiar to the individual galaxy and is not part of an overall cosmic motion.

The rate of the expansion of space is reduced by the presence of matter and energy. If the average mass density of the universe is less than a critical value (about 10^{-29} gram per cubic centimeter), the expansion will go on forever. If the average mass density is more than the critical value, the expansion will slow to a stop and turn into an implosion. The mass density also determines the large-scale geometry of the universe. If the mass density is greater than the critical value, the volume of the universe is finite; otherwise the volume is infinite. So far the mass density of the universe has not been established accurately enough to say for sure whether the universe is finite or infinite. Fortunately for most of the calculations of the big-bang theory the issue is not critical. We shall assume that the average mass



ABSOLUTE MOTION OF THE EARTH through space has been determined by measuring slight differences in the temperature of the three-degree cosmic background radiation reaching the earth from various directions. The earth travels in its orbit around the sun at 30 kilometers per second and, as the sun's gravitational captive, is being swept around the center of the galaxy at 300 kilometers per second. The new aether-drift experiment shows that the earth's net motion in space is about 400 kilometers per second. The vector of the earth's net motion lies in the same plane as its orbit around the sun and at an angle tilted sharply upward (northward) from the plane of the galaxy. In this diagram the vector of the earth's net motion is depicted as a colored arrow centered on the sun, since the two bodies travel together. Both are being carried along by the galaxy's own "peculiar" motion through space (the motion peculiar to the galaxy and not a part of the overall cosmic motion). In order to account for the earth's motion with respect to the three-degree radiation the galaxy must be traveling at about 600 kilometers per second, or more than 1.3 million miles per hour, in the direction shown by the heavy black arrow.

density is equal to the critical value, which has the added advantage of implying that the average curvature of space is zero. Therefore we can work with the familiar Euclidean geometry.

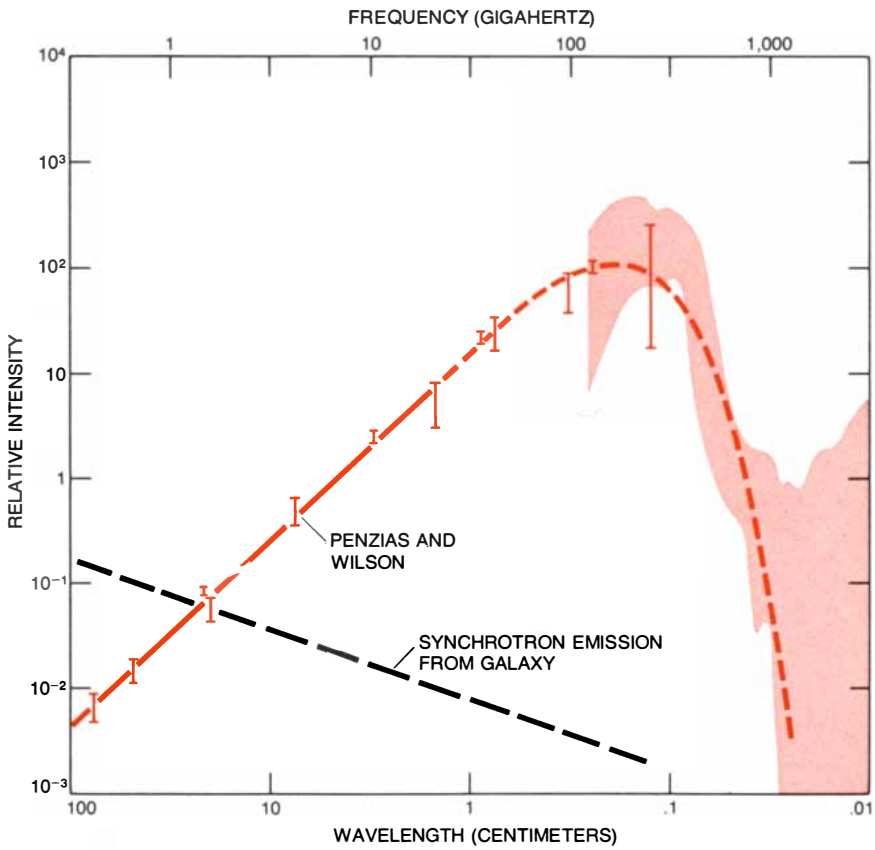
The concept that the distance between two objects can change without the objects themselves moving seems strange because it is completely foreign to our everyday experience. It is hardly stranger, however, than the curvature of space itself. Fairy tales and much science fiction describe events in which space is flexible. What distinguishes the general theory of relativity from mere flights of fancy are specific equations that relate the geometry and volume of space to its previous history and to its mass-energy content.

Hubble's law fits naturally into the big-bang theory. The relation follows from two facts: not only is space uniformly occupied by matter but also space is being created at a uniform rate. Thus the greater the distance separating two galaxies, the greater the amount of space created between them. Hubble's observation that all galaxies are moving away from our own does not mean that our galaxy is at the center of the universe; a similar observation would be made from every other galaxy.

The uniform expansion of space applies only to distances on an intergalactic scale. It does not hold, for example, in the vicinity of massive objects such as the sun, where the geometry of space can be quite different. It also does not hold at the distances between the atoms in a molecule or the electrons in an atom. Such distances are determined by electromagnetic forces rather than gravitational ones. Even if the expansion of space tended to move the constituents of atoms and molecules apart, their internal electric fields would draw the constituents back. If this were not the case, human observers and their meter sticks would grow at the same rate as the universe, making the expansion of space unobservable.

The great initial success of the big-bang model came when George Gamow, Ralph A. Alpher and Robert Herman extrapolated the expansion back to a period when the universe was more than 10^{30} times denser than it is now. They postulated that the early universe would be extremely hot and that the combination of high temperature and density would initiate thermonuclear reactions, converting the plasma of protons, electrons and neutrons into deuterons and helium nuclei. Within only a few minutes the expansion of the plasma would reduce the temperature and density below the level needed to sustain further reactions. The conversion would be incomplete and just sufficient to account for the present ratio of helium to hydrogen in the universe.

Another consequence of the Gamow-Alpher-Herman model, which went virtually unnoticed at the time, was that the hot plasma would emit and absorb electromagnetic radiation, just as the hot plasma at the surface of the sun emits light. The radiation would be scattered and rescattered by the free electrons until roughly half a million years after the big bang. At that time the density and temperature of the matter would have dropped to the point where its constituent ions (mostly protons and electrons) would unite to form electrically neutral atoms. This period (which actually lasted for several thousand years) is usually called the "moment of decoupling," since there is little interaction between the radiation and matter from that time on. The previously opaque universe suddenly becomes clear, allowing the electromagnetic radiation to travel unscattered through space and preserving an image of the plasma from which the photons were last scattered.

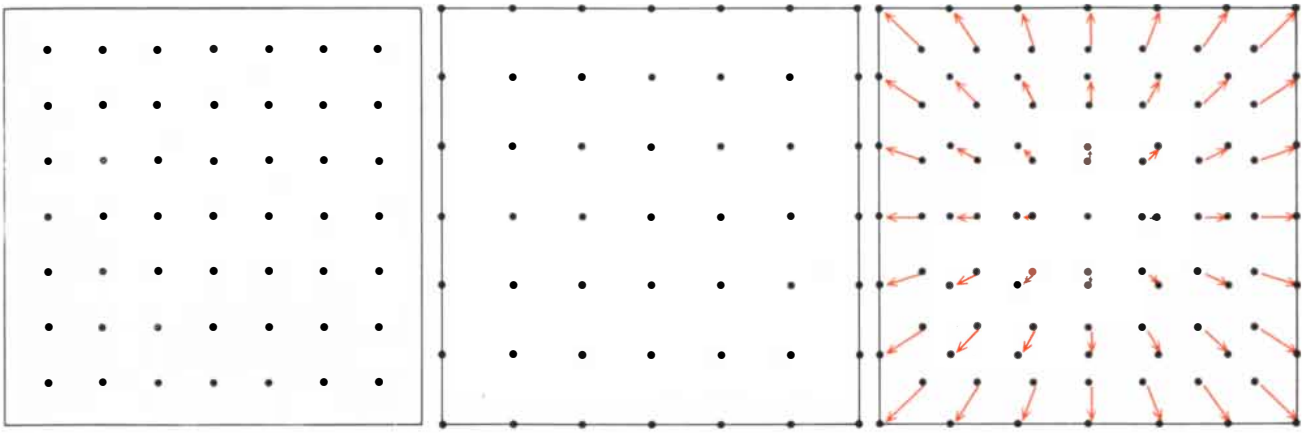


INTENSITY OF COSMIC BACKGROUND RADIATION follows the energy spectrum of a black body with a temperature of three degrees K. The first measurement of the radiation was made in 1965 by Arno A. Penzias and Robert W. Wilson, working with a microwave receiver tuned to a wavelength of 7.35 centimeters (corresponding to a frequency of four gigahertz). Most of the subsequent measurements were also done at single wavelengths, indicated by the vertical bars. Recently, however, Paul L. Richards and his co-workers at the University of California at Berkeley have measured the higher-frequency portion of the curve with a wide-band technique, obtaining the results indicated by the colored area. The broken line represents synchrotron radiation from our galaxy: radiation emitted by electrons as they spiral around lines of magnetic force. At frequencies below 10 gigahertz the anisotropy, or the directional nonuniformity, of the synchrotron emission masks the anisotropy in the background radiation.

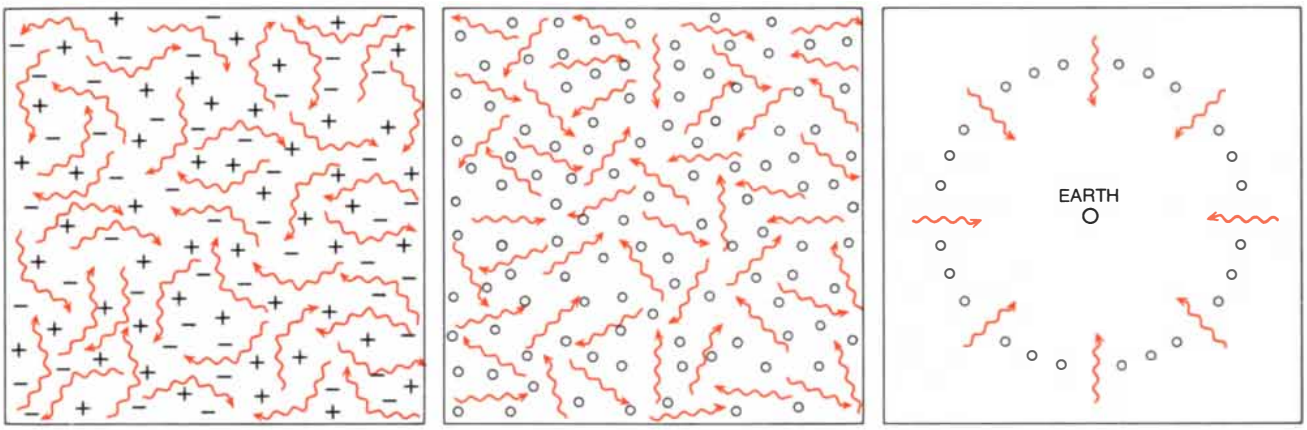
It is this radiation we now observe as the cosmic background. The radiation reaching us today was last scattered from a shell of plasma that completely surrounded our present position in space. If some of the matter in that plasma has formed into a galaxy far removed from our own, one can imagine it supports intelligent beings who are now observing the radiation that was last scattered in our region of space 15 billion years ago.

Originally emitted as visible and infrared radiation with a peak wavelength of about .7 micron, the cosmic background radiation has been red-shifted by a factor of 1,500, so that we now observe its peak wavelength to be at about a millimeter. The red shift is due to the tremendously high velocity of the expanding shell of radiation, or more properly the high rate at which space between us and the shell is increasing. The radiation itself has not changed its wavelength. Rather, we are observing it in a frame of reference that is "moving" at 99.9 percent the speed of light with respect to the matter that emitted it 15 billion years ago.

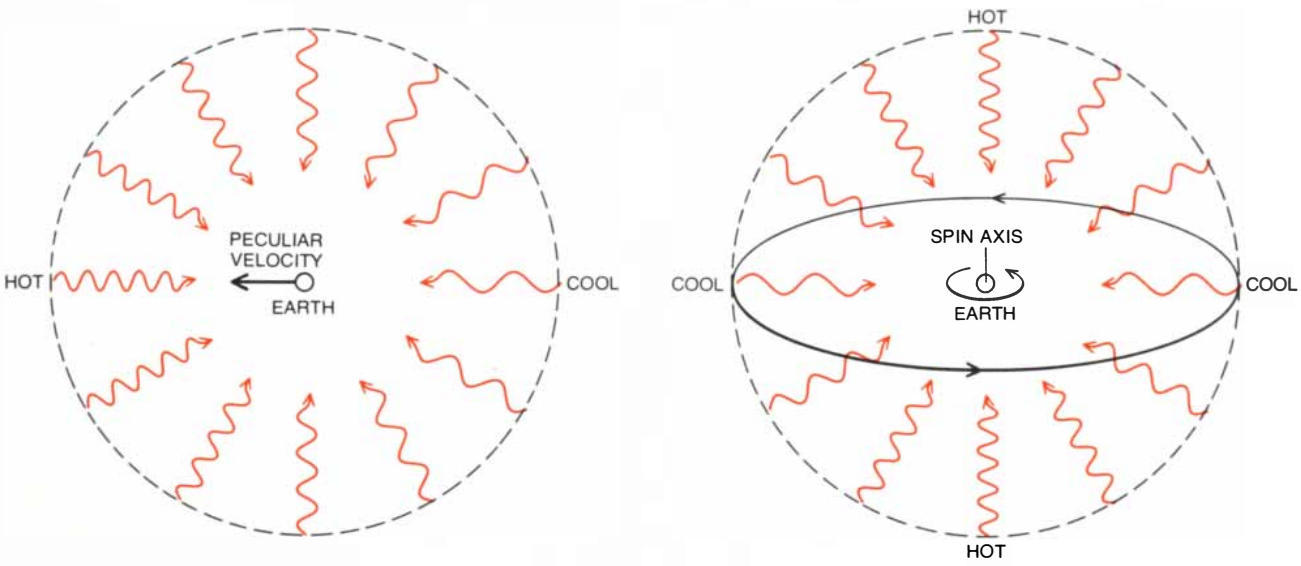
A remarkable feature of a black-body spectrum is that when it is viewed in a frame of reference moving with respect



UNIFORM EXPANSION OF SPACE accounts for the "law" discovered by Edwin P. Hubble of the Mount Wilson Observatory 50 years ago when he observed that distant galaxies are receding at a velocity proportional to their distance. Here the expansion of space is represented by the change in the spacing of galaxies (*dots*) in the arrays at the left and in the middle. In the diagram at the right the two arrays are superposed. Connecting arrows show the distance traveled by each galaxy as viewed from the central galaxy. The same pattern would be observed from every other galaxy. Although the space between the galaxies expands, the size of each galaxy remains the same.



ACCORDING TO BIG-BANG THEORY (*left*), the early universe is filled by protons (*plus signs*) and electrons (*minus signs*) that absorb and reemit photons (*color*). After 500,000 years (*middle*) the universe has expanded and cooled enough for the protons and electrons to combine into hydrogen atoms (*circles*), after which most photons are no longer scattered. Those photons (*redrawn at right*) last scattered from a shell surrounding the position at which the earth will form constitute the cosmic background radiation reaching us today.



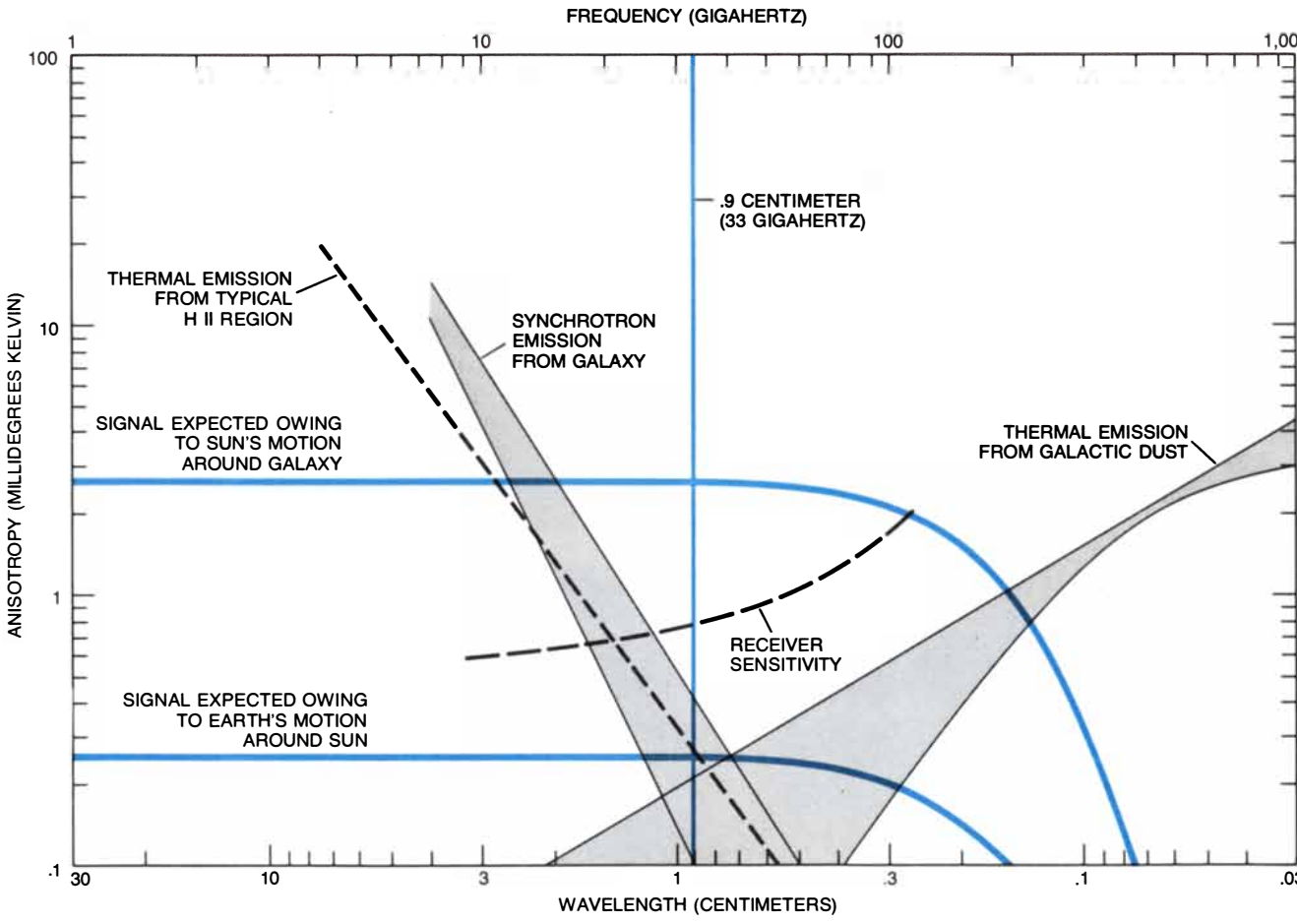
STUDY OF BACKGROUND RADIATION can provide clues to the large-scale structure of the universe. If the earth has a peculiar velocity (*left*), the radiation is slightly "bluer" (hotter) in the direction of motion and "redder" (cooler) in the opposite direction. If the shell of matter that last scattered the radiation was spinning with respect to our local inertial frame, the photons emitted at the shell's equator are slowed by their additional velocity (in accordance with the general theory of relativity) and hence appear redder than photons emitted toward its poles. The two possibilities can be distinguished by differences in the pattern of the observed temperatures. The temperature of the radiation will vary in the first instance as the cosine of the angle in the sky and in the second instance as the square of the cosine.

to the emitter, it retains the characteristic black-body shape, altered only in temperature. In a frame of reference moving with the plasma the characteristic temperature of the radiation is about 4,500 degrees K.; in our frame of reference it is three degrees. As time passes we shall continue to intercept the cosmic background radiation, but the signal we shall then observe will have come from even more distant regions in space. Since those more distant regions are moving away at still higher velocities, the radiation will be observed in our frame of reference to have a temperature lower than three degrees. In another 15 billion years the radiation reaching our present position in space should have a temperature of about 1.5 degrees. It will also be radiation emitted at the decoupling time, but from a region far more distant in space than the radiation we are observing today.

When one observes the cosmic background radiation, one is studying the structure of the shell of matter that scattered it half a million years after the big bang. If the universe were totally homogeneous and isotropic, the cosmic background signal would be totally featureless. Clearly the present universe is quite lumpy, containing as it does planets, stars, galaxies and clusters of galaxies. If large-scale clumping had begun before the moment of decoupling, the background radiation should exhibit bright and dark spots corresponding to the clumps. If such features were to be observed, one would obtain a fascinating glimpse of the early evolution of the universe. On the other hand, the absence of such features would indicate that large-scale structures, such as the clumping necessary to account for clusters of galaxies, had not yet appeared at the moment of decoupling.

The background radiation also provides an opportunity for testing some of the more speculative theories of the universe. For example, the universe may be spinning, a possibility allowed by the general theory of relativity. S. W. Hawking of the University of Cambridge was the first to point out that the spin would show up clearly as a particular departure from isotropy in the cosmic background radiation. If the shell of the last scattering were rotating with respect to our local inertial frame of reference, the plasma at the equator of the shell would have a transverse velocity not shared by the plasma at the poles of the shell. According to the time-dilation effect of special relativity, clocks and other oscillators along the equator of the plasma shell would run slow, with the result that light emitted from the equatorial region would have a small red shift over and above the recessional red shift. The additional red shift would result in a slightly lower temperature for the radiation coming from the equatorial region.

Although a spinning universe would be detectable according to the general theory of relativity, it would not be detectable according to a principle stated by Ernst Mach. Mach postulated that the very existence of local inertial frames of reference depended on the distant matter of the universe. Thus a local inertial frame would be inextricably linked to the distant matter, and it would be rotating if the universe as a



DETERMINING ANISOTROPY in the background radiation is complicated by the microwave emission from various sources that are themselves anisotropic. H II regions, for example, are concentrations of gas and dust heated by young stars. For the new aether-drift experiment it was necessary to select a frequency at which the expected anisotropy of the background radiation would predominate. A frequency of 33 gigahertz was considered to be optimum. The two curves representing the signals expected from the earth's motion around the sun (30 kilometers per second) and the sun's motion around the center of the galaxy (300 kilometers per second) are computed on the assumption of zero velocity for the galaxy. The experiment reveals that the galaxy's velocity is 600 kilometers per second.

whole were rotating. If analysis of the background radiation were to reveal the universe to be spinning, Mach's principle would be disproved.

If gravity waves of very long wavelength were generated during the early moments of the big bang, they too should give rise to a distinctive pattern in the cosmic background radiation. (Since the moment of decoupling for gravity waves is only a fraction of a second after the big bang, their direct detection would provide an even earlier glimpse into the history of the universe than the one provided by the cosmic background radiation.) One might also discover anisotropies revealing that the universe has not expanded uniformly in strict accordance with Hubble's law. Such phenomena would tend to form different patterns in the sky, making it possible to distinguish them from one another. Perhaps the most distinctive pattern to look for, however, is the anisotropy caused by the motion of the solar system with respect to the shell of plasma that emitted the radiation.

There can be only one inertial frame in any region of space where the background radiation is completely isotropic. In any other frame an observer's motion will reveal itself as a variation in the temperature of the radiation proportional to the velocity of the observer and to the cosine of the angle between his direction of motion and the direction of observation. P. J. E. Peebles, one of the physicists in Dicke's group who correctly identified the origin of the radiation, coined the term "the new aether drift" to describe the expected motion. Although it is not motion with respect to some frame of reference fixed in space, it is motion with respect to the most natural frame of reference in cosmology: the expanding coordinate system in which the galaxies are nearly at rest.

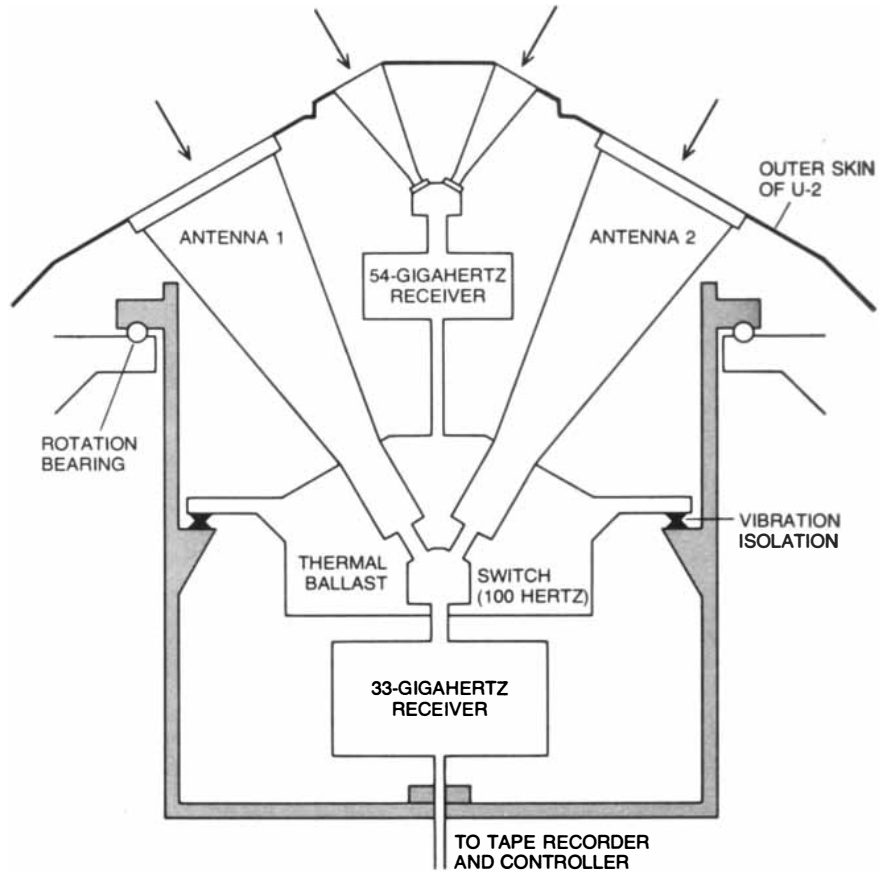
It was the realization that it might be possible to detect the new aether drift that inspired my colleagues and me to design an experiment that would improve significantly on previous measurements. We expected to discover that the motion of the earth was primarily due to the motion of the solar system around the center of our galaxy at about 300 kilometers per second, modified by a small factor to allow for the motion of the galaxy toward the Andromeda galaxy. (The relative motion of our galaxy and the Andromeda galaxy had been measured earlier by the Doppler shift of spectral emission lines as being 80 kilometers per second.) Only a small part of the expected aether drift would be due to the earth's motion around the sun at 30 kilometers per second.

Why were we excited about measuring such a well-known quantity? Our main interest was in the other possible effects: the spin of the universe, early signs of the formation of clusters of galaxies, gravity waves and an anisotropic Hubble expansion. In beginning a difficult experiment, however, it is reassuring to know that one will come out with a nonzero value of some kind. Although the other phenomena are interesting, and even a null result on them would be significant, it is frustrating to make precise measurements of zero.

When we began the experiment, the cosmic background radiation was known to be isotropic to a few millidegrees, or to better than one part in 500, owing largely to the careful measurements of Wilkinson and Robert B. Partridge of Princeton and Edward K. Conklin of Stanford University. Another Princeton experimenter, Paul Henry, had detected a small departure from isotropy, but his data did not fit a simple curve and the direction of maximum temperature was not accurately determined.

For our measurements we planned to use an instrument of the same general design as the one used in the preceding studies: a Dicke radiometer. With this device one measures not the absolute temperature of the cosmic radiation but differences in temperature between one direction in the sky and another. Although one might try to measure such differences by comparing the outputs from two receivers pointed in different directions, thermal noise in the two receivers and uncontrollable variations in their gain ("flicker noise") would swamp the minute differences expected. In the Dicke design the problem is avoided by switching the same receiver back and forth between two horn-shaped antennas pointed in different directions. If the experiment is carried out at the earth's surface, one tries to cancel the intense microwave emission from the oxygen in the atmosphere by pointing the two horns at the same zenith angle so that both "see" the same amount of oxygen.

To nullify small differences in the collecting power and emission of the two horns, or a possible asymmetry in the microwave switch connecting the horns to the receiver, the entire apparatus is rotated, interchanging the positions of the horns once a minute. With these precautions any asymmetry in the background radiation should show up as a



INSTRUMENT FOR MEASURING ANISOTROPY of the cosmic background radiation built by the author and his colleagues is shown schematically in cross section. The two large horn antennas are designed to collect cosmic background radiation in a narrow cone at a frequency of 33 gigahertz. The two smaller horns and their associated receiver monitor the emissions from atmospheric oxygen at 54 gigahertz. The apparatus is designed to measure not the absolute temperature of the cosmic background radiation but rather the difference in the temperature of the signals collected by the two large horns when they are switched alternately into a common receiver 100 times a second. To compensate for possible asymmetries in design and construction the apparatus is rotated 180 degrees every 64 seconds during collection of data.

fluctuation in the receiver output that coincides with the horn-switching rate.

In order to achieve a substantial improvement in sensitivity over earlier experiments we had to understand exactly what had limited the sensitivity of earlier measurements and to anticipate as best we could the problems that would be introduced by a new experimental design. The results of earlier experimenters had been limited in sensitivity primarily by the "synchrotron radiation" emitted by electrons accelerated in the magnetic fields of our galaxy. Although the intensity of the synchrotron radiation roughly follows the visible features of the Milky Way, its precise pattern in the microwave region of the spectrum is not known. The best one can do is to subtract an estimate of the synchrotron anisotropy from the total observed anisotropy and hope that what is left represents the anisotropy in the cosmic background radiation and not just an error in the estimate.

There is a straightforward way to reduce the interference introduced by synchrotron radiation, which is to move to wavelengths shorter than three centimeters. For example, between three centimeters and one centimeter the intensity of the synchrotron radiation falls by roughly a factor of three. Equally important, in the same wavelength interval the cosmic background radiation, following the black-body curve, becomes about 10 times stronger. The obstacle to operation at shorter wavelengths is the increased atmospheric emission: water vapor and oxygen make ground-based observations impossible at wavelengths shorter than about two centimeters. Water vapor is particularly troublesome because it can exist in patches that are not canceled by aiming a pair of antennas at the same zenith angle.

The obvious solution is to conduct the experiment at an altitude well above 50,000 feet, where the water vapor is almost totally frozen out. Mountaintop altitude is not enough. It is necessary to use either a balloon, an airplane or a spacecraft. Although we knew that a spacecraft experiment was potentially the most sensitive, an experiment in an airplane or a balloon is much less expensive and should certainly be done first. In discussing these problems with Hans M. Mark, who was then director of the Ames Research Center of the National Aeronautics and Space Administration, and Luis W. Alvarez of the Lawrence Berkeley Laboratory, we decided that the U-2 aircraft being operated by NASA for the study of earth resources would be an ideal platform for our experiment. At about the same time (mid-1973) Corey and Wilkinson at Princeton elected to use the gondola of a balloon as a platform for their anisotropy measurements. I shall not describe their experiment but instead concentrate on the problems that had to be solved for our U-2 undertaking.

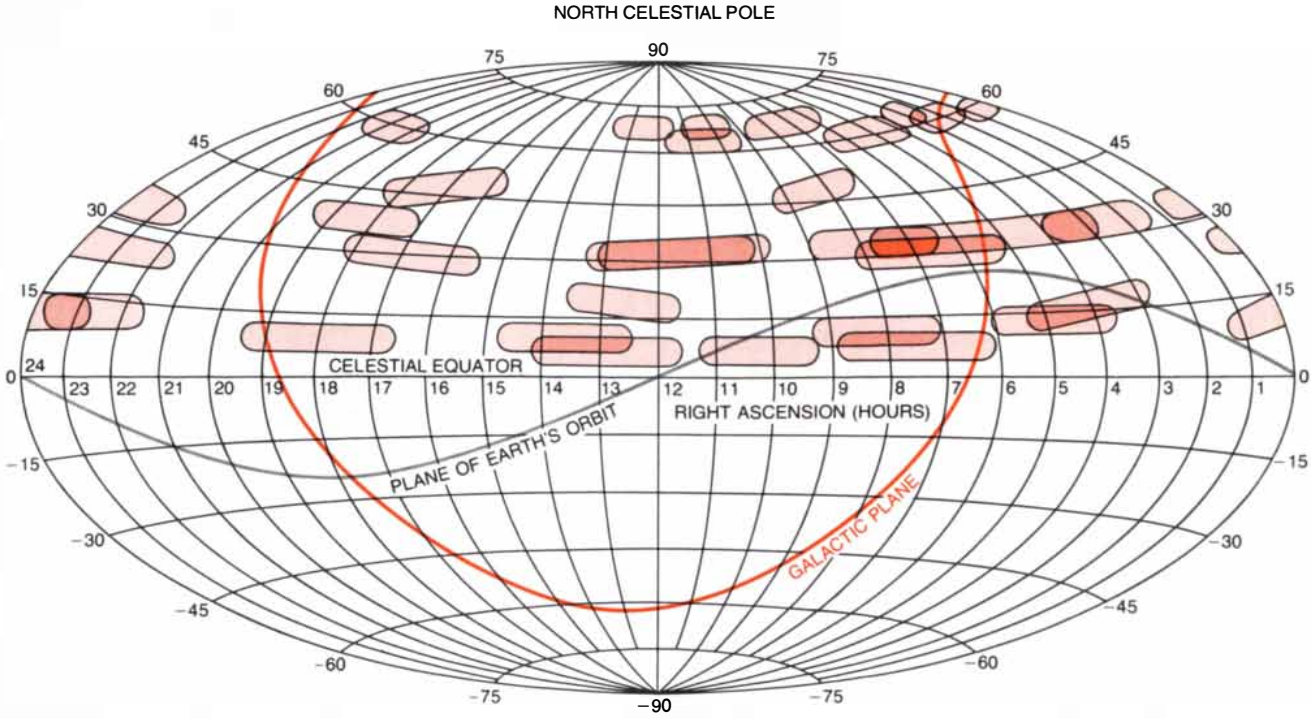
For an airborne experiment the time available is sharply limited, which meant that our receiver had to be as sensitive as possible. (In an experiment that can be conducted from the ground data can be averaged over many observations and provide sensitive results even without a low-noise receiver.) Unfortunately microwave receivers become progressively less sensitive at wavelengths below three centimeters. The constraints presented by receiver technology, the need to avoid troublesome interference from synchrotron emission at wavelengths much longer than 1.5 centimeters and strong atmospheric emission lines at wavelengths of several millimeters led us finally to choose a wavelength of .9 centimeter (a frequency of 33 gigahertz, or 33 billion cycles per second) as being optimum for the experiment. At that wavelength we thought our apparatus would be sensitive enough to detect an anisotropy of less than a thousandth of a degree, which would be more than adequate to determine the velocity at which the solar system is being swept around the galactic disk.

A major problem in an airborne experiment is the instability of the platform, which makes it difficult to ensure that both antenna horns are pointing at the same zenith angle and hence seeing the same volume of oxygen. We solved the problem by monitoring the zenith angle with a second radiometer tuned to a wavelength of .55 centimeter (a frequency of 54 gigahertz), a wavelength particularly sensitive to emission from atmospheric oxygen. With this arrangement we would be able to detect any asymmetry of the oxygen signal, whether it was due to a tilted airplane or to a tilted atmosphere. Since the earth is not a sphere but a quasi ellipsoid, the atmosphere is indeed often tilted with respect to the ground; the atmosphere is also tilted by weather fronts. If the tilt were large, the pilot would be asked to bank the plane in compensation. (The maneuver turned out not to be necessary.)

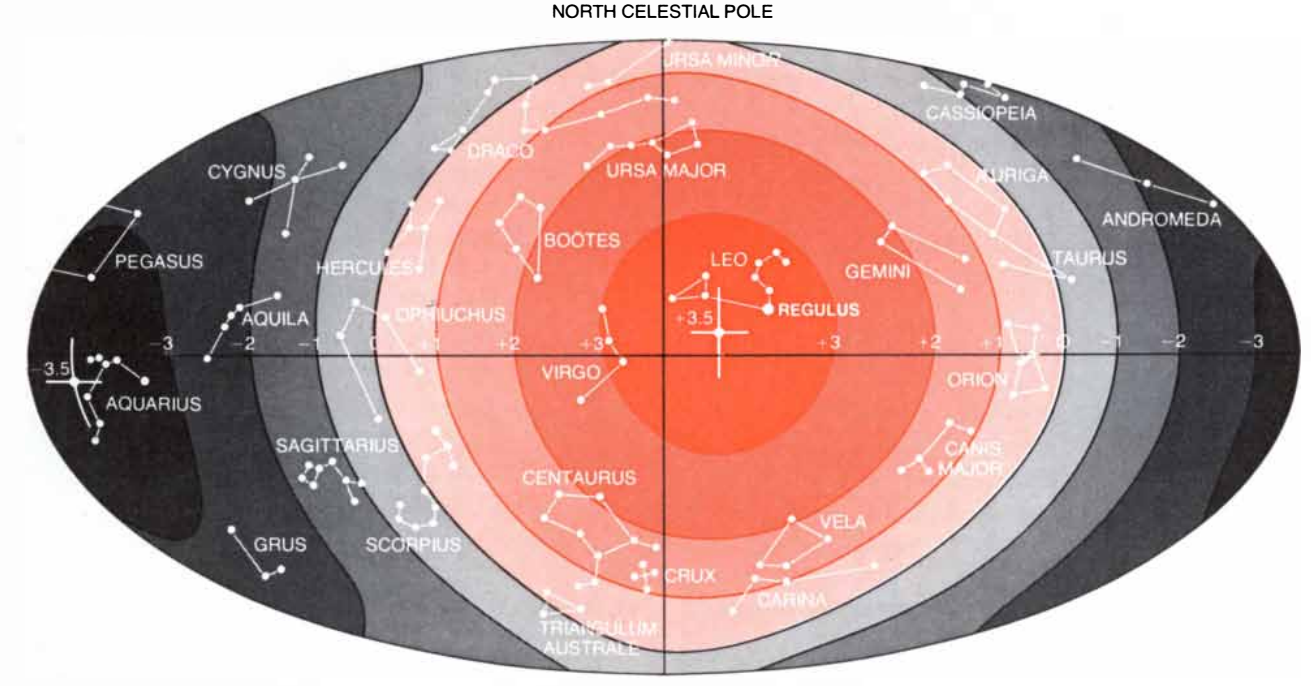
The size of our apparatus was severely limited by the space available within the rear hatch of the U-2, which made the design of the antennas particularly difficult. Since the earth is an intense emitter of microwave radiation, we had

PROBLEM	REMEDY
Synchrotron emission from galaxy	Make measurements at frequency above 10 gigahertz
Emission from galactic dust	Make measurements below 100 gigahertz
Emission from atmospheric water vapor	Collect data at altitude above 15 kilometers (with U-2)
Emission from atmospheric oxygen	Use twin horn antennas at high altitude and monitor oxygen emission at 54 gigahertz
Emission from sun	Fly at night
Emission from earth	Use dual-mode corrugated horns with narrow field of view
Emission from horn antennas	Symmetrize emission by careful temperature control
Thermal noise in receiver	Integrate signal for 20 minutes
Receiver flicker noise (= 1/frequency)	Switch between two horn antennas 100 times per second
Asymmetry of airplane	Reverse flight path every 20 minutes
Asymmetry in experimental apparatus	Rotate equipment itself every 64 seconds
Bias from earth's magnetic field	Carefully shield microwave switches
Radio emission from U-2	Place metallic shields around sensitive parts and minimize communications to U-2
Geometric distortion of atmosphere due to nonsphericity of earth	Determine "zenith" from oxygen signal rather than from earth's horizon or flight instruments

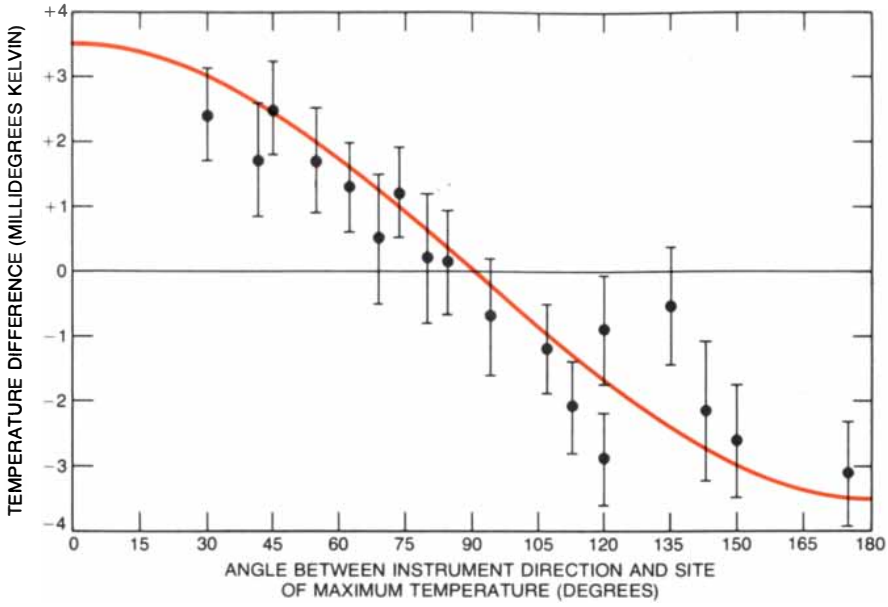
PRINCIPAL PROBLEMS associated with measuring the anisotropy of the background radiation are listed with the remedies adopted by the investigators. They and their associates spent three years planning the experiment and building the equipment before the first test flight.



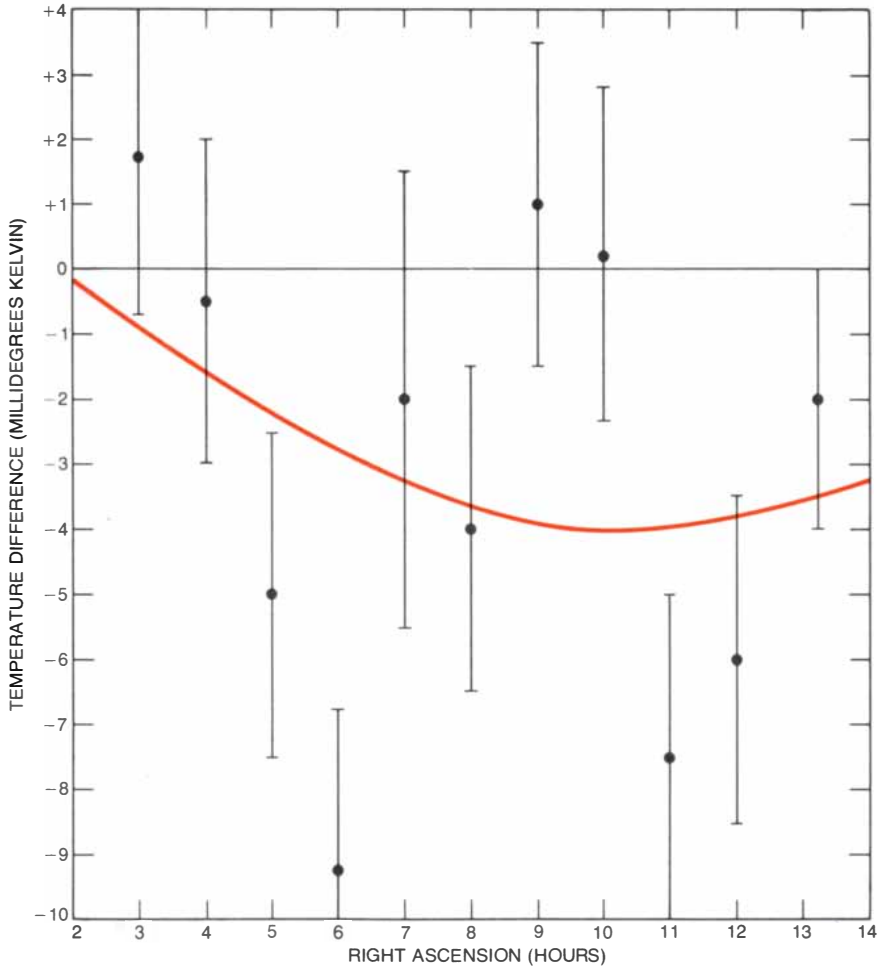
REGIONS OF SKY SURVEYED by the new aether-drift experiment are plotted on an equal-area projection of the celestial sphere. All the flights were made at night (in order to avoid the microwave emission from the sun) and were spread out over a period of roughly a year (in order to scan as much of the sky as can be observed from a base in northern California). Flights in the Southern Hemisphere, which are proposed for the current year, will help to verify the pattern of the detected anisotropy in temperature. Typical flights lasted four hours and surveyed four different regions of the sky. Each of the horn antennas was sensitive to a region of the sky about seven degrees across. The length of each scan was determined primarily by rotation of the earth rather than by the 400-knot speed of the airplane.



ANISOTROPY OF THE BACKGROUND RADIATION, as deduced from the U-2 survey, is plotted on the celestial sphere in contours of one millidegree K. The "hottest" spot, indicating the direction of the earth's maximum relative motion toward the background radiation, lies in the constellation Leo at right ascension 11 hours (±.5 hour) and latitude six degrees (±10 degrees). The "coldest" spot, the direction in which the radiation is most "reddened" by the earth's relative motion away from the incoming photons, lies 180 degrees away in Aquarius. If the temperature difference between hottest and coldest points is plotted against distance, the result is a cosine curve.



COSINE CURVE provides the best fit for the data (averaged into 18 points) taken by the author and his colleagues in the new aether-drift experiment. The horizontal axis represents the angle made by a line connecting the two horn antennas and the direction of maximum temperature in Leo. The cosine curve is temperature distribution to be expected in the cosmic background radiation if the solar system's peculiar velocity toward Leo is 400 kilometers per second.



FIRST SIGNIFICANT DEVIATION FROM ISOTROPY in the cosmic background radiation was detected by Paul Henry of Princeton University with an instrument that was carried aloft by a balloon. The anisotropy in the radiation shows up in the preponderance of data points lying below the zero line. The scatter in the points, however, made it impossible to establish distribution of anisotropy or to determine precisely direction of maximum temperature.

to find a way to shield our antennas. Ground-based experiments had solved the problem with large metallic reflectors that intercepted and reflected the earthshine. Our solution was a special horn antenna designed to have an extremely small pickup from directions more than 60 degrees from the horn axis. The small space available in the U-2 also required that the apparatus be fully automatic, since there was no room in the airplane for a scientist passenger. Another nontrivial problem was that the U-2 is designed to carry cameras that look down, and we wanted to look up. One does not cut a hole in the top of a skin-stressed airplane such as the U-2 without considerable planning, but the modification was achieved with the help of the NASA staff at the Ames Research Center and engineers of the Lockheed Aircraft Corporation, which was responsible for the maintenance of the aircraft.

These were just a few of the problems we had to address in the experiment. Part of the challenge of a novel experiment is trying to anticipate new problems and deal with them. Much credit belongs to my collaborators Smoot and Gorenstein, who had the chief responsibility for transforming a theoretical plan into a successful experiment.

After three years of planning, construction and testing we mounted the apparatus in the U-2 in July, 1976. We made various modifications after a series of test flights and continued to make others during the data-taking period, which began in December of that year. All the data-taking flights were made at night, since even our special horn antennas picked up microwave signals from the sun. There was also no practical way to shield our apparatus from uneven solar heating. Microwave emission from the moon, when it was at the correct angle for it, provided a handy way to calibrate the receiver gain in flight.

The data collected from the first few flights revealed an unmistakable departure from isotropy in the cosmic background radiation. To get a clear picture of the anisotropy, however, we had to have flights spread out over a full year so that the antennas could scan as large a fraction as possible of the celestial sphere visible from northern California. By the end of last year the data from 10 flights plotted into the distinct cosine curve one would expect if the solar system were moving with a high cosmological velocity. A similar anisotropy was detected at a wavelength of 1.6 centimeters by the 19-gigahertz radiometer flown in the gondola of a balloon by Corey and Wilkinson. In both the Berkeley and the Princeton experiments the magnitude of the anisotropy was consistent with that first reported by Henry.

Our data indicate that the temperature of the cosmic background radiation

reaches a maximum of .0035 degree (3.5 millidegrees) above the average value in a direction defined, in the usual celestial coordinates, as 11 hours right ascension and six degrees north latitude, or about 15 degrees east-southeast of Regulus, the brightest star in the constellation Leo. The velocity of the solar system in that direction can be computed by dividing the maximum temperature difference, .0035 degree, by the average temperature of the cosmic background radiation, 2.7 degrees (the best current value), and multiplying the result by the velocity of light. The answer is a velocity of 390 kilometers per second.

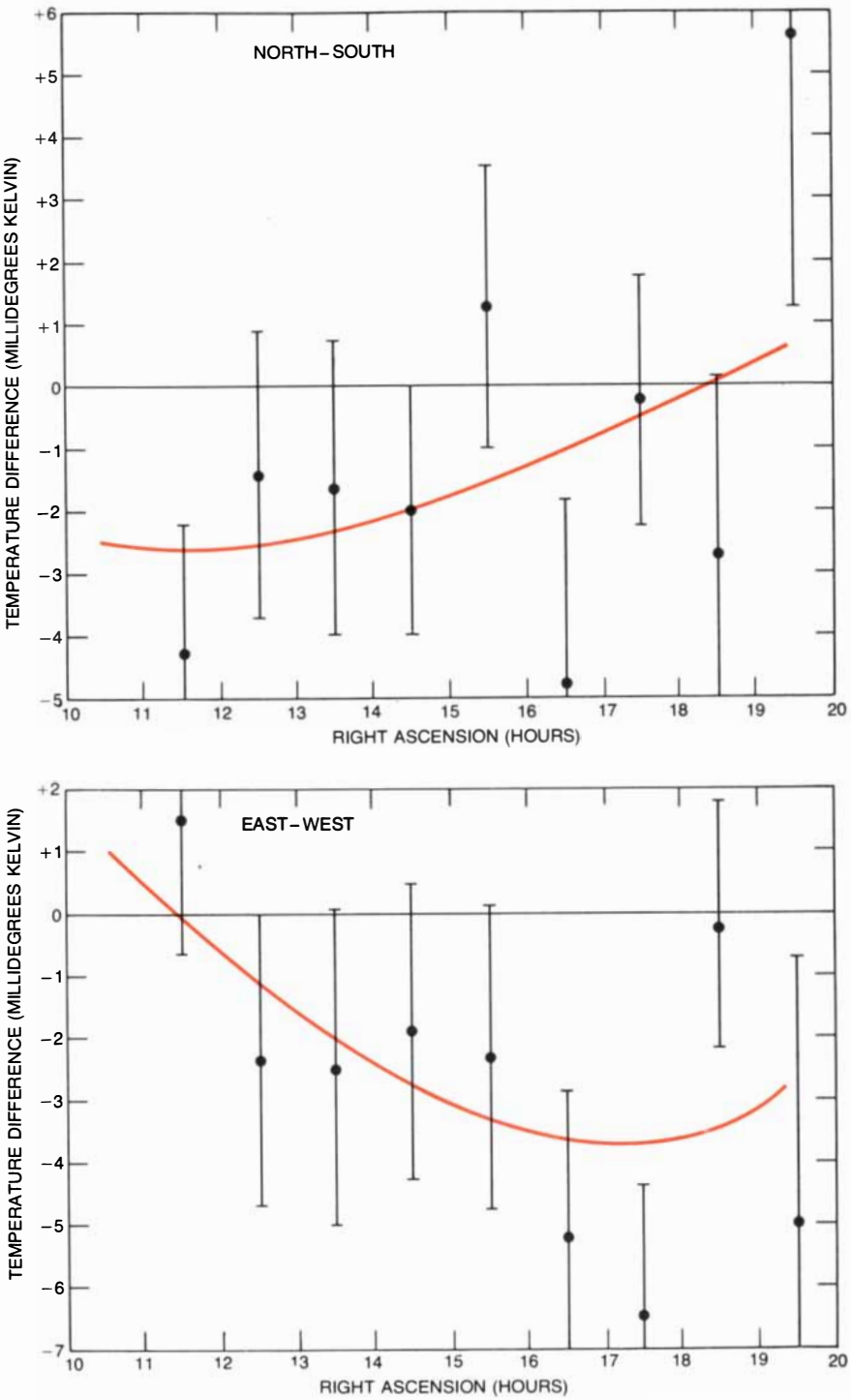
Although this velocity is not much greater than that of 300 kilometers per second expected from the solar system's motion around the center of the galaxy, it is in a different direction. Since the velocity of the solar system is the sum of the velocity due to the rotation of the galaxy plus any peculiar velocity of the galaxy, we could take our measured number and by properly handling the vectors calculate the peculiar velocity of the galaxy. When we did this, we found that the galaxy must be moving at about 600 kilometers per second with respect to the cosmic background radiation.

Except for the cosine variation in temperature the background radiation was found to be isotropic to better than one part in 3,000, placing strict limits on several of the phenomena I have mentioned. If the universe is rotating, its rate of rotation must be less than 10^{-9} second of arc per century. If large-scale gravity waves exist, they do not have sufficient energy to close the universe or to reverse the Hubble expansion into an implosion. The expansion itself must be isotropic to one part in 3,000. There is also no evidence of the early formation of clusters of galaxies, indicating that very-large-scale clustering did not exist at the moment of decoupling.

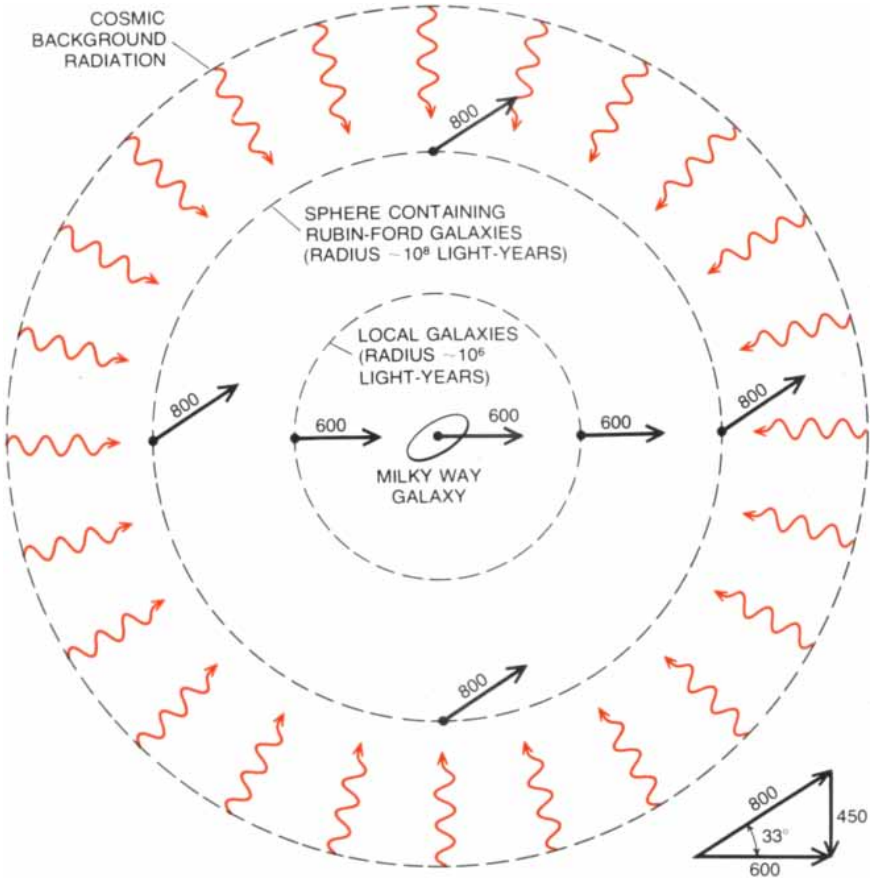
Perhaps the most fascinating and unexpected result of the experiment is the size of the implied cosmological velocity of the galaxy. Since the motion of our galaxy relative to the Andromeda galaxy is small (80 kilometers per second), the Andromeda galaxy must share this high velocity through space. Moreover, it is known that the peculiar (non-Hubble) motion of our local group of galaxies relative to the nearest large cluster of galaxies, the Virgo cluster, is small; thus the entire Virgo cluster must have a cosmological velocity similar to ours. The picture that emerges is of a vast volume of space, tens of millions of light-years in radius, moving with a velocity of roughly 600 kilometers per second with respect to the distant universe.

The picture becomes more complicated when we look farther out into the local regions of space. Prior to our work Vera C. Rubin and W. Kent Ford, Jr., of the Carnegie Institution of Washington's Department of Terrestrial Magnetism had with their colleagues analyzed the motion of our galaxy relative to an all-sky sample of spiral galaxies some 100 million light-years away. They concluded that relative to the sample the solar system has a net velocity of 600 kilometers per second. After allowing for the fraction of the velocity of the solar system that is due to galactic rotation, they calculated that our galaxy is moving relative to the sphere of reference galaxies at a velocity of about 450 kilometers per second.

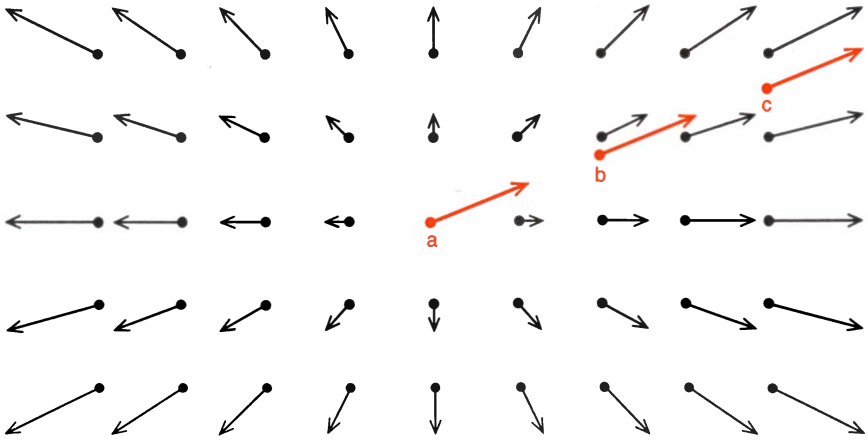
Our measurement of our galaxy's peculiar velocity, as determined from the



SECOND PRINCETON EXPERIMENT, conducted by David T. Wilkinson and Brian E. Corey with a balloon-borne instrument operating at a frequency of 19 gigahertz, supports the Berkeley U-2 measurements. Because the Princeton workers plot their data differently (with a north-south projection and an east-west projection) the similarity between their results and the Berkeley ones is not readily apparent. It is clear, however, that the Princeton data define cosine curves. Princeton group concluded that the earth is moving at 300 (±70) kilometers per second toward right ascension 12 (±2) hours and latitude −10 (±20) degrees in the celestial sphere.



FANTASTIC VELOCITY PICTURE emerges when the peculiar velocity of our galaxy, evidently shared by all the members of the local cluster of galaxies, is plotted in relation to a sample of galaxies 10^8 light-years away whose velocities were analyzed spectrographically by Vera C. Rubin and W. Kent Ford, Jr., of the Carnegie Institution of Washington's Department of Terrestrial Magnetism. Their results imply that our galaxy is moving at 450 kilometers per second with respect to those in the reference sample. The diagram shows how the Rubin-Ford velocity can be reconciled with the peculiar velocity of 600 kilometers per second determined for our galaxy by the anisotropy in the cosmic background radiation. The Rubin-Ford sphere of galaxies would require a peculiar velocity of 800 kilometers per second displaced roughly 33 degrees from the direction in which our galaxy is moving. Diagram at right shows how our galaxy would then be carried toward the Rubin-Ford galaxies at 450 kilometers per second. In view of uncertainties in measurements the velocities are rounded to 50 kilometers per second.



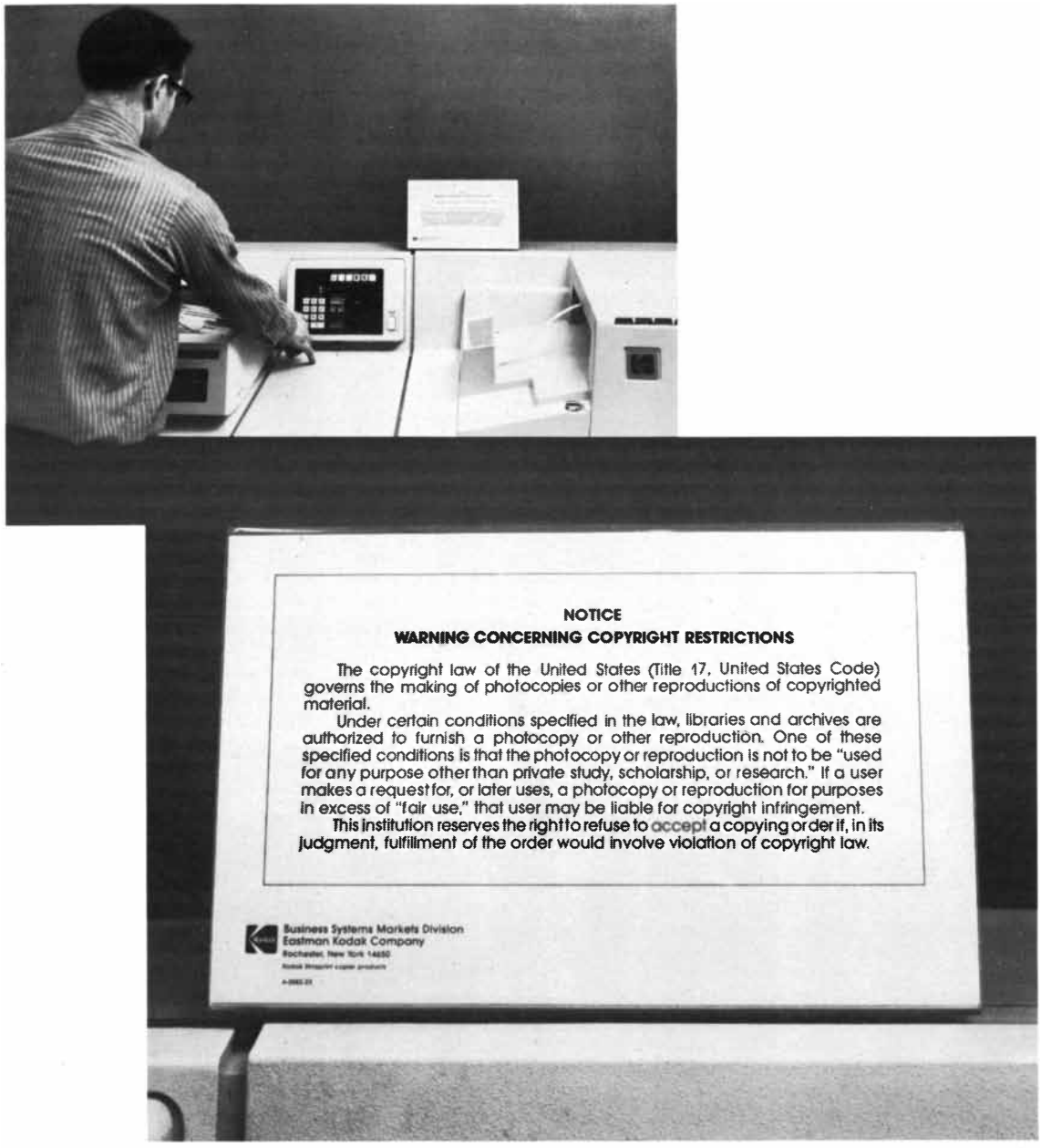
CONVERSION OF PECULIAR VELOCITY into Hubble velocity, the cosmic velocity of expansion, can be expected to take place in time. The vector arrow *a* represents the current peculiar velocity of our galaxy, shown embedded in a space that is expanding uniformly. As our galaxy moves outward it will overtake other galaxies (*b*) until it reaches a region (*c*) where its velocity matches that of neighboring objects. Our galaxy will then no longer exhibit a peculiar velocity; its motion with respect to nearby matter will tend toward zero. A similar argument shows that in the past our galaxy's peculiar velocity must have been greater than it is today. This line of reasoning is invalidated, of course, if the peculiar velocity arises from a local effect, such as the rotation of a cluster of galaxies, in which case the peculiar velocity would oscillate.

cosmic background radiation, not only is a third greater than the Rubin-Ford velocity but also differs in direction from theirs by more than 100 degrees. The two sets of velocity measurements can be reconciled by assuming that the Rubin-Ford sphere of galaxies is moving with a cosmological velocity of about 800 kilometers per second in a direction offset by approximately 33 degrees from the direction in which we are drifting at 600 kilometers per second through the radiation "aether" left by the big bang.

This remarkable picture is even more surprising when one realizes that a high peculiar velocity today may imply a still higher one in the past. As a galaxy moves through space with a high peculiar velocity it eventually catches up with other galaxies whose recessional velocity corresponds to the average Hubble expansion. Hence a high peculiar velocity is gradually transformed into a typical Hubble velocity, with the net result that peculiar velocities must decrease with time. Extrapolating backward, one finds that at the moment of decoupling the peculiar velocity of the stuff of which our galaxy was made must have been close to the speed of light. On the other hand, if the peculiar velocity were due to local turbulence or to orbital motion around a distant point, such an extrapolation might not be correct. The velocity of our local group of galaxies with respect to the nearby (on a cosmic scale) Rubin-Ford galaxies does in fact suggest there is considerable turbulence in the universe.

Before one accepts this turbulent picture of the large-scale structure of the universe, one should recall that our observation of the cosmic background radiation shows that except for the cosine component the radiation is uniform to at least one part in 3,000. It is not obvious how to reconcile the featureless nature of the background radiation with a high degree of local turbulence. To be sure, the local peculiar velocities are characteristics of the present universe, whereas the background radiation is a snapshot of the universe taken 15 billion years ago. Conceivably the universe possesses some large-scale structure, such as the rotation of a supercluster of galaxies, that will reconcile the apparently contradictory results.

Perhaps the most perceptive criticism of the homogeneous isotropic big-bang model is that it is far too simple to represent reality. One is easily tempted to assume that the unknown is simple. It is possible, indeed likely, that there are large-scale structures that play an essential role in determining the nature of the universe. With recent measurements of the large-scale clustering of galaxies and the anisotropy of the cosmic background radiation we may be just beginning to detect that structure.



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Take our Dasher Sedan. Inside you'll find rich, crushed velour seats and deep cut pile carpeting. It's not only beautiful to look at, it's beautiful to listen to — with a

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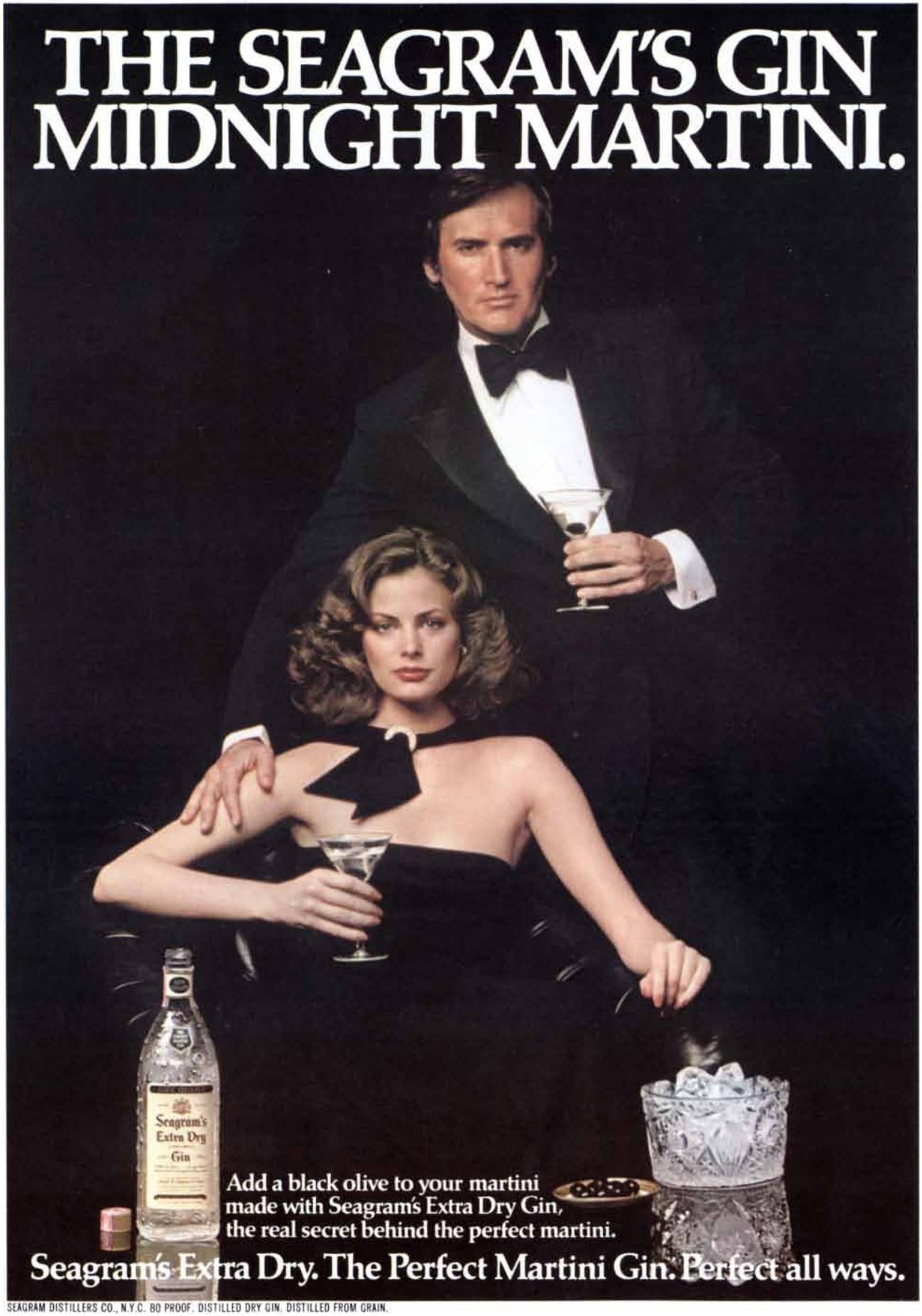

SCIENCE AND THE CITIZEN

The Infertile Society

If the current trend toward reduced fertility continues, most of the world's developed countries are heading for an era of negative population growth. Indeed, there are already more deaths than births per year in Austria, Britain, East and West Germany and Luxembourg. Declines in fertility suggest that population will begin to decline in Belgium, Denmark, Czechoslovakia, Hungary, Norway and Sweden within two years, in Bulgaria, Finland, Greece, Italy and Switzerland by 1990 and in France and the Netherlands by 2000, that the remaining countries of Europe will not be far behind and that deaths should outstrip births in the U.S. by about 2020. The question, of course, is whether or not fertility rates will continue on their present course. According to Charles F. Westoff of Princeton University, writing in *Family Planning Perspectives,* "The honest answer is that nobody knows." Westoff thinks, however, that fertility will continue to decline, and he gives his reasons.

One consideration, he points out, is the improvement and diffusion of contraceptive technology. "Virtually all American married couples" practice contraception, and among those couples three out of four were relying in 1975 on the most effective methods: sterilization, the pill or the intrauterine device. Abortion is widely available, and new fertility-control technology is being developed: "We are fast approaching the perfect contraceptive society." The fact that couples can avoid unwanted children does not mean they will necessarily choose to have few children or none, but the historical trends point toward smaller families. Moreover, a look at "current social trends and their demographic outcomes" provides signs that changes in marriage and the family will cause fertility to decline to new lows. Westoff considers in particular evidence from the U.S. and "from two Scandinavian countries that historically seem to be in the avant-garde of social change."

The proportion of women not married by the age of 24 increased from 28 percent in 1960 to 43 percent in 1976 in the U.S., from 44 percent in 1970 to 59 percent in 1975 in Denmark. In Sweden there were 30 percent fewer marriages in 1975 than in 1966. In the U.S. about 2 percent of all couples living together were unmarried in 1976; in Denmark about a quarter of all women between 18 and 25 are living with a man to whom they are not married; in Sweden a few years ago about 12 percent of all couples living together were unmarried. The "very high" U.S. divorce rate makes it clear that "the traditional concept of one partner forever has disappeared" for many people. Divorce does not necessarily reflect on the institution of marriage itself, but now the remarriage rate has started to decline in the U.S., as it has by about 50 percent in Sweden since 1965. Out-of-wedlock births reached 14.2 percent of all U.S. births in 1975 (with the greatest increase among white women from 20 to 29 years old); the proportion was 18.8 percent in Denmark in 1974 and is now about a third in Sweden. Even if all these changes mean only that formal marriage is giving way to other monogamous unions, "such informal arrangements will hardly contribute to increasing fertility."

The trends in marriage and reproduction "are tied in one way or another to the growing economic independence of women." Westoff cites the large increase in the proportion of women of reproductive age who are employed outside the home in the U.S. and in Europe. "There is little doubt that women's work and fertility are negatively related on the whole" or that more women will work in the future. Westoff sees demographic trends as "both a cause and a consequence of changes in the family." Less childbearing frees women to work toward economic equality, "which in turn makes marriage and childbearing less of an automatic social response. The future seems less and less compatible with long-term traditional marriage." In addition to the decline of marriage there is apparently an increase in childless marriages. Among U.S. women between 25 and 29 who were or had been married, 12 percent had never had a child in 1965, 22 percent in 1976. "It is not difficult to visualize a society in which perhaps one-third of women never have any children," in which case the remaining two-thirds would need to bear an average of three children each to maintain a steady-state population.

If fertility rates keep declining, is there any reason to assume that there will come to be "a magical balance of births and deaths at low levels," or precisely zero population growth? The expectation "may be more aesthetic than realistic." Westoff thinks fertility in the U.S. and other developed countries will fall to very low levels, "probably below replacement." In order to maintain replacement fertility, financial incentives to encourage childbearing may eventually become necessary.

Breeders as Incinerators

To opponents of nuclear power the terms "breeder reactor" and "plutonium economy" are the ultimate epithets for a technology out of control. The terms raise the specter of great volumes of purified plutonium flowing in worldwide traffic impossible to secure from the depredations of the next generation of terrorists. To a large degree the fear of terrorist theft has supplanted simple proliferation—an increase in the number of nuclear powers—as the Carter Administration's principal reason for opposing both the reprocessing of spent nuclear fuels and the further development of the fast breeder reactor. The alternative being favored is the "once through," or "throwaway," fuel cycle, in which the depleted, highly radioactive fuel rods from nuclear power plants, containing about 1 percent of unspent uranium 235 and an equal amount of plutonium, would simply be stored indefinitely. This is one of the options now being examined by experts of the 40 countries participating in the International Nuclear Fuel Cycle Evaluation program (INFCE).

A totally different view of the breeder reactor and the plutonium problem has recently been presented by Walter Marshall, deputy chairman of the United Kingdom Atomic Energy Authority. To Marshall the specter raised by the throwaway fuel cycle is the worldwide proliferation of waste-fuel storage sites, each, in his words, a potential "plutonium mine." Although it is true that spent fuel rods are initially so "hot" as to discourage theft, the level of radioactivity falls rapidly: by a factor of 300 over the first year and by a factor of 2,000 over the first 10 years. Marshall classifies as "inacessible" the plutonium in fuel rods still so radioactive that separation of the plutonium would require construction of a sophisticated reprocessing plant, which itself would take about 10 years to build. He classifies as "extractable," however, the plutonium present in fuel rods "sufficiently old" for it not to be "beyond the limits of imagination that a [subnational] group might be successful *somewhere* in the world" in separating out the contained plutonium. Marshall suggests that a sufficient aging period would be no more than 30 years.

For this reason Marshall concludes "that a policy of using thermal reactors alone in the once-through cycle is not a satisfactory non-proliferation policy.... With this policy every nation with a nuclear power plant and a spent fuel element storage facility has set up a target for plutonium diversion and has established an option to construct weapons in ways that are easier and easier to operate as the stored plutonium becomes associated with less and less radioactivity." Some 300 power reactors are now operating in 24 countries. Barring an immediate moratorium on all future construction, Marshall estimates that by the year 2,000, if the once-through fuel

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The TC-K7 II front-loading cassette deck is its own best spokesman.

Switch it on, and that disciplined Sony engineering will come through loud and clear.

And no wonder. Sony's been making tape recorders for 30 years. And today, we're still pushing back the frontiers. The K7 II shows how.

Its transport mechanism is a DC servo-controlled motor, with a frequency generator. It emits a signal which is relayed to electronic circuitry that locks in the tape movement exactly.

Our heads are ferrite-and-ferrite. And they're Sony's own formula—we don't buy them, we use our heads and make them.

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The K7 II also speaks for itself with Dolby Noise Reduction System.™ Large, professionally calibrated VU meters. Three LED's for peak level indication.

There's also bias and equalization switches for standard, Ferri-Chrome and Chromium Dioxide tapes. In fact, with nine possible combinations, any tape possibility of the future can be accommodated.

So if you're intrigued by quality that speaks for itself, get down to your Sony dealer and check this new cassette deck.

Before they're all spoken for.

Sony quality that doesn't speak at all.

But it won't be silent for long. Because the moment you record on one of our blank tapes, that quality will make itself heard.

Witness our Ferri-Chrome cassette.

Everybody knows that ferric-oxide tapes are ideal for reproducing the low frequencies. And that chromium dioxide is ideal for the high frequencies.

As usual, Sony wouldn't settle for anything but the best of both.

And as usual, Sony's engineers solved the problem. With a process that allows a coating of chromium dioxide to be applied over a coating of ferric-oxide.

Our two coats are leaving other brands of tape out in the cold. Because Ferri-Chrome boasts shockingly low distortion and startling dynamic range.

Sony is this advanced because we make more than tape. We make tape heads and tape recorders, too. (No other consumer company is that involved.) Because we know where tape winds up, we're better able to design and produce it.

Of course, in addition to Ferri-Chrome, Sony makes a complete line: Chrome, Hi-Fidelity, Low Noise, Elcaset and Microcassette.

Sony's been making tape for 30 years.

So when it comes to answering the tough questions about the manufacture of tape, no one fills in the blanks like Sony.

SONY AUDIO

cycle is adopted, the plutonium mines of the world will contain enough nuclear material for the construction of a quarter of a million atomic bombs.

This is reason enough, Marshall argues, to reject the once-through fueling concept and to opt instead for reprocessing of fuels and rapid adoption of fast breeder reactors, since they alone have the capability of consuming the recovered plutonium and reducing the inventory of that material, which will otherwise keep growing inexorably. Marshall thinks that critics of the breeder are misled when they argue that since the fast reactor breeds plutonium it necessarily implies a "plutonium economy," that is a large-scale commitment to handling, processing and transporting purified plutonium. The actual situation, says Marshall, is that "it is possible to operate [the fast breeder] so that it either produces slightly more or slightly less [plutonium] than it incinerates.... It follows that the use of fast reactors instead of thermal reactors can immediately put a *brake* on the growth of plutonium in the world [and] can be used to *decrease* the total amount of 'extractable' plutonium in the world provided we make the fuel out of the old plutonium obtained from thermal reactor spent fuel." In effect, the breeder can be "fine tuned" not to breed at all but simply to consume the plutonium created by thermal reactors.

To the objection that large-scale recovery of plutonium from spent fuel would make plutonium available in precisely the extracted form that would tempt a non-nuclear nation to divert it or a terrorist group to steal it, Marshall has an answer. The reprocessing can be done in such a way that the plutonium is not extracted in pure form, as it is in current practice, but is left mixed with about 80 percent depleted uranium and a few percent of highly radioactive fission products so that it cannot produce a bomb and cannot be handled and further purified except with facilities equivalent to those in a fully shielded reprocessing plant. The plutonium-uranium mixture can be fabricated by remote-control techniques into fuel elements satisfactory for a breeder reactor. Such a process has in fact been studied jointly by the British and the Electric Power Research Institute (EPRI) in the U.S. Named Civex, to emphasize its civilian character, the process was recently described at the Fifth Energy Technology Conference in Washington. The Marshall-EPRI proposal, in sum, is that a dilute plutonium mixture can be safely recovered from spent fuel in Civex plants and incinerated in fast breeder reactors.

Whatever Became of...?

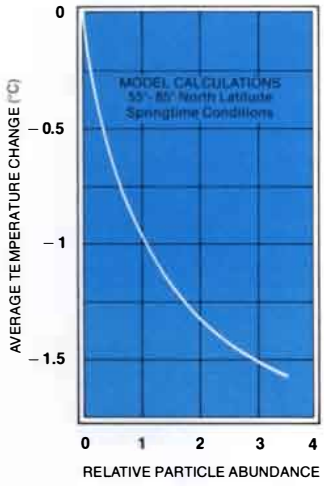
The transplantation of the human heart is a surgical procedure that has now passed its first decade. Little re-

Global temperature... looking toward 2001.

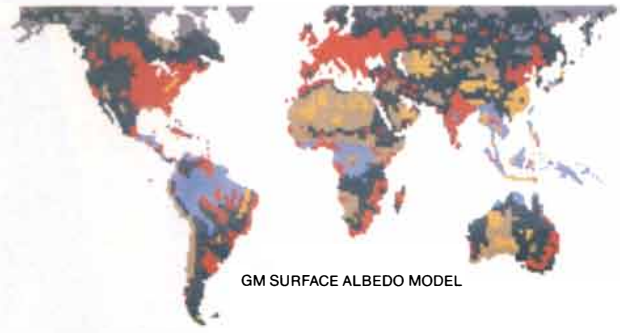
Churning throughout the earth's atmosphere are substances that could change the climate of tomorrow. One way in which scientists the world over try to anticipate the possible effects of these substances is via mathematical modeling. That's the approach we've been taking here at the General Motors Research Laboratories.

Our scientists started with one of the most complex atmospheric representations in existence: the radiative-convective model developed at Princeton University. They then reformulated it to include airborne particles.

Among the early uses of this new tool was an attempt to correlate an ice buildup in the Far North in 1971 with a reported jump in particle abundance. Just prior to the jump, four volcanoes had erupted in this region. Calculations with the model indicated that the particle increase could indeed have lowered temperature, thus delaying the spring melt and hastening the fall freeze (see graph).



In other experiments, we studied over 30 parameters . . . gas concentrations, albedos (reflectivities of the earth's surfaces), cloud and particle abundances, Rayleigh scattering coefficients. The goal has been to understand global temperature response to changes in O_3, CO_2, particles, and the chlorofluoromethanes.


GM SURFACE ALBEDO MODEL

So far, our findings lead to these main conclusions:

- Surface albedo exerts the most influence on global temperature change. Next in importance are Rayleigh scattering, humidity of the lower troposphere, and CO_2.
- Atmospheric particles work against the temperature increase attributed to CO_2 (the greenhouse effect).

Global temperature modeling: One of the many ways we're helping to explain, and maintain, this planet Earth.

General Motors Research Laboratories
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POLAROID INTRODUCES

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THE SECOND REVOLUTION IN

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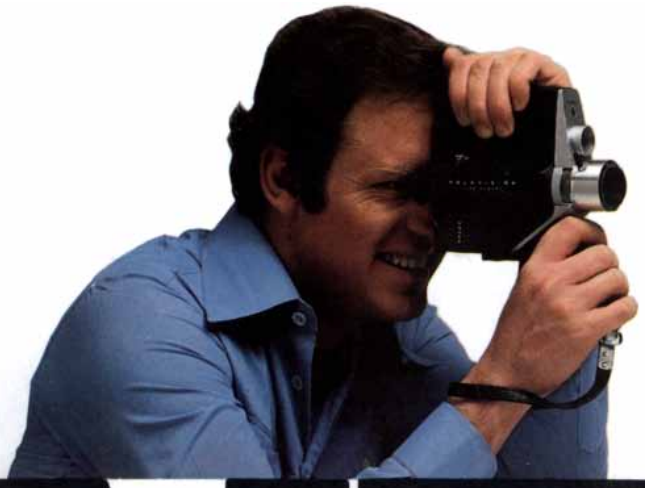
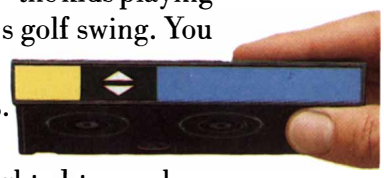


NT PHOTOGRAPHY IES

Polaroid, the inventor of instant pictures, introduces the second revolution in photography. Movies you can see in brilliant color seconds after you've taken them. Movies you can take even if you've never held a motion picture camera before. Movies your family can view again and again, on a compact, elegant player that sits out on a table or tucks into a bookshelf. See how simple it is:

1. Drop a cassette into the lightweight, automatic Polavision camera. Squeeze the trigger, and you're making your movie—the kids playing ball, a family party, your wife's golf swing. You can zoom in for dramatic close-ups or pull back for wide shots.



2. When your movie is finished (and you'll be delighted to see how many sequences you can shoot in 2½ minutes), drop the cassette into your Polavision player.

3. In seconds, your instant movie appears on the screen. (That simple-looking cassette has actually recorded in breathtaking detail the images you saw through the viewfinder.) The picture is sharp, the colors rich and clear. There's no projector or movie screen to set up, no threading or winding. To start the player, you just drop in a cassette. Children can entertain themselves indefinitely replaying the cassettes. Treat your family to a Polavision system. Enjoy the new experience of making instant movies, and start building a living diary of the memorable moments of your life.

SIMULATED PICTURE

POLAVISION FROM POLAROID

mains of the excitement and curiosity that followed the first transplantation by the South African surgeon Christiaan Barnard in December, 1967, and the high expectations that were held for the procedure as a means of dealing with heart disease. Looking back in an editorial in *The New England Journal of Medicine,* W. Gerald Austen of the Massachusetts General Hospital and the Harvard Medical School writes: "After an initial flurry of excitement, and widespread trial in many centers, recurrent failures led to disillusionment and virtual abandonment of the procedure, in all but one or two institutions."

In retrospect the stir of 10 years ago seems to have been based more on hope and the boldness and originality of the procedure than on rational considerations. Tissue rejection, which had been the main problem in the transplantation of other organs, proved to be equally difficult in the transplantation of the heart. The effort to override rejection by suppressing the patient's immune reaction against foreign tissue made infection a major risk for the recipient of a transplanted heart. The shortage of hearts for transplantation has been a continuing problem. Among other reasons legal complications over the definition of death have held down the size of the donor pool.

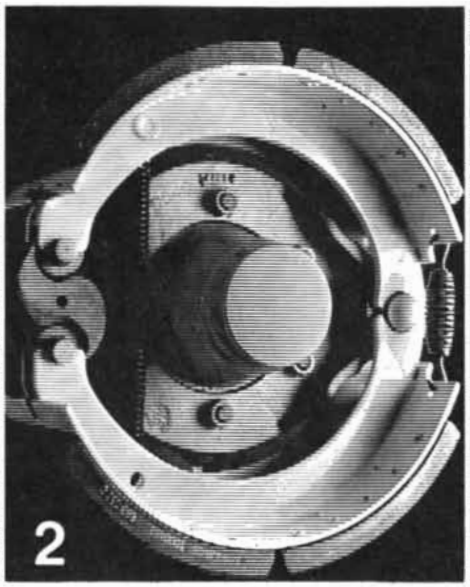
As of the beginning of this year about 360 heart transplantations had been done worldwide. More than a third of them were done at the Stanford University Medical Center, where Norman E. Shumway and his colleagues are continuing with their experimental program. Progress there has raised the level of survival to about 68 percent after one year and 56 percent after five years. Austen writes: "Today, therefore, heart transplantation offers a rational therapy for a few carefully selected patients with end-stage heart disease who otherwise would surely die soon. Does this progress mean that the procedure should now be revived in cardiac surgical units throughout this country? Certainly not. Heart transplantation is still undergoing clinical trial, and requires much further refinement and evaluation."

Of Men and Naked Mice

The clinical testing of an experimental cancer therapy often raises ethical dilemmas for the physician because the possible benefits of the procedure must be weighed against the risks or discomfort to the patient. In order to avoid such painful choices many attempts have been made to test novel therapies in model systems such as animal tumors or human cancer cells maintained in culture. Such approaches are of limited value because human tumors vary markedly from animal tumors in their responses to therapies, and few human tumor-cell lines grow well in culture. The more desirable alternative—to grow human tumors in laboratory animals—also seemed impossible because the human tumors are normally recognized as being foreign by the immune system of the animals and are rejected like any piece of tissue from an unrelated donor.

In 1966, however, investigators in Glasgow reported a mutant strain of mice that were totally hairless ("nude") and also lacked the thymus gland, a critical component of the immune system. The nude mice could still manufacture antibodies, but they were unable to make the thymic lymphocytes (T cells) essential for the rejection of grafts of foreign tissue. The unexpected arrival on the scene of these genetic "mistakes" seemed to be a windfall for cancer investigators, since it meant that it would finally be possible to transplant various human tumors into the animals and directly assess the effectiveness of novel therapeutic agents in selectively destroying the tumor cells.

The initial enthusiasm was dampened somewhat, however, when the difficulty of breeding the nude mice was realized. Since they are lacking in immunological



Eaton Update:

1 Getting the power around the corner

Eaton hydrostatic transmissions offer designers of agricultural equipment great flexibility by replacing awkward mechanical linkages with hydraulic lines that can go around or through other components. They allow the equipment to work more efficiently because operators have an infinite selection of operating modes.

Eaton's commitment to hydrostatics started in the mid-sixties. A new plant in Spencer, Iowa, is operating at maximum capacity, and we are planning another expansion to serve this growing market.

2 The advantages of being single

With Eaton's Single Anchor Pin brake system you can reline a truck brake in just two minutes—and the only tool you need is a screwdriver. With conventional double anchor pin systems the job can take hours, even with special tools.

This Eaton exclusive is saving down-time for truckers all over the country. But it's only one of our many contributions to trucking efficiency. We're a leader, worldwide, in axles and heavy-duty transmissions, and we're winning an ever-stronger position in components like brakes and anti-lock systems, fan drives, and air conditioning.

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The Eaton Proving Ground at Marshall, Michigan, subjects truck and automobile components to horrendous treatment. The facilities include a 1.6 mile oval track for sustained endurance testing; road surfaces that are just plain hostile; a salt bath for corrosive brake lining tests; and a 1200-foot skid pad that can simulate any skid condition.

It's all part of Eaton's total commitment to quality. We market new engineering ideas only after having proved that they excel at surviving in the real world.

Eaton is a family of technologically related businesses with a balanced combination of manufacturing and engineering skills. We're always looking for new ways to use these skills in markets where needs are growing. This approach to the management of change has been achieving record sales and earnings. For the complete story, write to: Eaton Corporation, 100 Erieview Plaza, Cleveland, Ohio 44114.

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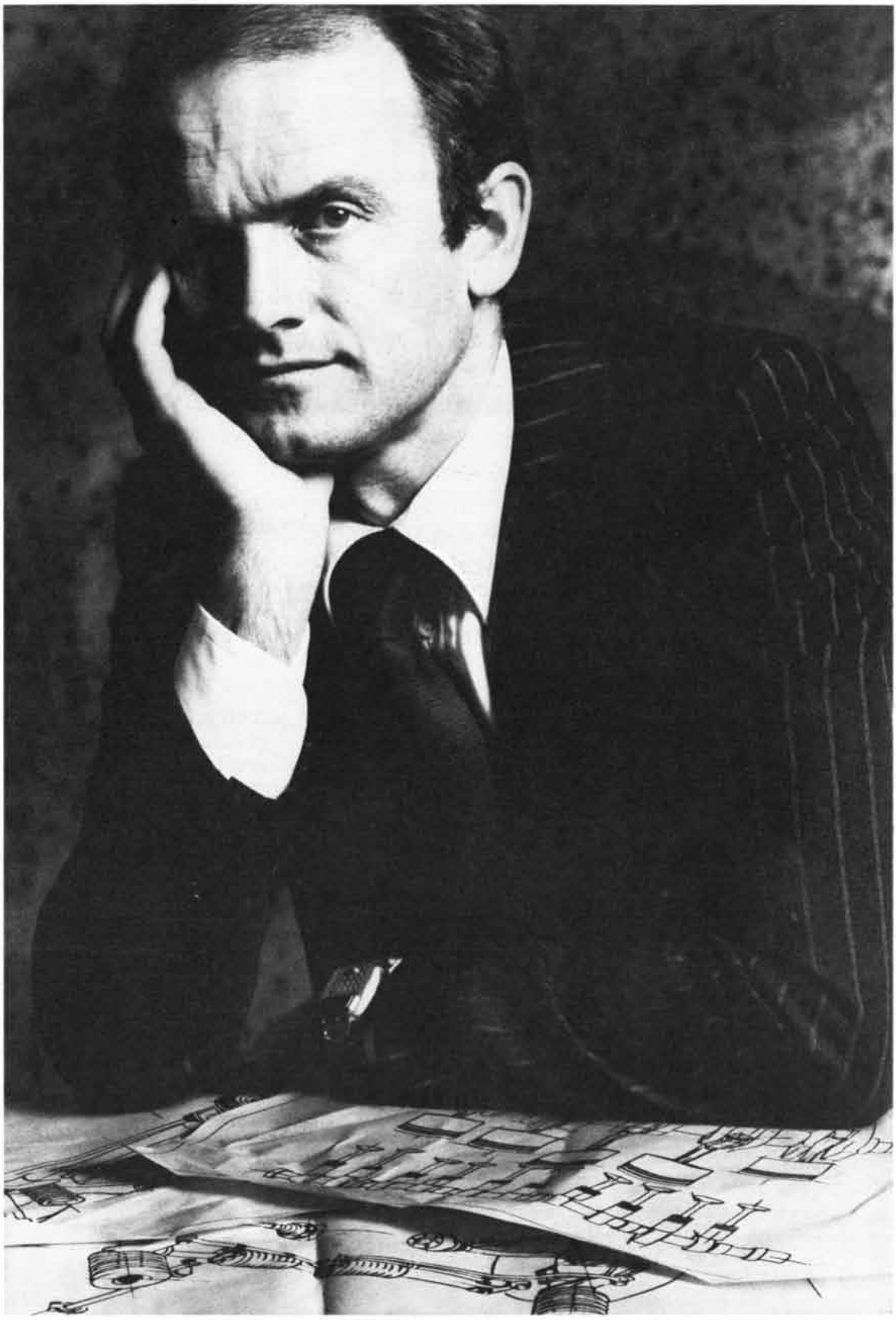

"I USED TO DESIGN RACING CARS. BUT THE AUDI 5000 WAS A BIGGER CHALLENGE."

AN INTERVIEW WITH FERDINAND PIËCH, AUDI 5000 PROJECT DIRECTOR

Sir, how long did you design racing cars?

Piëch: Ten years in all. I brought six cars from the drawing board to the race track and all six went on to win world championships. It was all very exciting.

And you say designing a passenger car was more of a challenge?

Piëch: It was for me. A racing car can be designed to last for a few races only. But a passenger car obviously has to be designed to do much more and to last much longer. In addition to excellent performance and handling I had to consider things like room, comfort and price.

What about the price?

Piëch: I was determined from the beginning to prove that a large German luxury sedan could be produced for under $9,000.*

Well, you succeeded with price, but did that mean you had to compromise a lot?

Piëch: No. I don't think so. It was a question of eliminating unnecessary things. The greatest example of that is our five-cylinder engine. Five cylinders, because a four was too small for the weight of the car, and a six was too extreme. Designing the perfect engine for the vehicle can hardly be called making a compromise.

Your racing background? Did it come in handy?

Piëch: Yes, yes. Very much so. The way the Audi 5000 handles, for instance. The ride is not in the least bit mushy. Our suspension, our rack-and-pinion steering and our weight distribution have a lot to do with that. Which is why we suggest that people pick a rainy or snowy day to take a test drive. This car is at its best when the weather is at its worst.

Is it possible to build a car with a soft, mushy ride, and still retain great responsive handling?

Piëch: No, not at all. They are exactly opposite. Some people feel that a soft, mushy ride is luxurious. We, the engineers at Audi, do not. We think it's tiring because you seem to be correcting the car's handling so often. We believe that a truly luxurious car is one that does what you want it to do when you want it to do it. That's why we engineered the Audi 5000 to be so precise and responsive.

What do you think of American cars?

Piëch: Like everything else, there are good things and bad things. The good things we tried to incorporate in the Audi 5000. More comfort. More room. To be quiet. To give it cruise control as standard equipment. And you can order a powerful, American type air conditioning system for your places like Florida.

Quickly, what would you say to convince Americans to buy an Audi 5000?

Piëch: I would say they can now buy a European car that was designed with American needs in mind. What we have tried to build is the one car that's the best of both worlds. I hope that doesn't sound, ah, what do you say...corny?

*Suggested 1978 retail price under $9,000 P.O.E., transp., local taxes, and dealer delivery charges, additional. Come test-drive the Audi 5000 at your local Porsche + Audi dealer.

defenses, nude mice are highly susceptible to infection and must be raised in a germ-free environment in which the food, water, cages and bedding have been sterilized. Even when such precautions are taken the majority of the mice usually die before weaning, and those that survive grow slowly, have difficulty reproducing and often succumb within a few months. A colony established by Nathan O. Kaplan and Gordon H. Sato of the University of California at San Diego, however, has proved to be an exception: they have managed to breed a thriving group of nude mice that now numbers about 2,500. Kaplan suspects that the success of the colony may have something to do with the paucity of viruses in the La Jolla environment, but the precise explanation remains mysterious.

In any case Kaplan and Sato have exploited their good fortune to grow more than 30 different lines of human tumors in their nude mice. Most of the tumors were removed from patients during surgery at nearby hospitals, sterilized with antibiotics, minced to separate the cells, and injected beneath the skin of a nude mouse within four hours after surgery. Each tumor is transplanted from one mouse to another every two or three months to keep it growing; in this way its progress can be monitored and the effect of various drug therapies observed. Kaplan says: "This [technique] offers clinicians and researchers the unprecedented opportunity to observe the continued growth of a patient's tumor after it has been removed from the patient."

The San Diego investigators have had various degrees of success in growing various human tumors in the nude mice. Malignant tumors from the colon, the skin and the lung are easy to establish, whereas those from hormone-sensitive tissues such as the prostate, or from lymphoid tissues, are very difficult to grow. The latter failures may be due to the requirement of the tumors for particular hormones or to the residual immune response in the nude mice. Moreover, benign tumors inevitably stop growing in the nude mice after about three transplantations over a period of about a year. Why the benign tumors stop growing is not understood, but it may be due to the "senescence" of the tumor cells or to the depletion of an essential growth factor that is found in human beings but not in nude mice.

Although their work is still in the experimental stages, Kaplan and Sato plan to increase the size of their nude-mouse colony to more than 5,000 animals so that they can process human tumors on a large scale. They predict that in the future every cancer patient's tumor will be carried in nude mice, so that the best possible therapy for his type of cancer can be devised and tested on the transplanted tumor before being administered to the patient. Surprisingly, the procedure is not expensive: it now costs between $150 and $200 to maintain a tumor in nude mice for a year, and the price should decline as the colony expands in size.

Another important factor in the development of an effective cancer therapy is that it should act like a "magic bullet," killing cancer cells while doing a minimum of damage to normal ones. Since normal human tissues can also be transplanted to nude mice, some estimation of the possible toxicity of an experimental drug or procedure can also be evaluated in the animals. Kaplan and Sato, in collaboration with Stephen B. Howell of the University of California at San Diego School of Medicine, have transplanted human tumors on one side of a nude mouse and normal human tissue (such as skin or bone marrow) on the other side. This technique promises to enable investigators to make direct comparisons between the tumor-killing effectiveness and the toxicity of novel chemotherapeutic agents before they are administered to human patients.

The Redundant Maya

How does one read an unknown language? A case in point is ancient Maya, which is currently yielding further to modern scholarship. By the time the Spanish were firmly entrenched in Mexico and Guatemala in the mid-16th century not much Maya writing remained. From the libraries all that had escaped the conquerors' flames were three gatefold manuscripts painted on deerskin, now known as the Dresden, Madrid and Paris codexes. In addition there were 64 hieroglyphs written down for Diego de Landa, Bishop of Mérida, by surviving Maya scribes in about 1566. A number of hieroglyphic inscriptions also survived, some painted on pottery but most carved on monumental standing stones, on the walls of public buildings, on the edges of altar stones and even on the balustrades and risers of stone stairways that the Maya had built at various centers in the lowlands and highlands of southern Mexico, Guatemala and Honduras over a span of some 1,200 years.

The Maya inscriptions in stone are still being catalogued; more of them, and more inscriptions on pottery, turn up every year. Judging from the inscriptions available for analysis, Maya hieroglyphic writing was based on 400 to 600 individual glyphs that sometimes stood alone but more often appeared in combinations of two or more. Western scholars of the 19th century quickly grasped the Maya system of numerical notation; studies since then have unraveled the intricacies of the calendar system and even outlined the achievements of Maya astronomy. Until recently, however, efforts to "read" noncalendric Maya inscriptions met with results that

DP Dialogue

Notes and observations from IBM that may prove of interest to the engineering community

Here, telemetry devices transmit experimental data to a mobile laboratory. Similar advanced technology is reflected in Deere's worldwide data base of thousands of components, letting engineers utilize existing parts when developing new products.

At John Deere, No One Reinvents the Wheel

Engineers at John Deere don't spend time reinventing the wheel or designing new hydraulic pumps or valves when existing ones will do the job. At their fingertips are data on all Deere parts and design parameters on commonly used parts and components. This multinational manufacturer of machines for farm and construction has created a multilingual data base called WISE—Worldwide Information System for Engineering.

"If an engineer in, say, our Mannheim, Germany plant needs a hydraulic cylinder design," says Gordon Millar, vice president of engineering, "he can use an online terminal to call up complete descriptions of similar cylinders already in use in Deere worldwide. He will probably find a design he can use with little or no change.

In Four Languages

"Since WISE is literally a worldwide system, it cuts across barriers of language, distance and culture," adds G.T. Underwood, manager of Deere's corporate engineering standards department. "Our master list of terminology is already in four languages: English, French, German and Spanish and all dimensions are in metric and English. WISE has greatly enhanced our worldwide standardization efforts. Also our engineers around the world can readily access design specifications, application information, cost, vendor lists and the like."

"WISE was the first element of a corporate parts data base," says Larry Moore, administrator of engineering information in Deere's corporate engineering standards department. "Now it has links to other business systems in the company, supporting applications in such areas as service parts, warranty service, and parts catalog publications.

"Currently there are about 50 CRT (cathode ray tube) and 100 computer output microfiche display stations in 20 design centers in the U.S., Europe, Argentina, Australia and South Africa. CRT's access our IBM System/370 complex in Moline through the same telephone lines that carry our voice communication.

"The engineer can search the data base by attribute, such as the size or pressure rating of a hydraulic cylinder. In effect, he describes a desired part to the system and automatically receives back a listing of all Deere parts which fit the description.

"We're achieving better parts commonality, and better, faster communication among engineering and manufacturing groups all around the world, by means of the computer."

CADAM is Brought to Martin Marietta Engineers

Engineers are using a multiple-site version of the Computer-Graphics Augmented Design and Manufacturing (CADAM) system at Martin Marietta Aerospace. CADAM converts freehand sketches, made with a light pen directly on the screen of a CRT display, into fully detailed and dimensioned drawings.

At Martin's Orlando (Florida) Aerospace Division, which designs and builds sophisticated guided missile systems, the interactive portion of CADAM runs on a System/370 Model 138 in the division's main engineering facility. The data base of drawings, graphics standards, and design data is stored in a host computer operated by Martin Marietta Data Systems in a computer center five miles away.

"With this approach, we can bring CADAM to the engineer in his work environment, and at the same time give him access to a centralized data base," says Kermit E. Gay, director of the Orlando Aerospace Account for Martin Marietta Data Systems (also a subsidiary of Martin Marietta Corp.). "Despite the constant stream of revisions, CADAM assures us that all engineers working on related projects use the same version of the design data. And everyone uses the same library of graphic standards for fittings, hardware and other repeatedly used graphic elements."

To calculate geometry and make engineering drawings of missiles, Martin Marietta uses CADAM, a program product available from IBM.

Adds Thomas Boulter, engineering task leader/CADAM for the Orlando Division: "Putting functions 'outboard' in a dedicated processor creates a simple, responsive local system for us. And CADAM is oriented toward me as an engineer; it does things the same way I do.

"Today, we are developing everything from early concept to production drawings on CADAM, and doing it four or five times faster than before."

Engineer Paul Arnold designs stabilized-platform gimbal systems and other precision electromechanical equipment at Orlando. "CADAM takes over much of the math required to lay out a mechanical system," he says. "We handle many cylindrical and conic surfaces, and the system takes care of all the geometric calculations—coordinate transformations and the like. We can observe gear engagement, gimbal articulation, and similar part compatibility on the terminal screen—blowing up the scale of miniature assemblies as large as necessary to see any interference. We can make parts move on the screen—'precessing' or rotating a gyroscope, for example, through its full range of travel."

"CADAM also helps us prepare design concepts for proposals," Boulter notes. "Working interactively at the terminal, an engineer can reach an optimum configuration quickly.

"CADAM is easy to learn," he adds. "I was teaching others to use it after only 30 hours of instruction myself."

Decision Tables Automate the Programming of Logic

	01	02	03	04	05
Red Signal	No	No	Yes	Yes	Yes
Right turn intended	–	–	No	No	Yes
Pedestrian present	No	Yes	Yes	No	No
Go	X				X
Stay		X	X	X	

This simple table makes the go, no-go decision for an automobile where right turns on red are legal. Each vertical column is a rule to be read from top to bottom. The conditions above the double line lead to the actions below it. DTABL routines would determine that one more rule is needed ("Yes, Yes, Yes, Stay") and that rules 03 and 04 can be condensed into one by the use of "don't care," indicated by a dash.

Decision tables are not as well known as they deserve to be. They are a powerful tool for coping with complex decision-making in such engineering applications as image analysis, flight simulator control systems, and utility station or other large plant control systems. A less obvious example is the design of an electronic circuit to find the simplest layout with the fewest crossovers.

On paper, decision tables are a clear, concise and self-documenting notation for program logic. With computer programs called decision table processors, such tables can be converted into executable programs by the computer itself.

In the simple decision table above, each vertical column on the right is a rule. The number of possible rules rises rapidly, even for small problems: as 2^N with "N" the number of conditions. Electrical engineers will note a resemblance to the notation used in "truth tables" for switching logic.

IBM's APL Decision Table Processor (DTABL) accepts decision table input in a simple format. The processor checks it for validity and completeness, then determines the most efficient flow sequence through the logic. Finally, DTABL generates a program in a standard computer language such as APL, PL/1, COBOL or ALGOL. Or DTABL can express the program flow in a user-written "pseudocode" (e.g., "Close valve no. 37"), readily expandable into any desired programming language.

In a complex application, it is easy to overlook ambiguous, missing or redundant rules, especially when "don't care" states are introduced. The DTABL error-checking logic reports such errors before it compiles a program.

When a program must be executed many times, as in a real-time control system, its length becomes crucial. DTABL helps here with an optimization function which usually generates programs as short as, and sometimes shorter than, those produced by experienced programmers.

Although DTABL is implemented in the APL programming language, it can be used with no knowledge of APL. The engineer thinks in the logic of his application; he need learn only a few simple notation rules for filling in the decision-table form to obtain the power of DTABL.

Who's Zoo: A Social Register for Animals

One American zoo needed a Celebes ape not long ago. Another needed an echidna (or spiny anteater). A computer helped each identify a zoo with a surplus of the desired animal.

The American Association of Zoological Parks and Aquariums, in conjunction with Federal agencies and private foundations, sponsors a project that some day will store data on every animal in every zoo in most countries of the world. The association's International Species Inventory System (ISIS), headquartered at the Minnesota Zoological Garden, Apple Valley, has already placed in an IBM computer detailed information on 25,000 mammals and 10,000 birds located in zoos in the United States, Canada, and Europe. ISIS will someday also include data on reptiles, amphibians, and fish.

A Vital Task

Says Janice M. Olsen, systems manager of ISIS: "A vital task of modern zoos is to develop and maintain self-sustaining populations of captive wild species and—in certain cases—to provide the only reservoir of species on the verge of extinction. To do this, we must collect data and share it.

"ISIS tells us the captive numbers and reproductive rates of animals on the endangered species list, such as the Indian rhinoceros, Siberian tiger and orangutan. This information aids the development of breeding management programs for captive wild animals."

Finding Rare Mates

Another valuable service of ISIS—the acronym spells the name of the Egyptian goddess of motherhood and protection—is the finding of a mate for a rare species in a zoo that does not have one of each sex. The computer, which is an IBM System/370 Model 158 in the state data processing center in St. Paul, Minnesota, helps to match animals needing mates with available candidates, to the benefit of the rare species themselves and of zoos all around the world.

The International Species Inventory System (ISIS), a computer data base of animals in zoos, is helping endangered species like this Siberian tiger.

Data Management and Retrieval Aids for APL Users

These program products, implemented in the user-oriented APL programming language, are operated interactively, through a terminal.

1. A Departmental Reporting System (ADRS) allows the engineer to produce reports customized to his needs. It extracts the required information from an existing data base.

2. APL Data Language is a powerful data management facility: a dictionary-driven, data-independent, data storage and retrieval system. Complements the extensive data manipulation capabilities of APL.

3. APL Data Interface is a general-purpose facility for inquiry into many types of data files. A simple and economical way to interactively access data to obtain immediate answers to unanticipated questions.

For more information on these and other IBM program products, contact your local IBM branch office or write to the Editor of DP Dialogue at the address on the right.

DP Engineering Dialogue is designed to provide you with useful information about data processing applications, concepts and techniques. For more information about IBM products or services, contact your local IBM branch office, or write Editor, DP Dialogue, IBM Data Processing Division, White Plains, N.Y. 10604.

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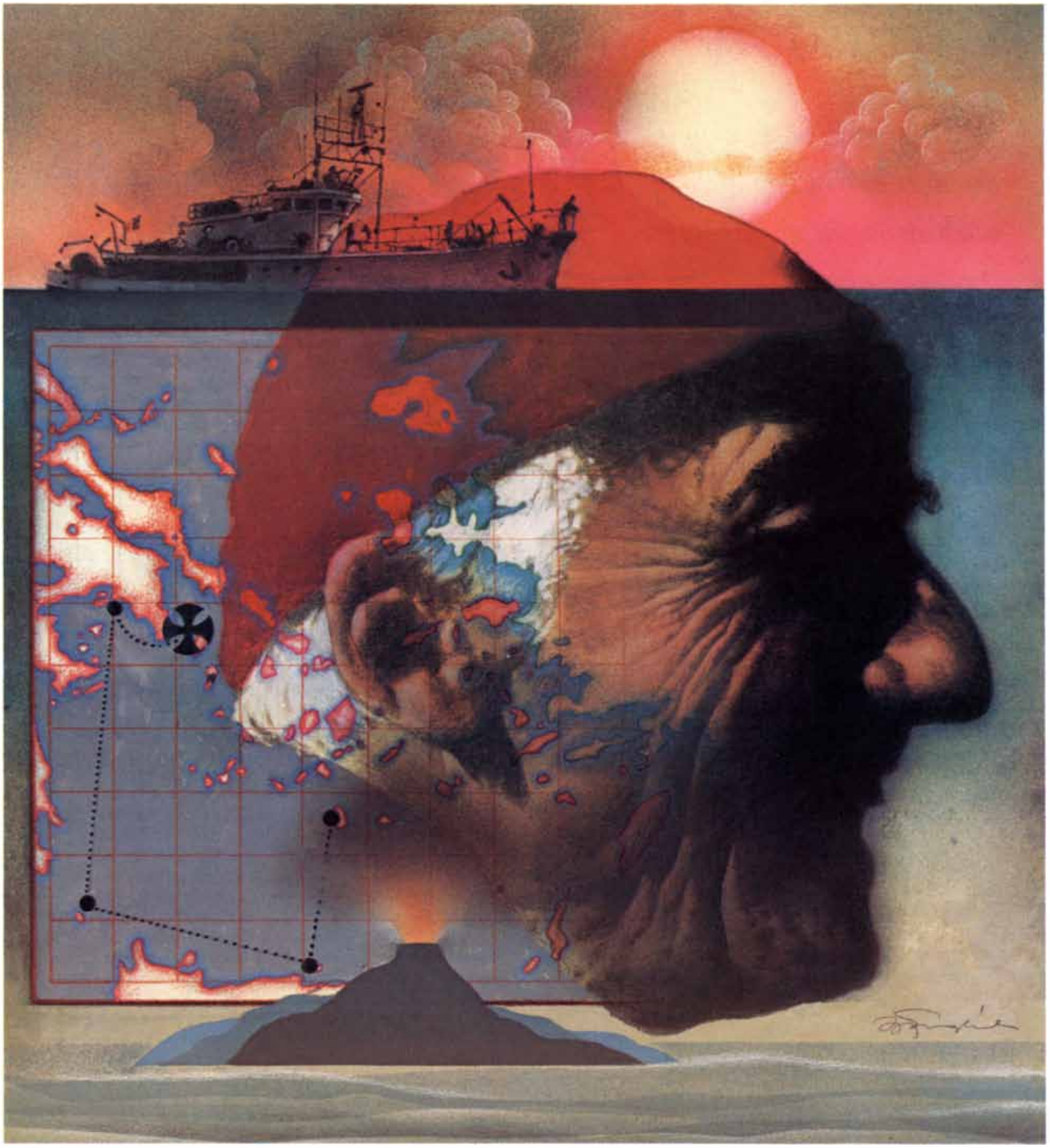
were usually ambiguous and often contradictory.

The situation has now changed greatly, much as when the "Linear B" texts of Crete and Greece became meaningful after Michael Ventris was able to assign specific phonetic values to specific signs. One crucial source of phonetic clues is Bishop Landa's transcription of some 30 hieroglyphs that, he believed, comprised a Maya "alphabet." It is now evident that the scribes who worked under Landa's direction were not writing down an alphabet of their own language but were faithfully transcribing each letter of the Spanish alphabet into the Maya glyph or combination of glyphs that had the same phonetic value as the letter did in spoken Spanish.

Four scholars are now collaborating in a study that embraces the Landa phonetics, other clues regarding the sounds represented by various glyphs and the invaluable but hitherto little exploited colonial and postcolonial bilingual Spanish "dictionaries" of various Maya dialects. They—Floyd G. Lounsbury, a linguist and epigrapher at Yale University, Linda Schele, a graphic analyst at the University of South Alabama, David H. Kelley, an anthropologist and epigrapher at the University of Calgary and Peter Mathews, a doctoral candidate in anthropology at Yale—are engaged in reading one of the longest-known Maya monumental inscriptions. That inscription is one found at Palenque, a Classical Maya site of the seventh to ninth centuries A.D. in the northern hills of the state of Chiapas in Mexico. Consisting of some 600 glyphs, the inscription begins inside one structure at the site, is continued in a second structure and is completed inside a third.

What were the Maya saying? The four collaborators estimate that it will take scholars another generation to tease out the relation between the many still unreadable glyphs and the various Maya words listed in the Spanish bilingual texts. Nevertheless, the present state of knowledge makes it possible to give meaningful readings of most monumental inscriptions, which average between 15 and 30 glyphs in length. One of the earliest Maya inscriptions to be discovered appears on a small jadeite engraving known as the Leyden Plate, made early in the fourth century A.D. The inscription, only 15 glyphs long, establishes a date in A.D. 321 (according to what is known as the Thompson correlation) and goes on to read: "[Undeciphered name] was seated, this ruler of the Sky family of Tikal." Tikal is a Classical Maya center in the Guatemala lowlands. The inscriptions on most of the Late Classical monuments in lowland Guatemala and adjacent Mexico record exactly this kind of information, set down in exactly the same manner.

The situation at Palenque is different. The native limestone is too brittle to be made into the conventional stelas, or standing stones, that carry most Maya monumental inscriptions. Having interior walls rather than stelas to work with enlarged the total area available to the Palenque scribes by at least a factor of eight. Challenged by the empty space the scribes chose redundancy as a means of filling it. Beginning with the accession of an ancestral goddess, the inscription lists 12 successive rulers, mythical and real, before concluding with highlights in the life of the 13th ruler in the Palenque line: his accession in A.D. 684, the 75th anniversary of his father's accession, the eighth anniversary of his own accession and the dedication of the inscription itself, which was completed in A.D. 702. The 13th ruler, named "Serpent-jaguar" (phonetically Chan-bahlum), is honored as one who suckles the gods by ritually letting blood from his penis. To fill the Palenque walls, the birth, pedigree, accession, military achievements, ritual acts and deaths of Chan-bahlum's 12 predecessors are repeated at least once in the inscription; in certain instances the information is repeated five times.



The Cousteau Odyssey

This spring, "The Cousteau Odyssey" continues with an extraordinary journey into a legend.

"Calypso's Search for Atlantis. Parts I and II."

In two hour-long specials for PBS television, Captain Jacques Cousteau explores a totally new theory about the lost civilization that has held the imagination of people everywhere.

As in his two previous Cousteau Odyssey specials, "Diving for Roman Plunder" and "Calypso's Search for the Britannic," Cousteau again manages to open new doors to the mysteries that have been buried under the sea. While putting the indelible stamp of his genius on a legend that is sure to keep inspiring people for all time.

"Calypso's Search for Atlantis." It's an adventure that takes us to one of the key sources of our civilization.

The production of "The Cousteau Odyssey" specials for PBS is made possible by a grant from Atlantic Richfield Company to KCET, Los Angeles, expressly for the funding of the broadcasts. The specials are produced by Jacques Cousteau and Philippe Cousteau in association with KCET.

Ultrasound in Medical Diagnosis

With ultrahigh-frequency sound waves and imaging techniques first devised for radar and sonar, it is now possible to explore structures within the human body painlessly, safely and at relatively low cost

by Gilbert B. Devey and Peter N. T. Wells

Techniques for examining the interior of the living human body have traditionally entailed distinct risks and sometimes considerable expense. For example, until recently the only way to get certain kinds of clinically invaluable information about the interior of the heart was to insert a long, flexible catheter into it through a vein in the arm, a procedure with a risk of death of between .1 and 1 percent and a typical cost of $1,500. To obtain information about other organs physicians have often had to resort to exploratory surgery and the insertion of hollow needles. In the main, however, physicians have examined the interior of the body with X rays. Even then the examination of soft tissues often calls for the introduction of X-ray-opaque substances, procedures that can be painful and that have hazards and costs of their own.

Within the past decade another agency has provided new methods of examining the interior of the body painlessly and with a minimum of risk and expense. That agency is ultrasound. Instead of organs' being investigated by surgery, needle or X ray they are probed with pulses of ultrahigh-frequency sound waves that send back echoes. From the echoes, by means of techniques first developed for radar and sonar, pictorial images of the organs can be constructed.

Although the possibility exists that ultrasound could affect the tissues and could even damage them, over the past two decades millions of patients have been examined by ultrasonic techniques and no adverse effects have been reported. Taken together with the negative results of experiments designed to discover the biological effects of diagnostic ultrasonics, to us that is convincing proof that the conditions of exposure with current techniques are innocuous. Therefore ultrasonic diagnosis is safer than methods employing ionizing radiation such as X rays, a fact that is of particular importance for the examination of pregnant women and young children. As a result ultrasonic techniques are now coming into their own as a means of obtaining pictorial cross sections of the body, of measuring the performance of the heart and the flow of the blood and of identifying tumors, cysts and other abnormalities, including certain types of cancer.

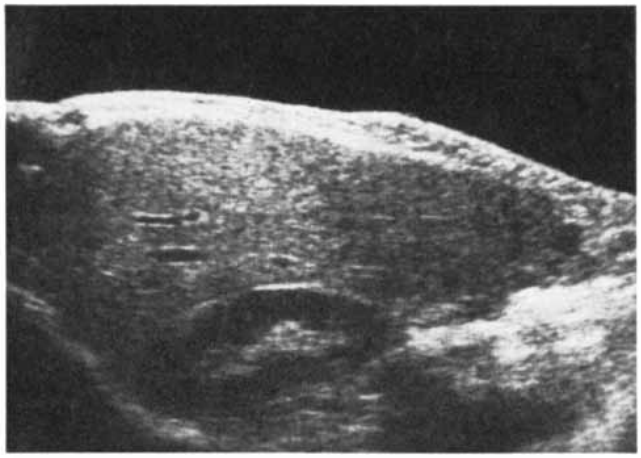
Although it has been only within the past decade that ultrasonic diagnosis has become accepted in a substantial number of hospitals, the first attempt to gain information about the structure of the human body with ultrasonic energy dates back 35 years. In 1943 Karl T. Dussik in Austria tried to map the outlines of the liquid-filled ventricles of the brain by recording in two dimensions how ultrasound is attenuated when it is continuously transmitted through the head. This method, which had been proposed 13 years earlier by S. Y. Sokolov in the U.S.S.R., failed because of the distorting influence of the skull. During World War II, however, on the basis of another suggestion by Sokolov, systems were devised independently by Floyd A. Firestone in the U.S. and D. O. Sproule in England to detect flaws in metals by sending pulses of ultrasound into the material and analyzing the echoes. Soon after the war J. J. Wild and J. M. Reid of St. Barnabas Hospital in Minneapolis and independently D. H. Howry of the University of Colorado School of Medicine succeeded in adapting the pulse-echo techniques to the investigation of biological structures. In 1957 Shigeo Satomura in Japan reported that he had monitored moving structures in the body by detecting the Doppler shift in the frequency of the ultrasonic echoes. Since then many experimenters have been actively working on refining these techniques.

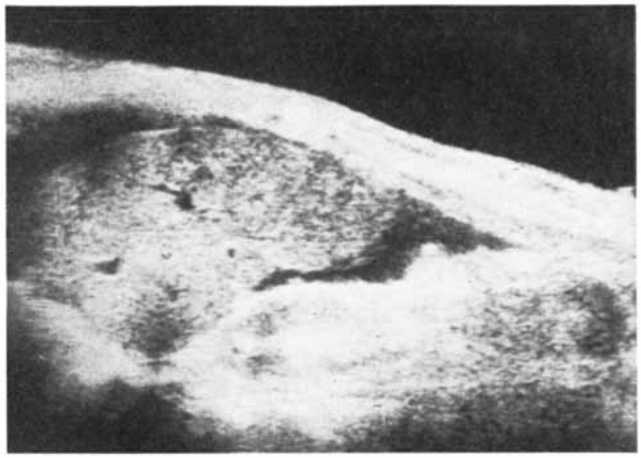
The Optics of Ultrasound

The ultrasonic waves used in medical diagnosis are sound waves with frequencies of millions of hertz (cycles per second), far above the range of human hearing. When pulses of ultrasound travel through a medium, they are reflected and scattered according to the same laws of optics that describe the behavior of audible sound. Most diagnostic applications of ultrasound depend on the fact that the pulses are partially reflected at boundaries between media that differ in their characteristic impedance. The impedance of a medium is equal to the product of its density and the velocity of sound through it. The density of soft tissues is close to the density of water; the velocity of ultrasound through tissues is close to the velocity of sound through water, ranging from 1,450 meters per second in fat to 1,600 meters per second in muscle. Therefore the difference between the impedance of one tissue and that of another is small, and the echoes reflected by the boundaries between them are faint.

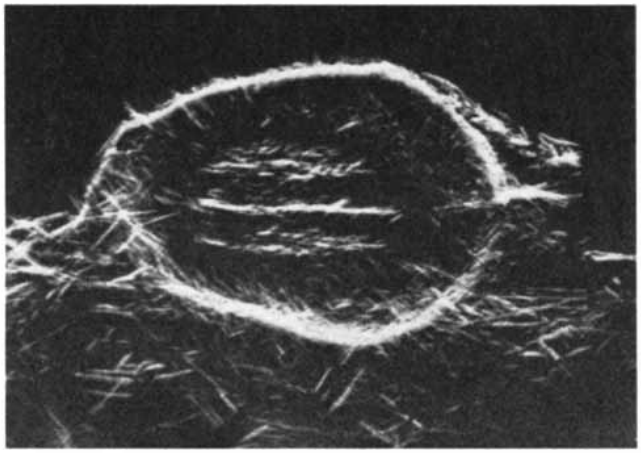
For example, at the boundary between kidney tissue and fat tissue only .5 percent of the incident energy is reflected. Such echoes are generally large enough, however, to be detected by a sensitive receiver. Furthermore, since so much of the ultrasonic energy travels across the boundary, it penetrates deeper and thus is an effective probe of organs deep within the body. On the other hand, the boundaries between soft tissue and either bone or gas return strong ultrasonic echoes because of the large discontinuity in impedance. These strong reflections limit the usefulness of ultrasonic diagnosis in some cases because they tend to mask the weaker echoes returned from the boundaries between soft tissues.

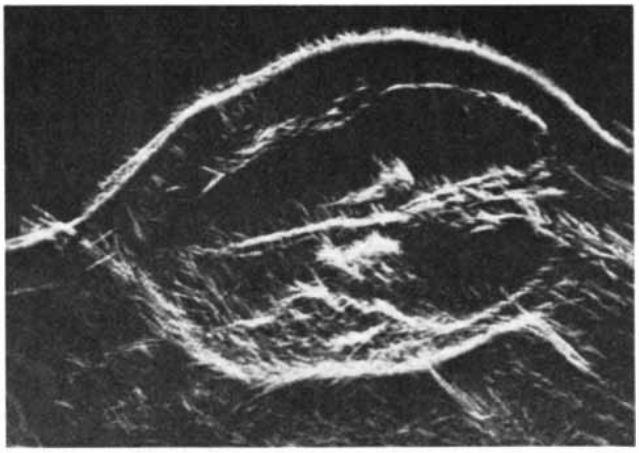
In any imaging system the resolution of the image is fundamentally limited by the wavelength of the radiation employed to form it. In principle the resolution is increased as the wavelength is decreased, and since the wavelength of the radiation is inversely proportional to the frequency, better resolution calls for higher-frequency radiation. In practice ultrasound is attenuated as it travels through biological materials by being spread, scattered and absorbed, and the rate at which ultrasonic energy is attenuated is directly proportional to the fre-



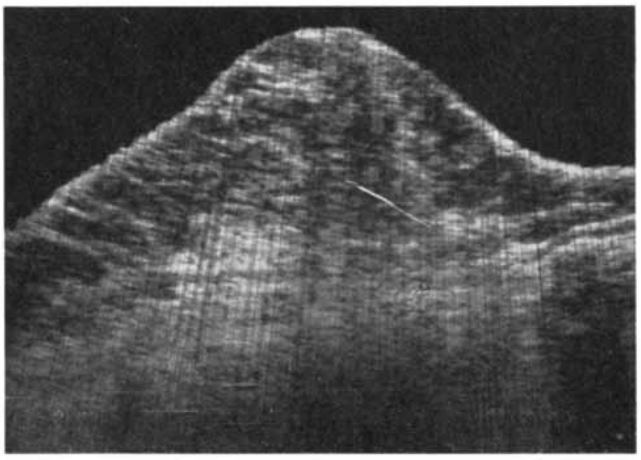


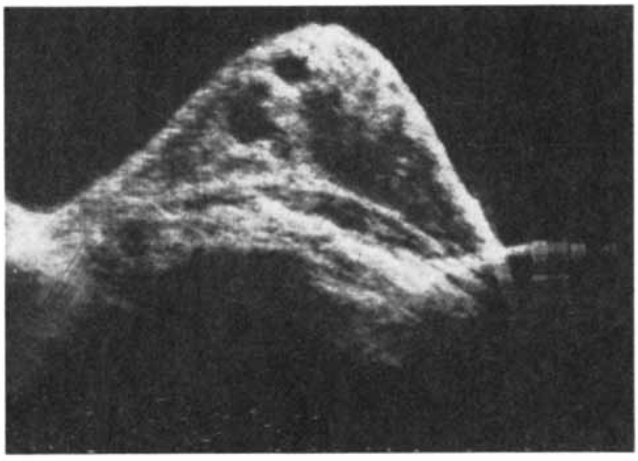
ULTRASOUND IMAGES OF THE LIVER compare a normal liver (*left*) with a cirrhotic one (*right*). In the image at the left the normal liver is the large, irregularly shaped gray mass in the center; the dark slits inside it are veins seen in cross section. The dark oval object below the liver is the kidney; the white band above the liver is the patient's skin. In the image at the right the cirrhotic liver is surrounded by fluid in the abdomen, which shows up as the black regions outside the organ that are particularly noticeable at the top left and bottom right. Both ultrasound images represent longitudinal cross sections through the body with the patient's head out of the picture to the left.



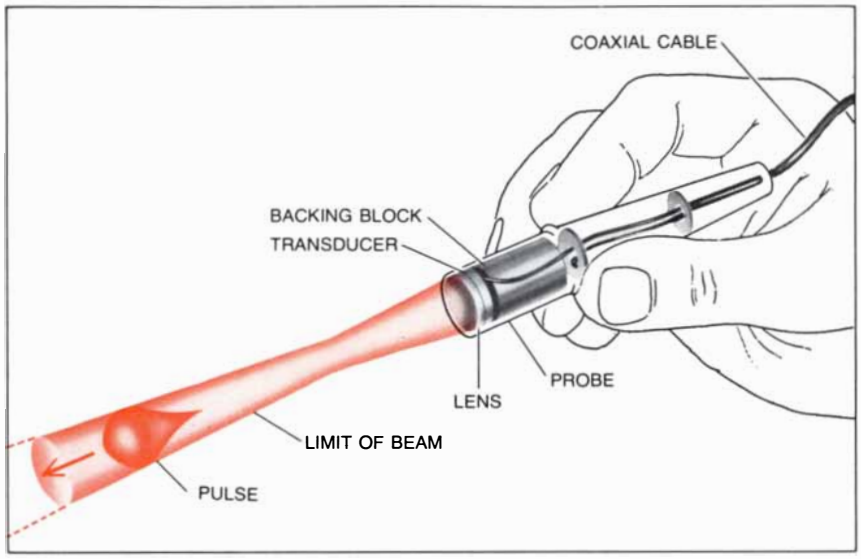


ULTRASOUND IMAGES OF THE HEAD of two one-month-old infants reveal hydrocephalus in one. Both images represent axial (horizontal) cross sections through the skull. The oval white line is the skull itself. The white line through the middle of the skull is the midline of the brain, and the white lines parallel to it are the boundaries of the fluid-filled ventricles in the brain. In the left image the ventricles are normal in size. In the right image an excess of fluid has greatly enlarged the ventricles and compressed the brain against the inside of the skull. (Short white lines resembling pieces of straw and lack of gray tones are artifacts of the machine that made the images.)

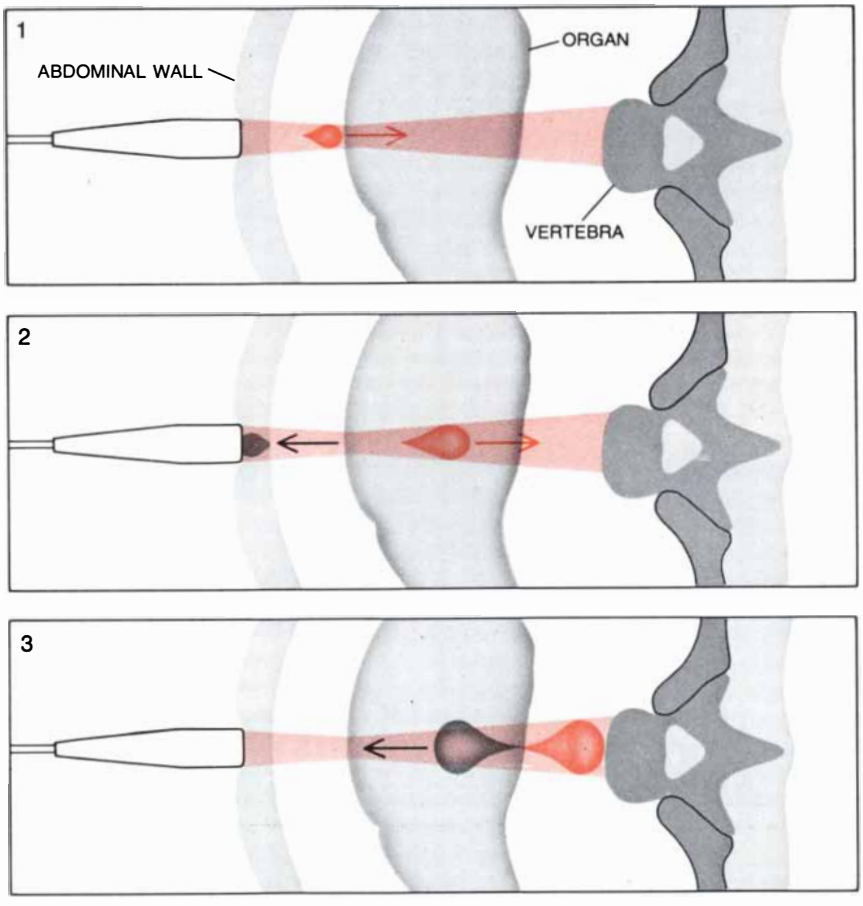




ULTRASOUND IMAGES OF THE BREAST reveal the presence of tumors. At left is an image of a normal breast; the regular mottled texture of the image indicates that the tissues are healthy. At right is an image of a breast with two small benign cysts; the cysts, which reflect ultrasound differently from the way surrounding tissues do, show up as the two black spots near left edge of breast. Both images represent longitudinal cross sections through the body with the head to left. All the images on this page were provided by Barry B. Goldberg of the Division of Diagnostic Ultrasound in the Department of Radiology at Thomas Jefferson University Hospital in Philadelphia.



PROBE for ultrasound pulse-echo diagnosis both transmits and receives the ultrasonic pulses. The transducer is a piezoelectric disk mounted on a backing block to damp its oscillation so that it is capable of sending out short pulses. The assembly is housed in a casing. A lens attached to the front face of the transducer slightly focuses the ultrasonic beam; in medical investigation the active portion of the beam is generally the region between the transducer and a point just beyond the focal point. The beam consists of a train of ultrasonic pulses that are emitted about a thousandth of a second apart. Each pulse, which is shaped like a teardrop, travels in the beam at the speed of sound and is reflected by the structures within the body.



ULTRASOUND PULSES ARE REFLECTED by organs and other structures in the body. This series of three panels shows the progress of a pulse (*color*) in "slow motion." The object of interest is the organ. The pulse first reaches the near wall of the organ (*1*); that wall returns an echo (*gray*), but most of the original pulse continues through the organ (*2*). At the far wall of organ a second echo is returned (*3*), but remainder of pulse continues on toward vertebra.

quency. Therefore in any particular application it is necessary to compromise between resolution and penetration by choosing a frequency that is high enough to give good resolution but low enough for the echoes from the deepest structures to be detected.

In most cases the optimum frequency is one that reaches the organ when it penetrates no more than 200 wavelengths. For example, at a frequency of three megahertz (three million hertz) the wavelength of the ultrasound is .5 millimeter, and it can yield good images of tissues that are as much as 100 millimeters deep. Hence at any particular depth the constraints on the wavelength control the scale of the anatomy that can be investigated. In abdominal and neurological examinations current techniques give optimum resolution at frequencies between one and three megahertz, corresponding to wavelengths of between 1.5 millimeters and .5 millimeter. In cardiovascular examinations the optimum frequencies range between two and five megahertz, corresponding to wavelengths of between .75 and .30 millimeter. In ophthalmological examinations the optimum frequencies range between six and 20 megahertz, corresponding to wavelengths of between .25 and .075 millimeter.

Ultrasonic Imagery

In an ultrasonic diagnostic system the ultrasonic pulses are generated by a probe that houses a piezoelectric transducer. Usually the same transducer serves for detecting the pulse echoes. As in radar and sonar, detecting the echoes yields information about the positions of reflecting interfaces within the medium through which the pulses are traveling. Ultrasonic echo-ranging depends on measuring the time interval between the moment the pulse is transmitted and the moment its echo is received. Since the pulse travels the same path twice (going and returning), the distance between the probe and the echo-producing interface is equal to half the product of the time interval and the pulse velocity. At a velocity of 1,500 meters per second the echoes require about 1.33 microseconds to travel each millimeter of the go-and-return path.

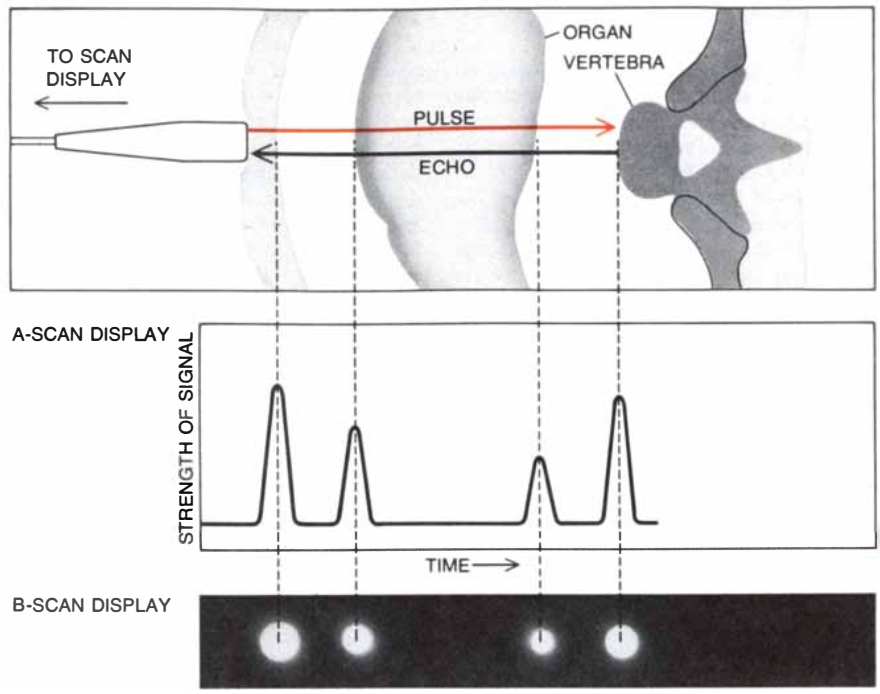
Pulse-echo information obtained from the human body can be displayed on a cathode-ray tube in several different ways. One way is a range-finding display called the A-scan display. In the A scan the horizontal axis represents the time required for an echo to return, corresponding to the distance between the reflecting structure and the probe; the vertical axis corresponds to the strength of the echo.

Interpreting a clinical A scan depends on prior knowledge of the anatomy of the structures lying along the path of

the ultrasonic beam. If the anatomy is known, two kinds of information can be obtained from the A-scan display. First, the distance between the probe and the echo-producing surface can be precisely determined. Such information is valuable for locating structures such as the midline of the brain. Normally the midline structure symmetrically separates the two sides of the brain, and its echo is found midway between the probe and the echo from the far side of the skull. The arrival time of the midline echo is advanced or delayed, however, if the midline structure is displaced by a space-occupying mass such as a tumor. The second kind of information that can be derived from the A scan is distinguishing between different kinds of mass: a mass of soft tissue returns low-amplitude internal echoes, whereas the liquid content of a cyst returns practically no echoes at all.

For most purposes the echo-ranging information contained in the A scan can be presented more effectively in the form of a brightness-modulated display called a B scan. In the B scan each ultrasonic echo is represented by a spot of light. The position of the spot represents the position of the echo-producing interface on an invisible time axis; the brightness of the spot represents the strength of the echo.

The B scan forms the basis of several display systems. One is the time-position scanning system, which can monitor moving structures such as the beating heart. The probe sends a regular series of pulses in the desired direction through the heart, and the line of returning echoes is displayed on a fiber-optic chart recorder; the positions of the echoes from the moving structures in the heart move correspondingly on the fiber-optic display. A continuous strip of light-sensitive recording paper is fed past the display, and the moving echoes are recorded as time-varying waveforms on the paper. If it is desired, the waveforms can be correlated with the trace from an electrocardiogram. If the probe is sequentially aimed in several directions through the heart, it is possible to assess the function of each of the heart valves and to evaluate the structure and function of the heart.



ECHOES OF PULSES ARE DISPLAYED on a cathode-ray tube, yielding information about the internal structure of the body. Two different types of display are shown. The upper one is the A-scan display, which is a graph of peaks showing the echoes received with respect to time. Strength of each echo is indicated by height of its peak. The first echo received is from the abdominal wall, the second is from the near side of the organ, the third is from the far side of the organ and the fourth is from the vertebra. Echo from the far side of the organ is fainter than the one from the near side because the ultrasound is attenuated as it penetrates deeper into the body. The echo from the vertebra is quite strong, however, because bone reflects a large fraction of the ultrasound energy and soft tissues reflect only a small fraction of it. The lower display is the B-scan display, which represents the echoes on the cathode-ray tube as a series of bright spots. Again the position of each spot represents the time required for the echo to return, but the strength of each echo received is represented by the brightness of its spot.

Two-dimensional Scanning Systems

The B scan also forms the basis of an imaging system that is particularly important in medical diagnosis: a system that forms pictorial images of two-dimensional cross sections through the body. In order to form such an image the ultrasonic probe is mounted on a mechanical scanner that moves in two dimensions. The scanner then provides data based not only on the strength of the echo and the distance of the source of the echo from the probe but also on the position of the probe and the direction of the ultrasonic beam. At each position of the probe on, say, the abdomen of a patient the echoes are returned from the organs lying along the path of the ultrasonic beam. As the probe is slid across the abdomen different organs lie along the beam. The position and brightness of the echo at each position are stored by the scanner, and when the probe has completed its motion across the patient's abdomen, the integrated image of all the stored signals is displayed, showing the patient's body in cross section.

There are several methods by which the two-dimensional image can be built up, stored and displayed. The simplest is photographic: a camera is set up facing a cathode-ray-tube display and the shutter is left open during the entire scanning procedure. The image is thereby integrated and stored on the film. The image can also be integrated on a cathode-ray tube of the storage type, but no storage tube currently available has an adequate gray scale, or dynamic range, for satisfactorily displaying the subtle differences between echoes of different intensities received from different structures. The result is that the contrast of the image is too high to be medically valuable.

Today most scanners store the image in scan converters. There are two basic types of converter: analogue and digital. The analogue scan converter is a vacuum-tube device resembling a cathode-ray tube, but the phosphorescent screen of the cathode-ray tube is replaced by a silicon target. The surface of the target consists of a mosaic of tiny silicon oxide elements, each of which stores a charge corresponding to the brightness of the image at that position. After the image is integrated it is displayed on a cathode-ray-tube monitor.

The analogue scan converter has excellent dynamic range and resolution, but its satisfactory operation depends on careful adjustment. To avoid some of the adjustment problem the most recent scanners employ solid-state digital scan converters. In the digital scan converter the image information is split up into a regular two-dimensional matrix of small picture elements; the matrix typically has 512 elements on a side. The position of each of the 262,144 picture elements corresponds to the location of a "word" in a random-access memory of a small computer. The brightness of each picture element corresponds to the value of the word. After the information of the image is integrated it can be dis-

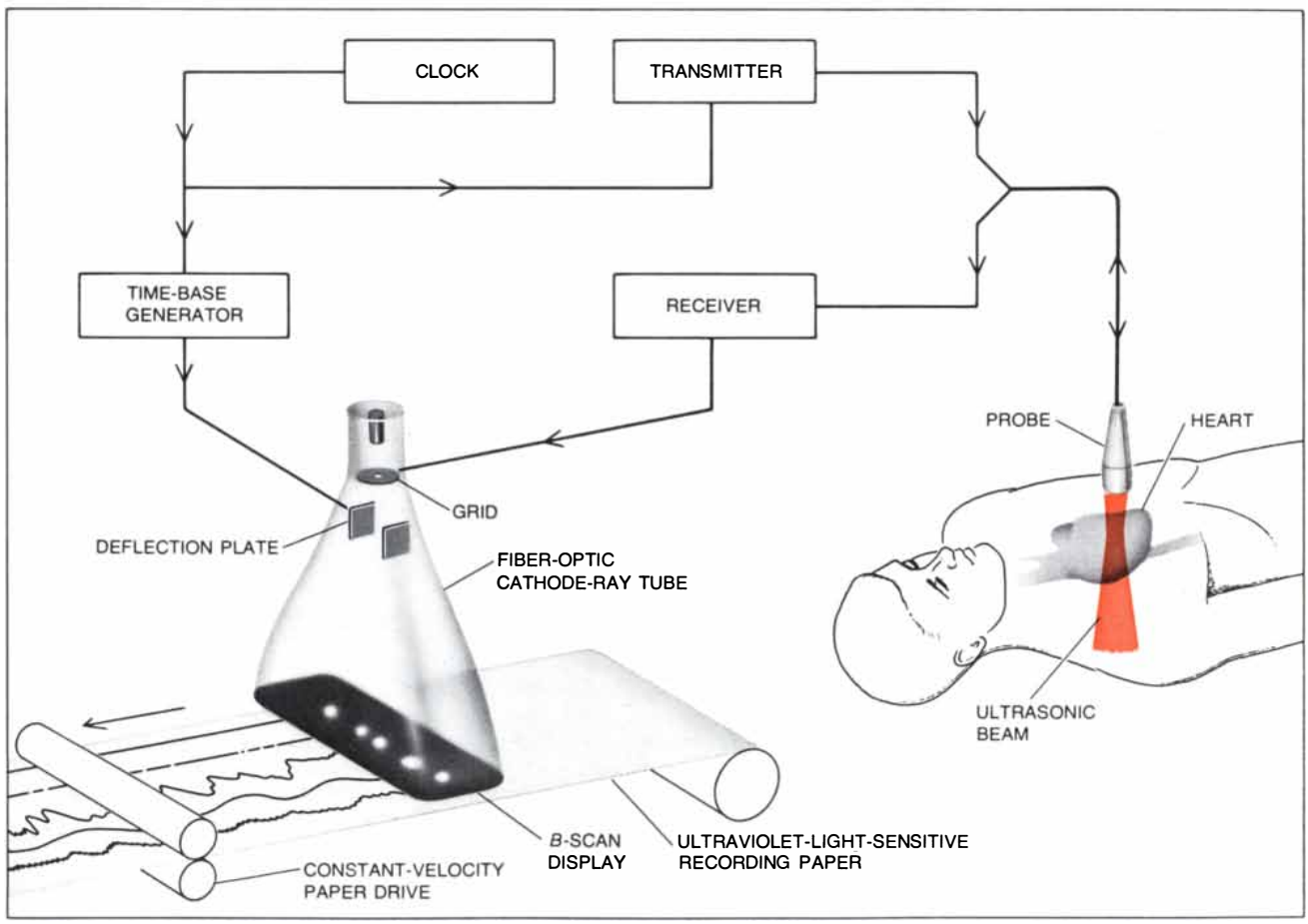
played on a cathode-ray tube and photographed.

From the beginnings of the application of ultrasound to medical diagnosis there has been much interest in the possibility of identifying malignant tumors, indeed of identifying the histology of any area of interest. To some extent the two-dimensional images showing both the boundaries of structures and the echoes arising from within the structures already enable physicians to infer the histological nature of suspect masses of tissue. The ability to positively distinguish among tissues of all types by means of noninvasive ultrasonic measurements, however, would represent a revolution in medical diagnostics. For this reason investigators in ultrasound laboratories all over the world are observing the way different tissues absorb, scatter and otherwise modify ultrasonic waves in an effort to identify and catalogue the ultrasonic "signatures" characteristic of different tissues.

Meanwhile scanning systems that do not rely heavily on tissue signatures serve for diagnostic purposes. For example, ultrasonic examinations are already valuable in obstetrics. With ultrasound it is possible to determine very early whether or not a woman is pregnant and to diagnose various complications of pregnancy such as polyhydramnios (excess of amniotic fluid), anencephaly (absence of the brain in the fetus) and hydatidiform mole (faulty development of a pregnancy). It is easy to determine the location of the placenta, and ultrasound should be the first method tried in examining patients suspected of having the placenta abnormally close to the birth canal. With ultrasound it is possible to accurately measure the biparietal diameter (the short dimension) of the fetal skull; during the second trimester that dimension provides a reliable index to the maturity of the fetus.

The two-dimensional scanner is also valuable in gynecology for revealing cysts and tumors. Moreover, the scanner can serve to diagnose cysts, abscesses and cancers of the liver, to examine the kidney and to assess aneurysms, or ballooned-out segments, of arteries, particularly the abdominal aorta. The scanner can also determine the exact location of tumors and delineate their shape, making it possible to plan radiation treatment more accurately and to monitor the effect of chemotherapy.

In all these investigations the scanner probe is held in direct contact with the skin and the ultrasound is coupled into the body through a layer of gel or oil. Such a system is convenient for rapidly scanning the abdominal region. In order to obtain an image of an organ, however, the operator must be skillful in moving the probe over the abdomen and must have a good knowledge of anatomy. Moreover, this type of scanner is not suitable for investigating superficial structures such as the thyroid, sensitive organs such as the eye and soft structures such as the breast that would be distorted by the pressure of the probe. In order to overcome such problems two-dimensional scanners have been developed where the transducer moves in a bath of water; the ultrasound is coupled



TIME-POSITION SCANNING SYSTEM employs the B-scan display to monitor moving structures such as those within the beating heart. A clock triggers the transmitter to excite the ultrasonic probe to emit pulses. Simultaneously the clock triggers a time-base generator to drive the deflection plates of a fiber-optic cathode-ray-tube display. Echoes returning from within patient's heart produce signals in the probe. The signals are amplified by the receiver, and strength of the signals modulates the brightness of the fiber-optic display. As the heart beats, the echoes from the moving structures move correspondingly on the display. Ultraviolet-sensitive recording paper is fed past the display at a constant rate and records the moving echoes as waveforms changing their position with respect to time.

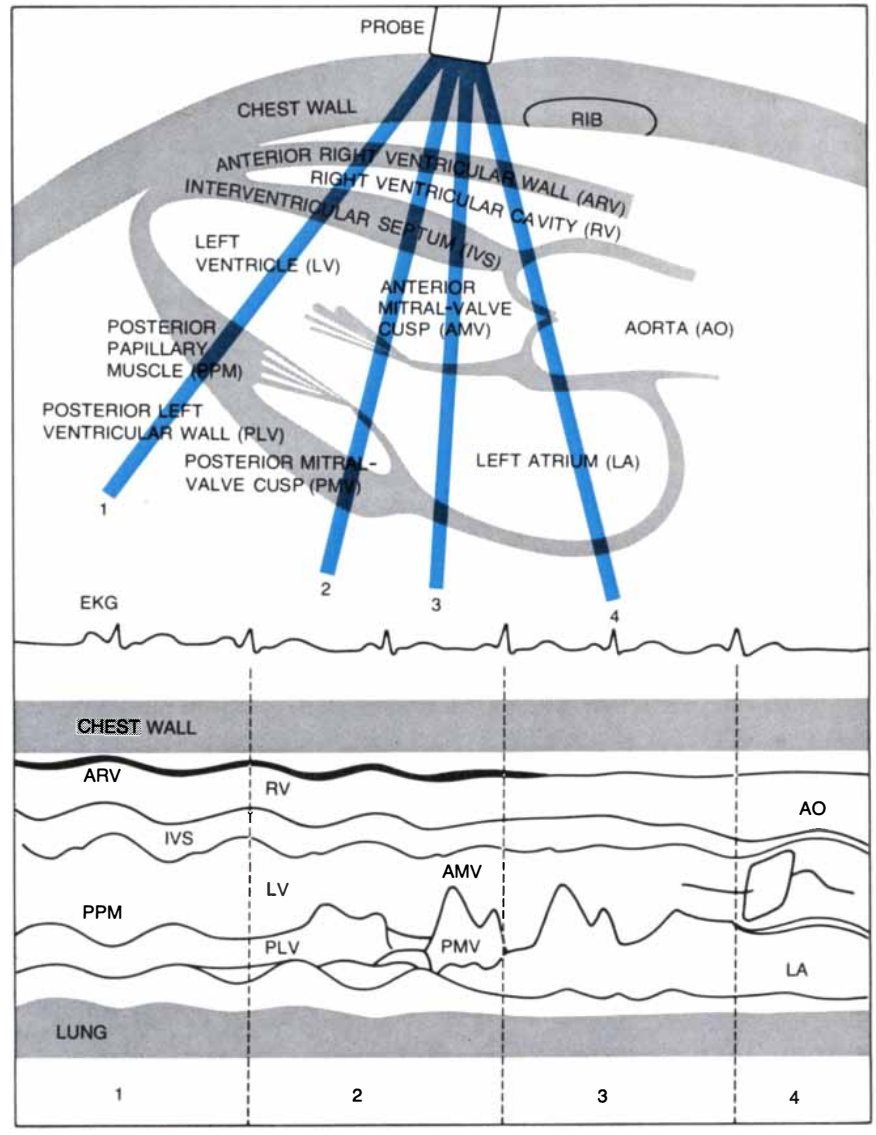
into the patient either by immersing the patient in the water or by placing in contact with the skin over the organ of interest a flexible membrane that forms one of the walls of the bath. The water-bath arrangement may be inconvenient, but in addition to making it possible to scan otherwise unsuitable structures it has two great advantages: the motion of the scanner can be automated so that skilled operators are not needed, and the transducer can be quite large so that resolution is increased.

Real-Time Scanners

The two-dimensional scanner we have been describing takes between three and 15 seconds to build up an image of one full cross section through the body. This type of scanner would not be appropriate for scanning moving structures such as the heart or rapidly searching a large volume for a particular feature. In such situations a real-time scanning system is needed: a system that rapidly forms an entire series of stop-action images. If individual frames from such a real-time study are viewed as still pictures, they are not particularly informative. They spring to life, however, when they are presented as a sequence of real-time moving images. Moreover, real-time two-dimensional scanners require less training to operate than the non-real-time two-dimensional scanning systems, and their moving-picture displays are often easier to interpret, enabling the physician and the machine to work together more effectively.

In principle there are two types of real-time scanner. The first type is simply an adaptation of the non-real-time two-dimensional instrument, designed so that the probe moves back and forth across the patient at such a high rate that the sequence of images it generates freezes the action of the moving feature.

The second type of real-time scanner has in its simplest form a fixed array of transducers that are operated one after another in rapid sequence in order to scan the organ repeatedly in a two-dimensional plane. This type of scanner has the disadvantage of each transducer in the array being rather small, so that it has low sensitivity and poor resolution. Those problems can be avoided either by processing the signals by computer or by having a large number of transducers in the array and activating them in groups of, say, four or five. Alternatively the transducers can be replaced by thin-strip elements placed close together side by side. Electronic circuits introduce appropriate time delays in the signal path of each element, depending on the element's distance from the target, and thus steer and focus the beam of ultrasound; the images that are built up from such focused beams have a high resolution.



CROSS SECTION OF THE HEART (*top*) shows the structures through which the ultrasonic beam (*color*) passes as it is aimed in four successive directions through the organ as a time-position scan is made. The time-position scan obtained is shown diagrammatically at the bottom, with the traces from several structures labeled. Position *1* corresponds to the apex of the heart, *4* corresponds to the base of the heart and *2* and *3* are in between. The time-position scan is shown in relation to a simultaneous recording from an electrocardiograph (EKG).

With all real-time imaging systems it is necessary to compromise between the line density (that is, the number of lines scanned per frame) and the number of frames scanned per second. When the motion of the target can be satisfactorily reconstructed at a low frame rate (with a corresponding increase in line density), flickering of the moving image can be avoided by storing the frames in a digital scan converter that allows each line to be refreshed sequentially, without the need to erase the entire image all at the same time.

Doppler Scanning Systems

The frequency of an ultrasonic wave reflected from a stationary structure is equal to the frequency of the incident wave. The case is quite different for flowing blood or a moving structure such as the beating heart. If the wave is reflected from a target that has a component of motion along the axis of the incident beam, the reflected wave has its frequency shifted by the Doppler effect. In any particular medium the velocity of ultrasound is constant. Movement of the target toward the probe compresses the wavelength of the reflected wave, increasing the frequency; movement of the target away from the probe lengthens the wavelength of the reflected wave, decreasing the frequency. The frequency shift is proportional both to the frequency of the incident wave and to the velocity of the target. For every

millimeter per second that a structure in the body moves, the frequency of the incident ultrasonic wave is shifted approximately 1.3 hertz per megahertz. For example, an ultrasonic wave with a frequency of five megahertz is Doppler-shifted in frequency by about 650 hertz when it is reflected from a target moving along the direction of the beam at a velocity of 100 millimeters per second.

For Doppler-shift measurements the ultrasound is transmitted into the body in the form not of pulses but of a continuous wave. As in pulse-echo diagnoses, the ultrasonic frequency is chosen to be as high as possible to give the best resolution and at the same time to be low enough to penetrate the body to the required depth.

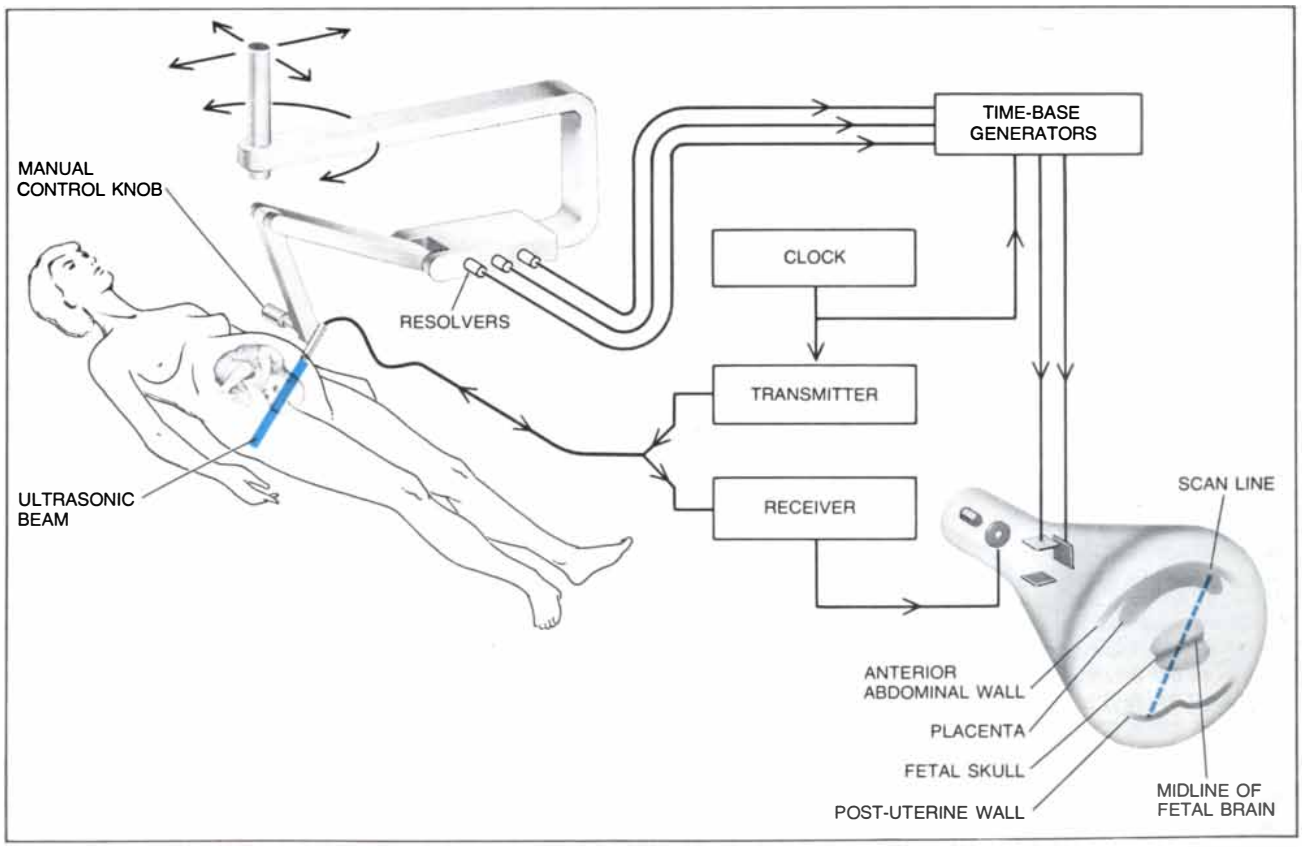
Two transducers are mounted side by side in the probe: one for transmitting the wave and the other for receiving its reflections. The transmitting transducer emits continuous low-intensity ultrasound toward the moving target; the receiving transducer detects echoes returned both from the target and from the stationary structures around it. The signals from the receiving transducer are electronically mixed with the reference frequency of the transmitting transducer.

Now, when two sound waves are mixed, four frequencies are obtained: the frequency of the first wave, the frequency of the second, the sum of the two frequencies and the difference of the two frequencies. The output from the mixer is filtered to stop all but the difference of the two frequencies: the Doppler-shift frequency. Depending on the velocity of the structure observed, the Doppler-shift frequency can be up to a few thousand hertz, which is in the audible range. The operator monitoring the moving target is therefore equipped with earphones. If the probe is aimed toward a stationary structure, the operator hears nothing; if it is aimed toward a moving structure, the operator hears a tone whose frequency is equal to the Doppler-shift frequency. If the structure is the beating heart, the tone varies with the heartbeats.

The most widely used Doppler-shift ultrasonic instrument is the fetal-heart detector. The detector is in effect a highly directional and sensitive stethoscope that is extremely valuable in determining whether or not the fetus is alive; in a normal pregnancy it is generally possible to hear the Doppler-shifted signals from the fetal heart after about the 12th week. Moreover, the fetal heart rate is a useful guide to the condition of the fetus during labor. For that application the transducers are designed to have a relatively large beam width, so that the heart can be continuously monitored even when the fetus changes position.

The flow of the blood can be detected by the Doppler shift in the frequency of the ultrasound reflected or backscattered from the blood cells. For peripheral vessels ultrasound frequencies of between five and 10 megahertz give the best compromise between resolution and penetration; for deeper vessels, such as the thoracic aorta, a frequency of two megahertz is needed.

The probe is scanned by hand over the skin, and the Doppler-shift signals are received only when the ultrasonic beam passes through the moving blood. Information about blockages in the vessels can be obtained simply by listening to the Doppler-shift signals as the probe is held at different sites over the suspect vessel. For example, deep venous thrombosis (the presence of a blood clot in a vein) can be detected in the femoral vein by an abnormal change in the Doppler-shift signals from the groin when the patient's calf is squeezed. The Doppler-shift signals can be followed to map the course of the blood vessels, en-



TWO-DIMENSIONAL IMAGE of a cross section through the body can be obtained with the B scan. Here the fetus is being examined in a pregnant woman. The probe, which is mounted on an articulated arm, is moved across the patient's abdomen by a technician. The changing position of the probe and the direction of the ultrasonic beam are measured by the resolvers on the arm and are recorded as electronic signals. Those signals control the time-base generators, which in turn control the deflection plates of the cathode-ray tube building up the image. The principle behind the building up of ultrasound image is shown in more detail in the illustration on page 106.

abling the physician to locate occlusions (blockages) or stenoses (constrictions) in vessels such as the carotid arteries that supply the brain. It is a quick, noninvasive and painless procedure, where employing X rays for the purpose calls for the hazardous injection of a contrast medium into the blood.

One trouble with the ultrasonic Doppler-shift technique in investigating most arteries is that the veins often lie close to the arteries, and signals from the blood flowing in the veins can interfere with signals from the blood flowing in the arteries. To be sure, the blood in the veins flows in a different direction from that in the arteries, but simple Doppler-shift instruments cannot distinguish between upward and downward shifts in the backscattered frequency;

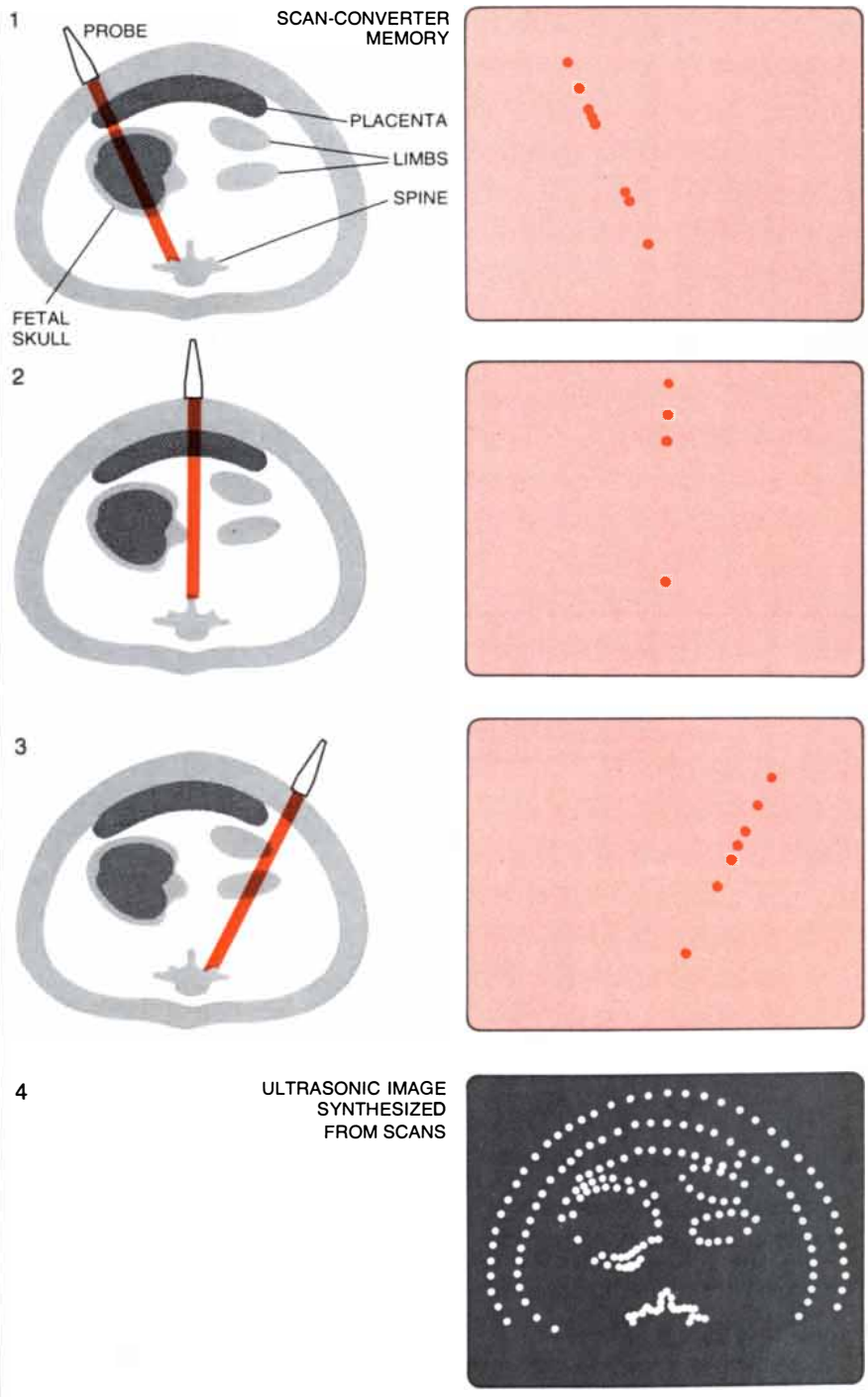


IMAGE OF A CROSS SECTION of the human body is built up from a series of B scans made at different angles through the body. The probe is slid around the patient's abdomen (*left*); at each angle (*1, 2, 3*) it sends out pulses and receives echoes. Position and brightness of echoes received at each angle are stored in a scan converter, which could be a storage tube or the memory of a small computer (*right*). At the end of the probe's traverse the information from all the scans is integrated in the scan converter and displayed as a cross section through the body (*4*).

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only the difference between the transmitted frequency and the received frequency is recorded, not its direction of change. More sophisticated instruments incorporate electronic techniques to retain this directional information.

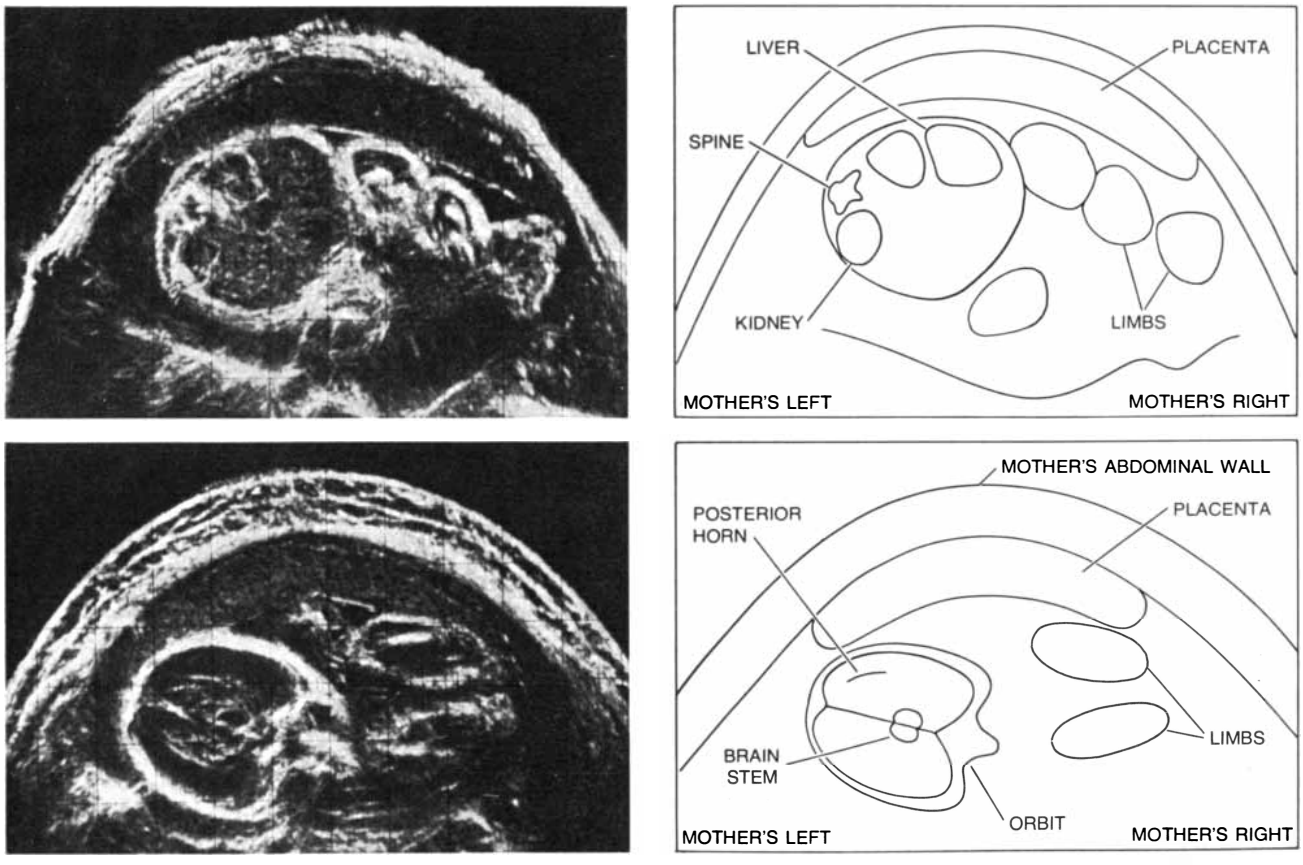
Additional information of clinical value can be obtained from Doppler-shift instruments by analyzing the frequency spectrum of the signals backscattered from the blood. In a frequency spectrogram time is represented on the horizontal axis, frequency is represented on the vertical axis and the intensity of the frequency is represented by the degree to which the recording is blackened. In an artery the blood at the center of the vessel moves at the highest velocity and the blood closer to the walls moves progressively slower. The profile of the flow across the artery is usually parabolic. Therefore at any one instant there is a band of Doppler-shifted signals, the signal of the highest frequency corresponding to the velocity of the fastest-moving blood. If there is an atheromatous (arteriosclerotic) plaque on the inner wall of the artery, it obstructs the flow of the blood; the obstruction alters the shape of the flow profile and hence the shape of the frequency spectrum. Analysis of the frequency spectra of Doppler-shifted signals can yield valuable data on the condition of the heart and the general state of the arteries.

Unlike the A-scan and B-scan systems, which employ pulses of ultrasound, the systems that rely on a continuous wave of ultrasound cannot measure the distance of the target tissue from the probe. Several systems have been devised to obtain the range information by time-coding the transmitted signals. For example, the transmitter can be "gated" so that instead of emitting an unbroken continuous wave it emits a long pulse. Just as in the A-scan and B-scan systems, the range of the target is then determined from the length of time it takes for the receiving transducer to detect the pulse. If the target is stationary, the frequency of the received signal is equal to the frequency of the transmitted one; if the target is moving, however, the frequency is changed by the Doppler shift.

Other Ultrasonic Devices

No review of ultrasound in medical diagnosis would be complete without mention of ultrasonic holography. For a time this technique seemed to hold much promise as a potential diagnostic tool: how ideal it would be to reconstruct three-dimensional pictures of the internal organs in their proper spatial relations! For some years much money and effort were devoted to investigating the possibility. The results were disappointing, and little work on ultrasonic holography is now being done.

It is easy to understand some of the physical reasons for these results. In ultrasonic holography the target object is illuminated with coherent ultrasonic radiation, that is, radiation in which all the waves are in phase. The reflections from the object are then allowed to interfere (either directly or electronically) with a reference beam of the radiation, and the interference patterns are recorded electronically on a sheet of photographic film. After the film is developed the holographic image is constructed by illuminating the film with another beam of coherent light radiation. Holography is a nonimaging process: the "camera" does not have a lens. The wide aperture needed to record the interference patterns therefore demands that the radiation illuminating the target be fairly intense. If the target is an organ inside the human body, there are biological limitations to the intensity of the ultrasonic radiation that can be employed. At bio-



ULTRASOUND IMAGES OF A FETUS in the uterus can be studied months before birth in order to monitor the progress of the pregnancy, the infant's maturity, its health and its position. Both images, made by George Kossoff at the Ultrasonics Institute in Sydney in Australia, are cross sections of same fetus made in different planes through the mother's abdomen. The map at the right of each photograph identifies the most prominent features in the image. The maps show that the brain and the internal organs of the fetus are revealed by ultrasound and can also be examined. The black grid crossing the photographs is the graticule on the face of the cathode-ray tube.

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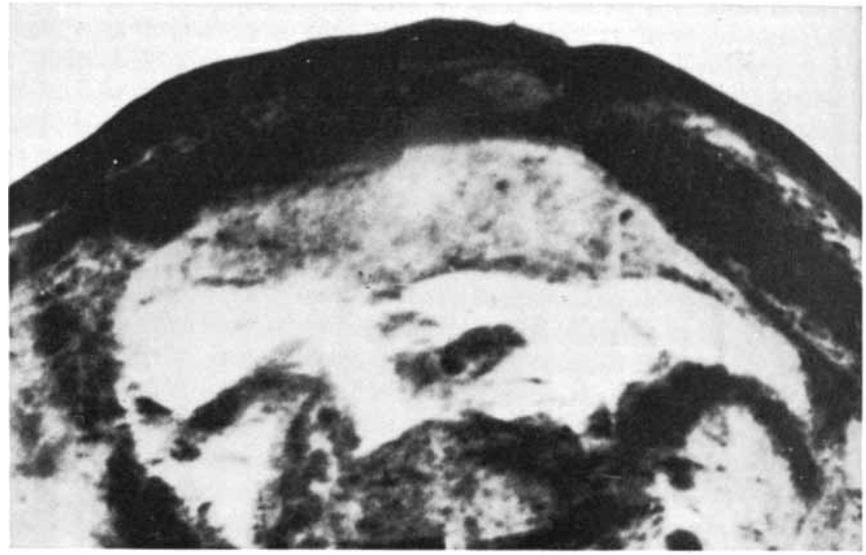
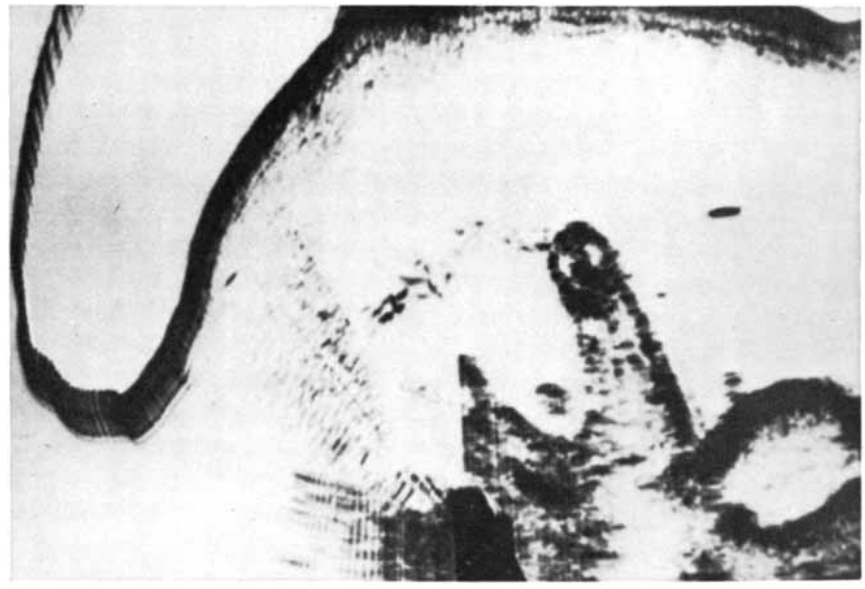
logically acceptable intensities of ultrasonic radiation, however, the wide aperture required for recording the reflected radiation yields an intolerably poor ratio of signal to noise.

That is only one problem faced by ultrasonic holography. The difference in the wavelength between the ultrasound that generates the hologram and the light that reconstructs the image enormously distorts the image when it is viewed. Variations in the velocity of the ultrasound in different tissues throw different portions of the ultrasonic beam out of phase, confusing the interference patterns. Because many organs appear to be smooth at the wavelengths of ultrasonic frequencies they act as specular reflectors, and the amplitude of the echoes from the organs depends strongly on the angle of the transmitting beam with respect to the film. Strong reflections mask weaker ones, and the presence of bones and gas-filled organs limits the anatomical sites that can be examined. The data are further degraded by the fact



NORMAL FETUS in the uterus is shown in this ultrasonic image. Curved black arch is the mother's abdominal wall; gray oblong region below it is the placenta with the umbilical cord leading to the fetus's abdomen. Fetus is lying face up with its head to the right, its body in the middle and its bent leg, foot and big toe to the left. This image, the one below and the one on page 112 are longitudinal cross sections through the mother's body with her head to the left. They also show black line on white background, whereas the ones on the preceding pages show white line on black background; no one way of displaying the images is considered standard.



EXCESSIVE AMNIOTIC FLUID, the condition known as polyhydramnios, has been diagnosed from this image. Polyhydramnios often accompanies other abnormalities. Two fetuses are visible: head of a dead fetus is the oval structure to the right, and the legs of a live fetus are extended in middle. As indicated by echoes from a scrotum between the legs, live fetus is male.

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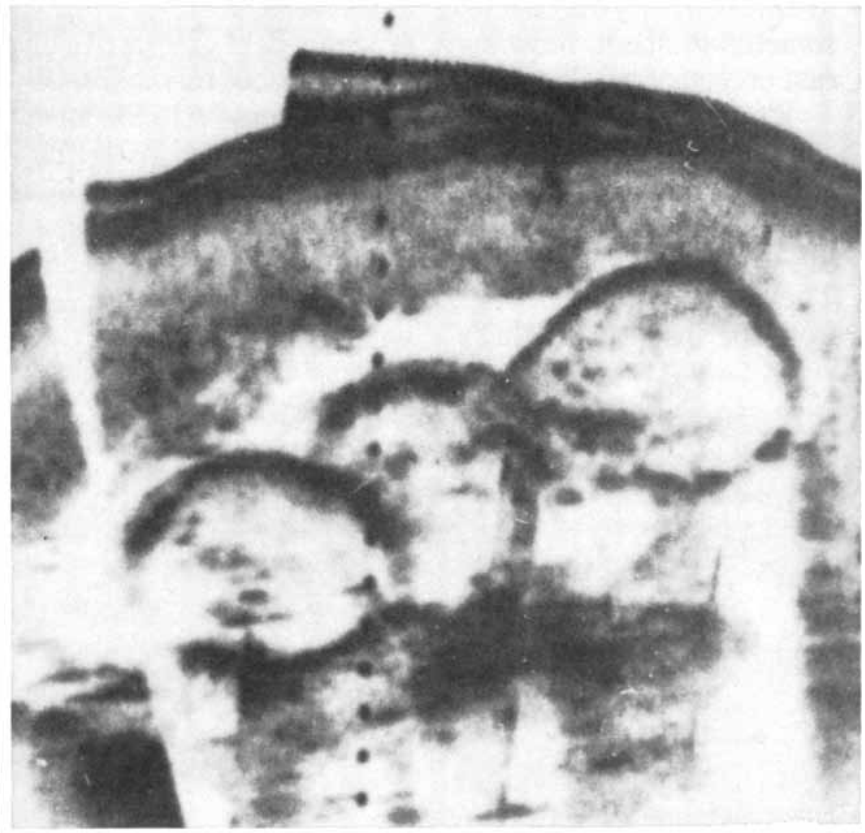
that during the lengthy recording procedure the patient cannot remain perfectly still: the heart beats and the lungs expand and contract. As a result the holographic image is blurred. Because of all these problems ultrasonic holography seems to be a dream that cannot soon be realized.

Overall Status

The wide range of the present applications of ultrasound in medical diagnosis gives ultrasound a distinctive role to play alongside other investigative techniques. In some specialties such as obstetrics ultrasound has virtually replaced other imaging methods. It has even been estimated that in two or three years obstetricians in the U.S. will require ultrasonic examinations to be made in half of their consultations with pregnant patients. In other specialties such as cardiology ultrasound has become one of a range of tools. Noninvasive ultrasonic examinations of the heart have reduced by 20 percent the need for the hazardous cardiac catheterization; moreover, the ultrasound examination costs only about $90 and does not require hospitalization.

In still other specialties ultrasound has not yet come into its own but seems very promising. For example, investigators are currently looking into the potential of ultrasound in examining the prostate gland. Malfunctions or diseases of the prostate afflict more than half of all men older than 50. Ultrasound promises to be a simpler, more comfortable and more effective means of examination than tactile probing by a physician. With ultrasound a medical technician can accurately measure and permanently record sections of the prostate and from them reconstruct three-dimensional images of the size and shape of the entire gland. Moreover, since ultrasound probes the interior of the gland, it can detect abnormal conditions such as inflammation (prostatitis) and tumors. Still another important possibility is that of detecting breast cancer very early by abnormal Doppler signals from the flow of blood in the tiny blood vessels that tumors develop to support their growth.

There are a number of technical and operational problems still to be solved before ultrasonic diagnostic instruments will become as commonplace in clinical medicine as the electrocardiograph or the X-ray machine. Improvements must be made in real-time systems and in Doppler-shift systems. With the plummeting cost of electronics, however, the capability per dollar of instrumentation is increasing at a dramatic rate. As a result the single biggest limitation to the widespread introduction of ultrasonic diagnostic techniques today is simply the training of the necessary personnel to implement them.



TRIPLETS are revealed in this image: the three fetal heads are the three oval structures in a row under the gray placenta. This image and those on page 110 were provided by Goldberg.

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The Lek Mating System of the Sage Grouse

In a lek system a large percentage of the females mate with a small percentage of the males. How the system operates among the sage grouse of the Rockies is examined in detail

by R. Haven Wiley, Jr.

Of all the bizarre rituals in animal courtship few are more impressive than the lek mating system of the sage grouse. On the high sagebrush plateaus of the Rocky Mountain region both sexes congregate during the breeding season at communal display grounds, or leks (originally a Scandinavian word meaning play). There the males display repeatedly. Although 50 or 60 male sage grouse may gather at a lek, most of the visiting females copulate only with the same one or two males, and most of the males find no mates at all.

The lek mating system, characterized by a transitory association of both sexes at a regular location and extremely unequal copulatory success among the males, has evolved among distantly related species of birds, including certain grouse, birds of paradise, sandpipers, weaver finches and the manakins and cotingas of Central and South America. It is also found among insects, fishes and mammals. Because the system is such a clear case of unequal matings by males it has long fascinated zoologists. I felt that an example as extreme as that of the sage grouse might clarify some general principles of animal mating systems. For this reason I recently undertook a three-year study of sage grouse mating.

In winter, when the sagebrush plateaus are swept by snow and high winds, the sage grouse depend almost entirely on one evergreen plant, the big sagebrush, for both shelter and food. These grouse are among the largest birds of their family and show a marked sexual dimorphism: adult males average 2.5 kilograms in weight and adult females only 1.2 kilograms. Beginning in the first warm days of February the males congregate at leks scattered on the sagebrush plains. Throughout March and April and on into May each male returns morning after morning to his particular lek and to a particular position within the lek. Female grouse visit the lek for a much briefer period, usually some 20 days in April.

Activity on a lek begins at first light, an hour or so before sunrise, and continues for three or four hours. During this period the males spend much of their time repeating what early observers of sage grouse dubbed "the strut." The male inflates his elastic esophageal sac by heaving the sac upward and then letting it fall. By doing so twice he expands the sac until it contains some four liters of air. Then, contracting the superficial muscles of his chest, he compresses the inflated sac and suddenly releases the compressed air. The result is a resonant popping sound, much like the sound of a cork being pulled from a bottle. Each cycle of inflation and release takes a little more than three seconds; between struts the male usually stands in a conspicuous attitude, his white neck feathers ruffled and his tail feathers cocked vertically. Elaborate displays are characteristic of lek-mating animals, but sage grouse reach an extreme of grotesque behavior.

When the female grouse visit the lek in April, they arrive in large numbers around sunrise and tend to congregate in a dense pack at the center. The one or two males near the center strut back and forth through the congregation of females and copulate with them at intervals. Each female usually copulates only once and then leaves to make her nest, sometimes as much as four kilometers away from the lek. The female lays six to eight eggs, incubates them for 26 days on the average and rears the young birds without any further association with a male.

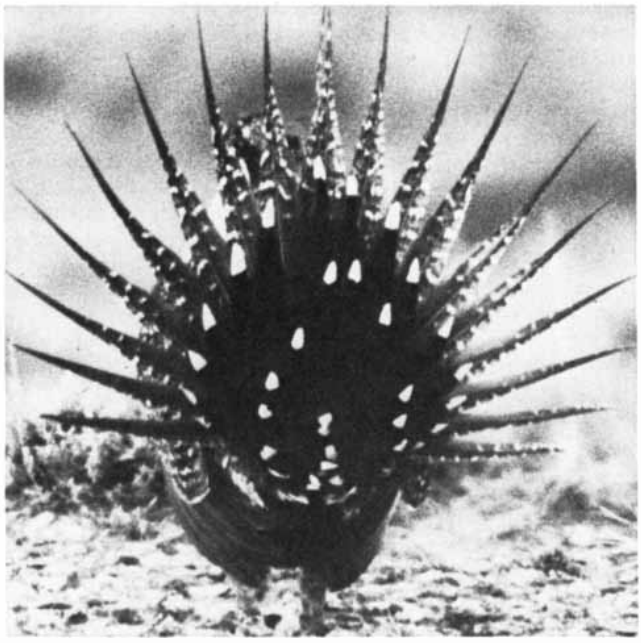
Of the 50 or 60 males that attend a lek during the breeding season the large majority never copulate at all and only a few copulate repeatedly. In the course of a season a successful male mounts from 20 to 60 females; I once recorded 34 successful copulations by the same male in a single morning. Overall at least 90 percent of the copulations at any particular lek are participated in by no more than 10 percent of the males present.

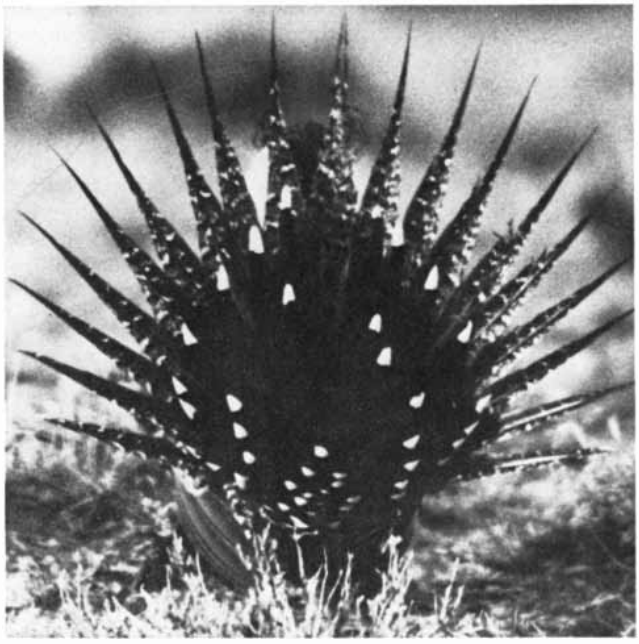
Earlier naturalists who were interested in Charles Darwin's theory of sexual selection were particularly intrigued by the lek mating system. For example, when Edmund Selous described the leks of the black grouse in England in 1909, he emphasized the competition among the males and the selection of the most vigorous males by the visiting females. Indeed, for decades before data on polygynous behavior in other animals became available lek-forming birds provided the prime examples for the theory of sexual selection. Today, with detailed studies, we are in a better position to understand the social interactions that generate the unequal distribution of matings on leks. My own studies show that sage grouse exhibit many features of behavior that are present in other lek-forming animals, although in a less exaggerated form.

One characteristic of leks is their traditional location. The sage grouse return year after year to virtually the same spot. For example, in 1949 Robert Patterson of the Wyoming Game and Fish Commission located all the sage grouse leks in 650 hectares (some 1,600 acres) of sagebrush in the western part of the state. He repeated his survey in 1950 and 1951. He found no new leks but observed that every lek recurred in the same location each year. The record for documented adherence to one location belongs to the Muddy Springs lek near Laramie, Wyo., first studied by John Scott of the University of Wyoming in 1940 and 1941. The location of the Muddy Springs lek had not changed when I worked in the area 28 years later.

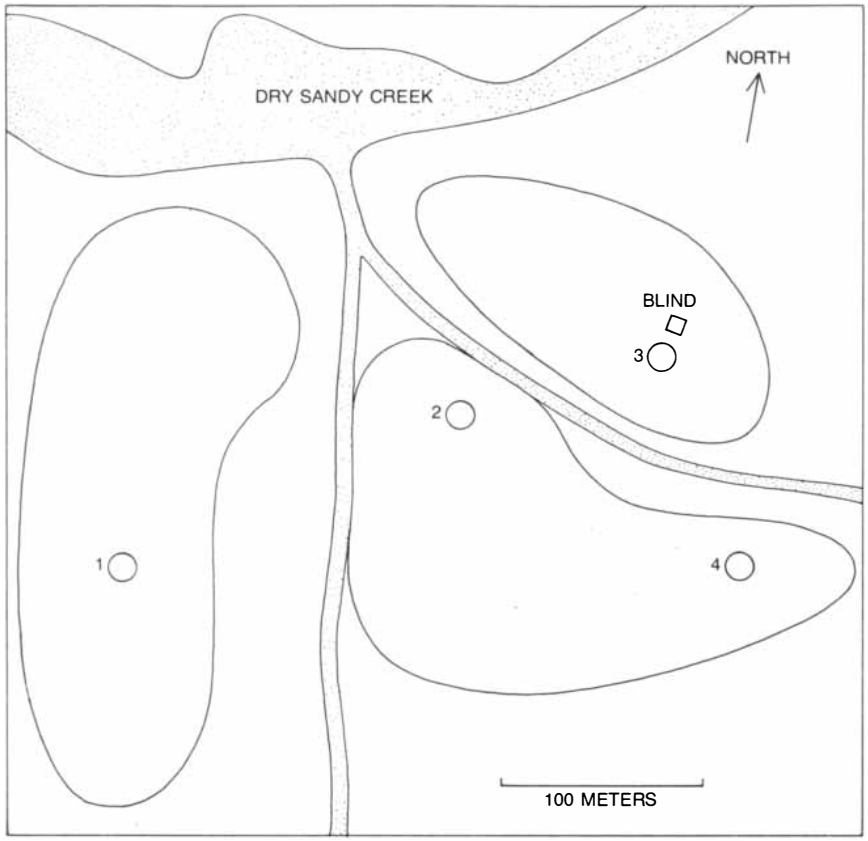
Not only the lek itself but also the mating center, a small inner area about 10 meters in diameter where most of the copulations occur, is found in the same

MATING CENTER at a sage grouse communal display ground, or lek, in Wyoming is crowded with female grouse. A male grouse, much larger than the females, here appears to be even larger than usual because it has inflated its esophageal sac with air in the course of a courtship display known as a strut. The skin over the sac protrudes prominently and the male's head is hidden in a ruff of white neck feathers.





UPRIGHT FAN of tail feathers is part of the male sage grouse's display posture. Raising the tail feathers brings the shorter, brown feathers under them into view; their white tips form a distinctive pattern that differs from male to male, as is evident in these photographs. Memorizing the different patterns enabled the author to identify individual males in sight of his blind and to follow their movements.



LARGE LEK IN WYOMING included three zones where males occupied territories; those zones contained a total of four mating centers, each center some 50 square meters in extent. Most of the females congregated at these centers. Every morning in season more than 250 males gathered at the lek. The author's blind was set up next to one of the four mating centers (*upper right*). Intermittent tributary streams feed Dry Sandy Creek; hence the name of the lek.

place year after year. Scott, Patterson and I have all observed this consistency of location, although in small leks or leks disturbed by human activities the location of the mating centers seems to be less consistent.

Sage grouse leks vary in the number of males in attendance. At some small leks only a few males congregate; some large ones have more than 400 males, although such a large number is unusual. In any event when more than 50 or 60 males congregate, the lek always has more than a single mating center. Thus in a really large lek one can expect to find one mating center for about every 50 males. This means that a large lek is in effect an aggregate of smaller ones, so that the basic unit of sage grouse social organization is a lek covering about two hectares (five acres) that is visited in season by as many as 50 or 60 male grouse and has a single mating center some 50 square meters in extent.

Even a biologist shivering in his blind at dawn, alone on the vast Wyoming plains, finds a big lek an imposing spectacle. Each arriving male grouse settles in its territory within the lek morning after morning to strut and to defend its boundaries against intrusion by other males. If one male should strut near the boundary of another male's territory, the challenged male will often respond by shifting its own strutting closer to the threatened boundary. Periodically neighboring males will interrupt their strutting for an outright boundary encounter. The encounters can begin suddenly, with one male rushing at another that has come too close to the line. The two males end up almost side by side, each facing past the other; they jockey back and forth a few steps at a time.

Occasionally tension mounts and actual fighting breaks out. Holding positions roughly side by side, the two males beat each other vigorously with their wings. Normally neither male is clearly defeated. As with territorial encounters in other animal species, the contestants soon back away into their respective domains. Injuries must occur occasionally, but I never saw a male hurt in one of these encounters.

Accurate observation of this kind of behavior requires an ability to identify every male grouse individually. Rather than risk upsetting the birds by capturing them for artificial marking, I learned to identify individuals by the unique pattern formed by the feathers under their cocked tail; the short feathers under the tail are chocolate brown with white tips, and no two patterns are exactly alike. In each year of my study I soon came to recognize every male within sight of my blind.

I was also able to plot the location of each boundary encounter within a radius of 30 to 50 meters from the blind by making a detailed map of the terrain; the map included every bunch of sagebrush and clump of grass in view. The plotting was further assisted by laying out small flags in a grid near the blind. I also used a 16-millimeter motion-picture camera to monitor the activities of the males. By filming at the time-lapse rate of one frame every four seconds I could generally record the behavior of as many as five males over a two-hour period beginning at sunrise. When I plotted the locations of boundary encounters on the map, it turned out that the lines of demarcation between adjacent males' territories were precise: many boundaries were defined to within a meter or less. Territories near the mating center were smaller than territories toward the outer edge of the lek: no more than 30 square meters compared with 100.

My observations established that each male sage grouse reigns supreme within its own territory. Most important, within its own territory each male can copulate without being challenged by a neighboring male. It is only when a male mounts a female close to a territorial boundary that the neighboring male dashes forward and precipitates a confrontation that interrupts the copulation. Any male grouse, regardless of its success or lack of success in mating with the females, is subject to a neighboring male's attack if it attempts copulation too near a territorial boundary.

To occupy a territory within or near the mating center of a lek is to enjoy a great advantage in copulation; a male so situated will copulate repeatedly, whereas its immediate neighbors copulate only rarely. In spite of this discrepancy the less successful neighbor will not intrude on the more successful male to interrupt copulation, and the more successful one will not intrude on the less successful one, unless either attempts copulation too near the territorial boundary. Clearly a male sage grouse becomes successful in mating not because of any ability to interrupt other males' attempts at copulation but because it has obtained a territory that coincides with a mating center.

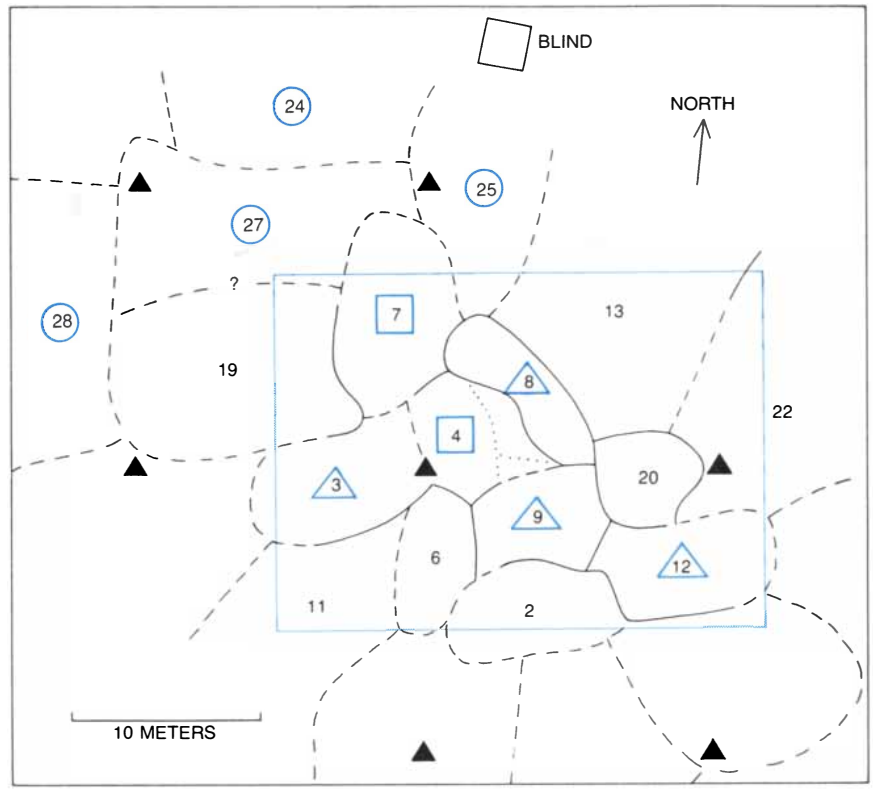
Naturalists in the past were uncertain whether the male grouse at leks evinced territorial behavior, in which neighbors meet as equals at mutual boundaries, or a dominance hierarchy, in which dominant males exclude subordinate ones from an opportunity to mate. Actually the social interactions of male sage grouse are a blend of these two classic patterns of behavior. Neighboring males meet at boundaries more or less as equals. They only occasionally in-

trude into each other's territories, even when one mates frequently and the other does not. Yet males are attracted to the mating center within a lek. As a result each male tends to strut most of the time near its territorial boundary closest to the mating center. At the same time it guards against intrusions from neighbors whose territories lie farther from the mating center than its own. I found that each male attacks those neighbors farther from the mating center more often than the neighbors attack the more central male. In effect the males practice "polarized territoriality": they are ranked in a dominance hierarchy in accordance with the distance of their territories from the mating center.

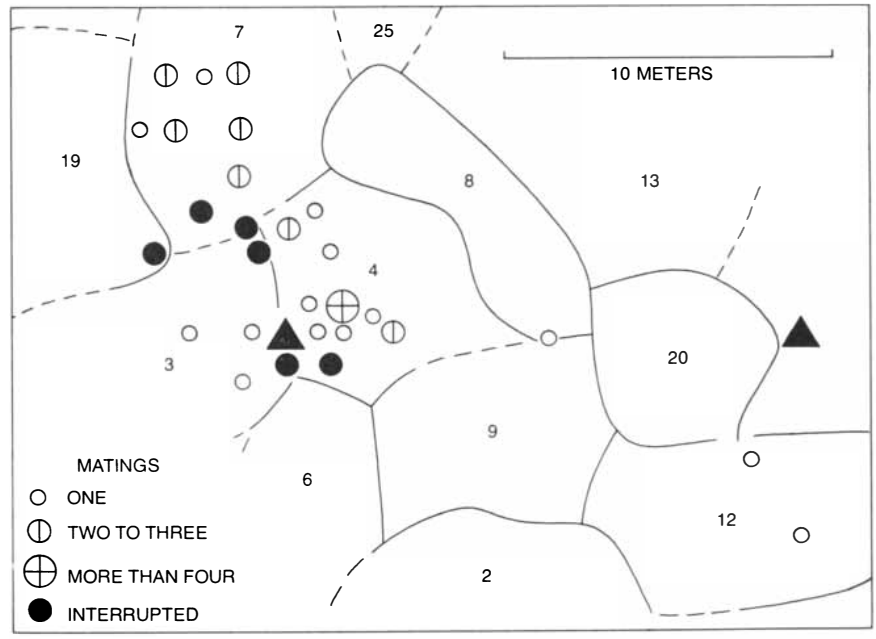
What behavioral responses of the female grouse establish the mating center? One hypothesis, proposed by the first naturalists to study leks, is that male grouse differ from one another and that the females, following some criterion of form or behavior, choose to mate with the most attractive male on the lek and thereby transform its territory into a mating center. The hypothesis seems plausible at first; the casual observer at a lek soon sees that the males adjacent to the breeding center strut more often than males farther removed, spend more time in the strutting posture and also have more frequent boundary encounters with neighboring males. Conceivably any one or all of these actions might attract females. One must be cautious, however, about accepting such an explanation. The possibility cannot be excluded that the greater activity of the males near the center is the result of the females' congregating there rather than the cause. If males are more active when they are near females, then regardless of how the females select a place to congregate the males at the selected site would exhibit the greatest activity.

To test these alternative explanations I recorded the activities of male grouse located either centrally or peripherally on the lek under conditions of equivalent proximity to the females. Time-lapse photography helped me to document the males' behavior in three different circumstances: when females were inside the territorial boundary of the male being observed, when females were inside the territory of an immediately neighboring male and when no females were in either the observed male's territory or the territory of any of its immediate neighbors.

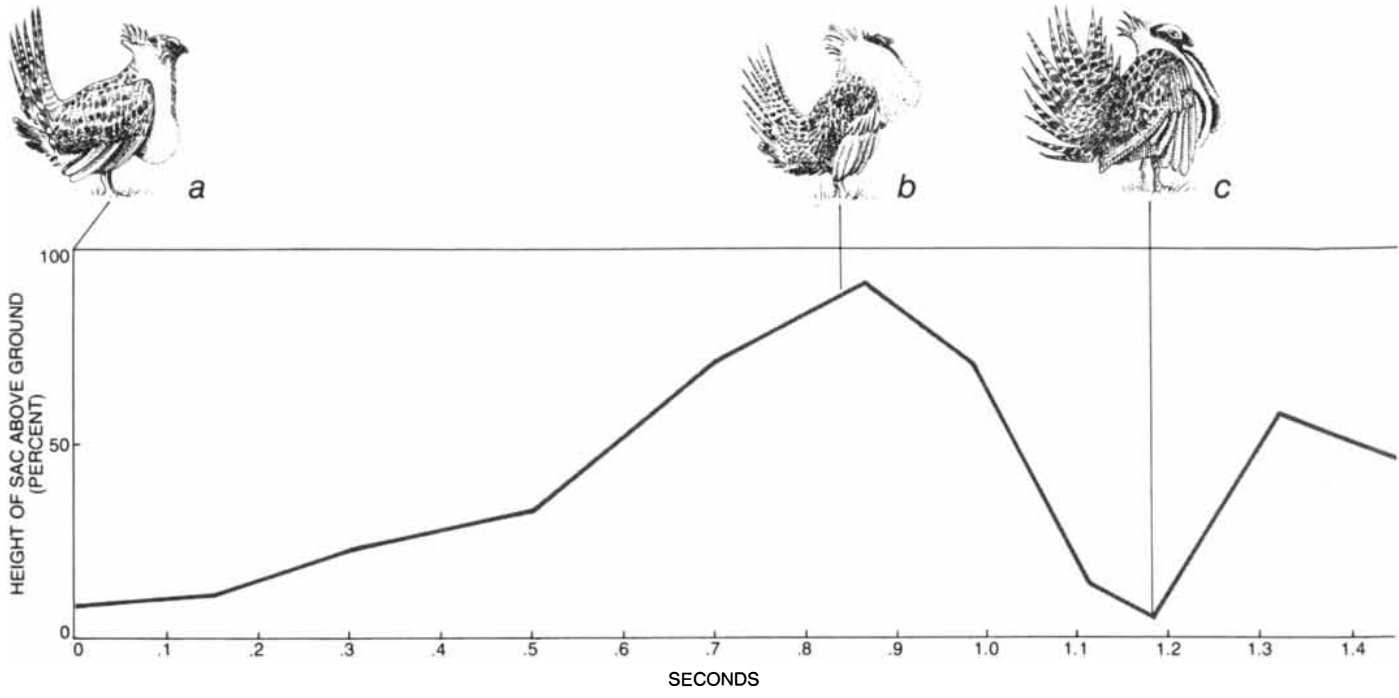
In the first instance I found that the males strutted frequently, often at an apparently maximum rate (in excess of six struts per minute). They strutted less often when the females were present only in a neighbor's territory, and they scarcely strutted at all when no females were in adjacent territories. Thus there were no consistent behavioral differences between successful and unsuccess-



MALE TERRITORIES surrounding one mating center at the Dry Sandy lek were occupied by 20 grouse at the time of the author's observations. Each bird was assigned an identifying number; the four numbers in colored circles identify yearling males in their first season on a lek. The two numbers in colored squares identify the most sexually active males; the four numbers in colored triangles identify males that also copulated but less frequently. Black triangles locate grid-corner flags, aids to territory mapping; boundaries with broken lines are known less accurately than those with solid lines. Colored rectangle outlines lek area shown enlarged in the illustration below. Only the six males so identified and none of the 14 other identified birds nor the many males with territories farther from the mating center succeeded in mating.



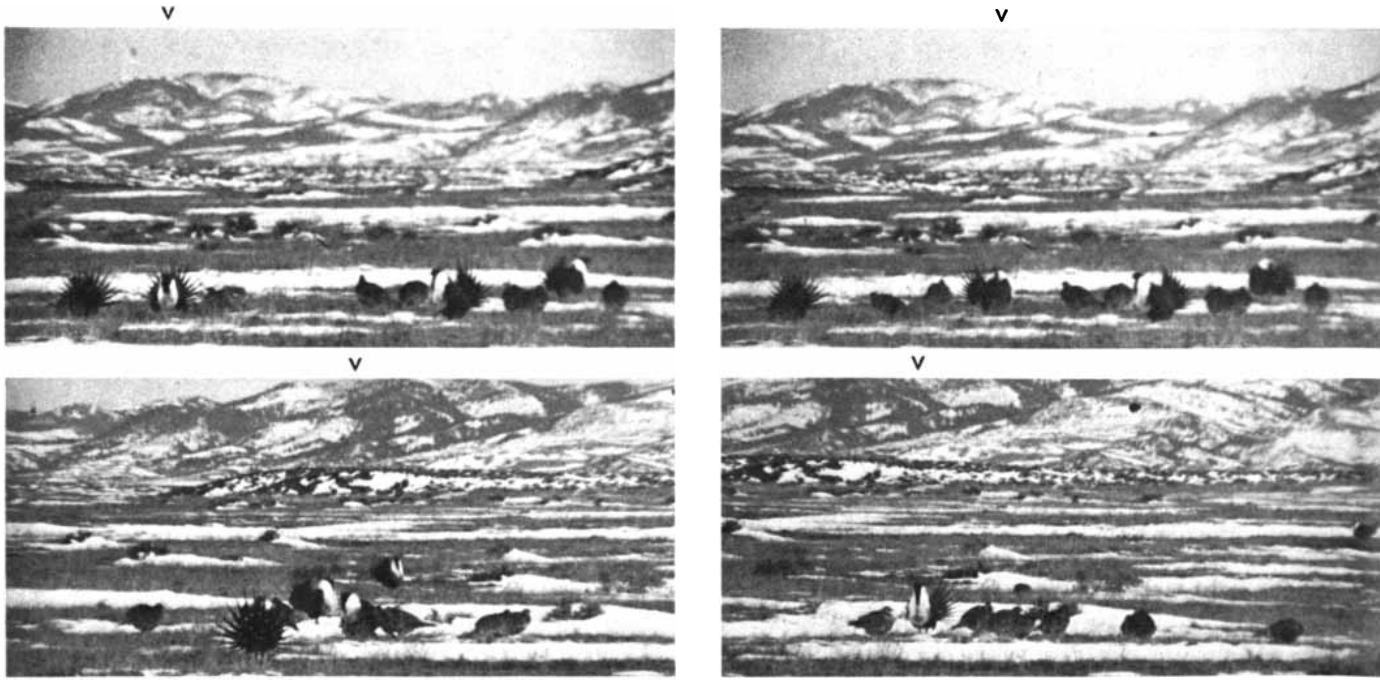
MATING RECORD over a 20-day period in April shows high activity on the part of males No. 7 and No. 4, lower activity on the part of males No. 3, No. 9 and No. 12 and no activity at all on the part of male No. 8. Six mating efforts were interrupted, all of them when the male concerned attempted copulation at a point too near the boundary of a neighboring territory.



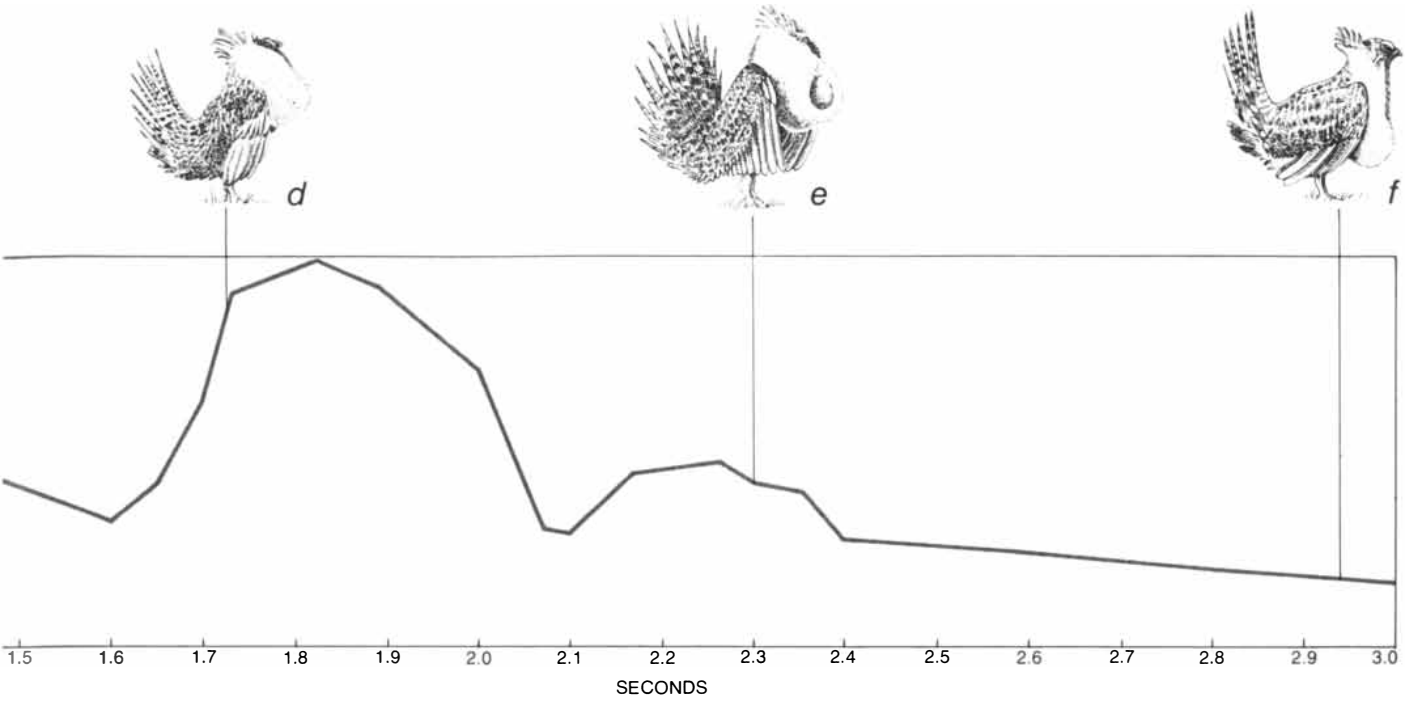
STRUTTING SEQUENCE of the male sage grouse during a single three-second strut is illustrated at the top. The graph at the bottom shows variations in the height of the male's esophageal sac expressed as a percent of the maximum; a near-maximum is seen in illustra-

ful males under conditions of equivalent proximity to females.

Jon Hartzler of the University of Montana has also attempted to discover individual differences between successful and unsuccessful male sage grouse at varying distances from females. For his criterion he used the absolute distance between the male and the female rather than the female's presence in the male's territory or absence from it. He found that successful males are slightly more active than unsuccessful ones at the same distance from the female. The difference in our respective findings might be due to our different criteria regarding a male's proximity to females. At the moment it is not clear whether behavioral differences of individual males affect the females' choice of a place to mate. The fact remains that the more frequent strutting activity of male grouse adjacent to the lek mating center is primarily the effect of the females'



MATING-CENTER ACTION during a 25-minute period in mid-April at the Ford's Creek lek in Montana can be followed in the eight frames from a time-lapse film reproduced here. The mating-center area coincided with the territory of one male grouse; a caret above each of the frames locates the male. Some seven females and four males can be seen in the first frame; the females are congregated inside the mating center (*middle*), and male *A* (*caret*) has just moved toward one edge of its territory to confront one of three neighboring males. The encounter lasted for less than four seconds; in the next frame male *A* has returned to the assembly of females. In the third frame, some five minutes later, male *A* has moved to the opposite side of the territory, where a female solicits copulation. In the fourth frame, less



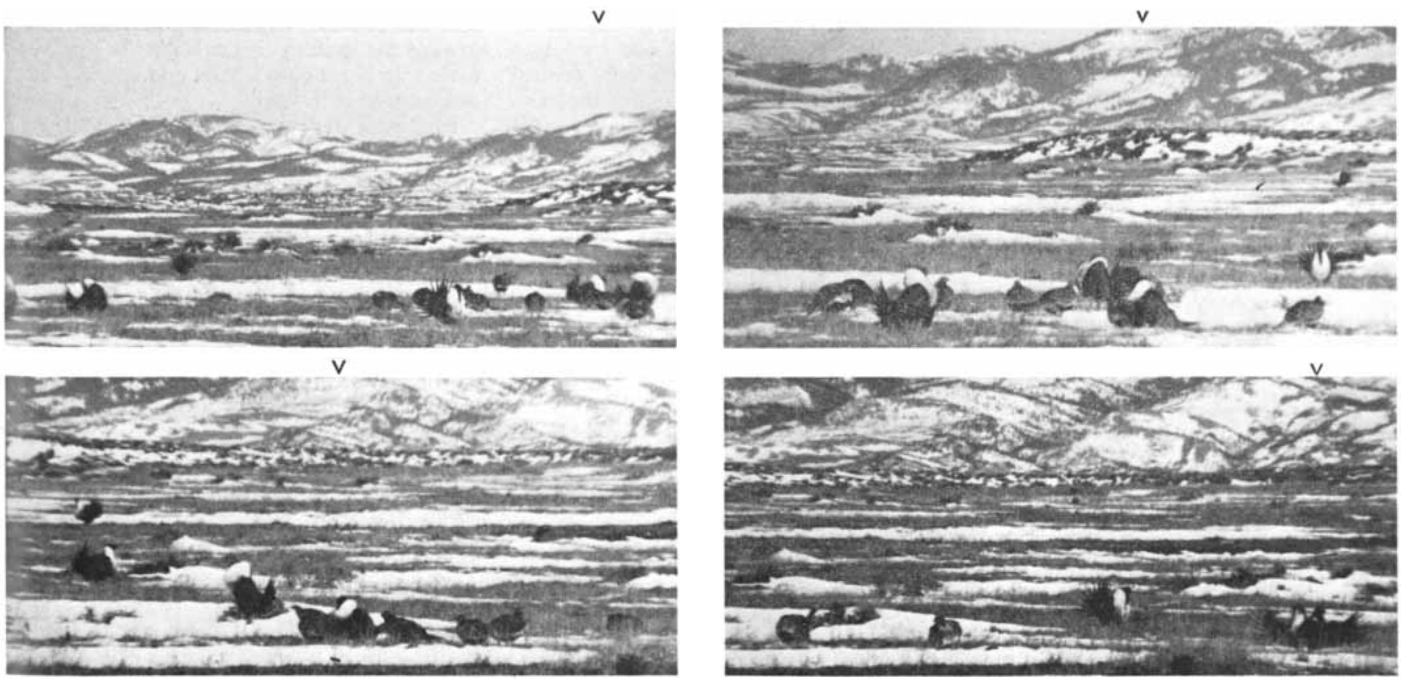
tion *d*. The upward toss that accompanies inflation of the sac is seen in *b* and *d;* the contraction that produces a popping sound is seen in *e*, some 2.3 seconds after the male begins its display. All male sage grouse strut in the same manner with only minor individual variations.

congregating there and not the cause.

In actuality a female grouse might choose a mating place in ways other than by discriminating between differences in the behavior of males. For example, the males' territories are smaller near the mating center than they are at the periphery of the lek, so that the congregation of males is densest near the center. The females might recognize this difference in density and choose to mate in the areas that have the denser concentration of displaying males. The density information, although not specific enough to locate the mating center exactly, would identify its general location.

Another possible cue is even more ambiguous. A mating center is usually located at a point within the lek where the growth of sagebrush is sparse. There are usually several such comparatively bare spots within the lek, yet only one will be the site of a mating center.

A highly specific cue for the location



than a minute later, male *A* copulates for the first time (*zoom lens close-up*). Some three minutes later (*fifth frame*) male *A* and a second female copulate; neighboring males continue to display. Less than two minutes later (*sixth frame*) the neighboring males are dispersed to the far reaches of their territories and only one of the three (*right rear*) is in camera range. Male *A* struts alone amid the female assembly. Some four minutes later (*seventh frame*) male *A* copulates for the third time. The bird copulated five more times in the next eight minutes, thereby inseminating all but one of the nine females that had gathered at the mating center in the morning. By the ninth minute (*eighth frame*) male *A* has moved to the right to confront the male that occupies this adjacent territory. The gathering of females is dispersing.

of the mating center is the presence of a tight pack of females. This information, however, would be available only to those females that arrived at the lek later in the morning than the rest.

My own observations show that females arriving at a lek tend to follow one another and to stop as a group even when they are still some distance from the mating center. This attention of the females to one another's behavior might enable the females that were breeding for the first time to follow more experienced ones to the mating center, but only if the experienced ones had already learned the location of the center earlier in the breeding season or remembered the location from a previous year. A characteristic of one-year-old females noted by Robert Eng of Montana State University and Paul Dalke of the University of Idaho and their colleagues provides a mechanism whereby experienced females might cue novices. Eng and Dalke found that novice females arrive at the lek later and lay their eggs later in the breeding season than second-season and older females do. In other words, mature guidance is available to the novices.

So far it is uncertain which combination of cues guides the female sage grouse in selecting a place to mate. Two facts—that females follow one another on the lek and that they gather in a dense cluster at the mating center—suggest, however, that interactions between the females themselves, and not merely the females' response to the males' displays, control most if not all of the females' breeding behavior.

The key question here is clearly not "How do females choose a particular male to mate with?" but "How do males acquire territories at a mating center?" The recurrence of a mating center in the same location within a lek year after year cannot reflect an enduring preference of the female grouse population for individual male grouse. This becomes obvious when one considers that mortality in the male grouse population runs at a rate of about 50 percent per year. To learn how some males reach the mating center one must focus on the social dynamics that regulate territorial accession.

On the leks that I observed the process of accession can be described as centripetally oriented filling of vacancies. Whenever a male grouse disappeared overnight, the vacancy it left was occupied by one or more neighboring birds whose territory was farther from the mating center. I never saw a male fill a vacancy that was farther from the center than its own territory.

The vacancy-filling process was gradual. Often on the first day none of the missing male's neighbors made any major intrusion on the vacant territory. Over the next day or two, however, a peripheral neighbor would extend its strutting activities farther and farther until the vacancy had been transformed into its new territory. The inward movement of course left the newcomer's former territory vacant and would initiate an inward shift by the next most peripheral neighbor.

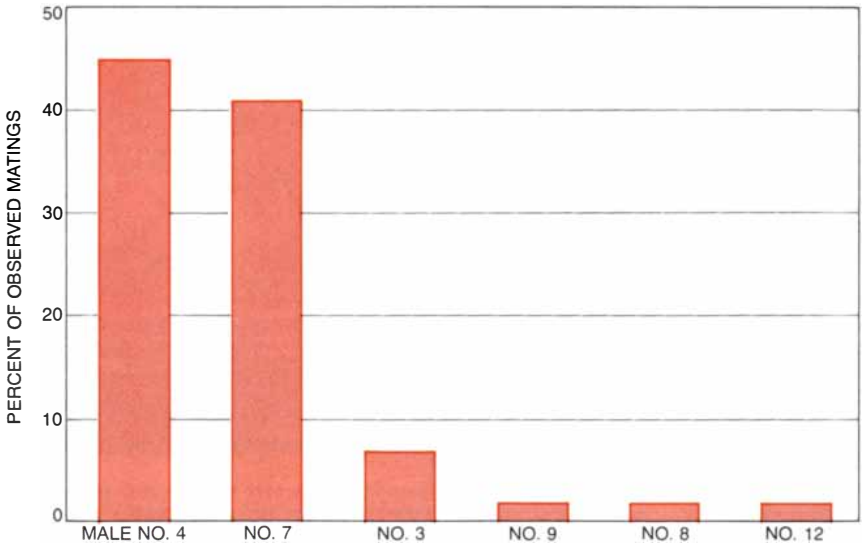
The process is not always precisely predictable, even though no males move in an outward direction and none leapfrog over an intervening territory. For example, two neighbors equidistant from the center sometimes divide a more central vacancy between them, but on other occasions one bird lays claim to the whole of the more central vacancy and the other ignores the newly created vacancy and remains in its old territory. Regardless of such details, within any one mating season the male grouse tend to move gradually closer to the mating center simply by filling vacancies.

That male grouse continue their progress toward the mating center year after year seems likely for several reasons. For one thing, in many species of lek-forming grouse the males maintain at least perfunctory contact with their leks throughout the year. On warm days in the fall and winter they visit their leks briefly in the morning. They do not usually strut much on these off-season occasions, but the visits could enable individual males to maintain contact with their lek neighbors on a year-round and even a year-to-year basis. In this connection, banding studies have demonstrated that once a male grouse has established a territory on one lek the bird rarely moves to another lek in subsequent breeding seasons.

Observations of lek activity in late winter, just before the male grouse begin to congregate in earnest, reveal an absence of vigorous competition for central positions. Only a few of the males established on the lek will show up on any one morning, and the birds are relatively inactive. Thus it seems reasonable to suppose the filling of vacancies due to winter mortality is a gradual process, beginning with the return of the surviving males to their approximate former positions. It is certainly the case among sharp-tailed grouse, as Henry Kermott of the University of Minnesota has documented in detail. He found that the process of gradual movement toward the mating center begins in the male's first breeding season and continues from year to year.

First-year sage grouse males, easily recognizable because their tail feathers are less sharply pointed than those of older males, arrive at the lek much later in the breeding season than the older males. The young males probably visit a number of leks before settling at one of them. Most of the first-year males have yet to establish their own territories on a lek by the time the female grouse arrive. By the middle of April, when copulation is in progress, the young males take up positions on the periphery of the lek. In due course they begin normal territorial behavior, coming regularly each morning to reoccupy their chosen domain. Here the luck of the draw can play a part in the young males' future success. Leks are seldom exactly symmetrical. As a result some of the first-year males will find fewer occupied territories between them and the mating center than others will. At the same time the advantage of a superior initial position can be nullified if the random death of older birds does not vacate intervening territories.

The evidence hence suggests a consistent hypothesis for male sexual success



SEASON-LONG RECORD of the six mating males at the Dry Sandy lek shows that the two most active birds were responsible for 86 percent of the 42 copulations observed at the center.

along the following lines. In its first year the male grouse establishes a territory at the edge of a lek. In successive years the bird tends to return both to the same lek and to the same general location within the lek. The bird's location shifts centripetally both within a season and from year to year, and its progression toward the mating center—and mating success—remains probabilistic throughout. Although there is undoubtedly a good deal of variation in the ages of males that reach the mating center, the first-year males will virtually never mate and the second-year males are less likely to achieve mating success than older males. Thus there is a regular ontogenetic trajectory, or developmental progression, by which a male achieves full reproductive success. In the simplest terms, the key to success is age before beauty.

What has been said so far applies to males. Is there any such ontogenetic trajectory for the female grouse? Evidently not. Almost all the females mate each season; they begin to reproduce in their first year and lay about the same number of eggs annually as long as they survive. The young male grouse, on the other hand, not only rarely reproduce but also are less developed than older males in terms of morphology and physiology. Their plumage is not as developed as the older males', and even at the height of the breeding season their testes are smaller.

I have termed this difference in the life cycles of male and female sage grouse sexual "bimaturism," a condition analogous to sexual dimorphism. Bimaturism is characteristic not only of the sage grouse and other lek-displaying birds but also of most if not all animals with polygynous mating systems. Even human society is not exempt: where polygynous marriage is practiced the difference in age between the male (older) and the female (younger) at first marriage is substantial.

So far I have attempted to analyze the behavioral mechanisms that regulate the structure of the sage grouse lek system. How might such a social system have evolved? One feature of the system—the congregation of displaying males—could have evolved, at least among grouse, in a straightforward way. Clustering at mating time would have adaptive value for grouse in open habitats by virtue of protecting the displaying males from predators' surprise attacks in the dim light at dawn. Polygynous grouse that live in forests do not form leks; the individual males occupy large territories and perform their displays at widely dispersed locations. In open country, however, the males of all polygynous grouse species display in aggregations. The presence of so many watchmen, so to speak, affords each male some protection from predators

such as eagles and coyotes. Indeed, I have witnessed several close escapes from attacking eagles that seemed to know the location of the lek. The predators, flying close to the ground, used low ridges for cover, and often they approached unobserved within 100 meters of the lek before their final dash.

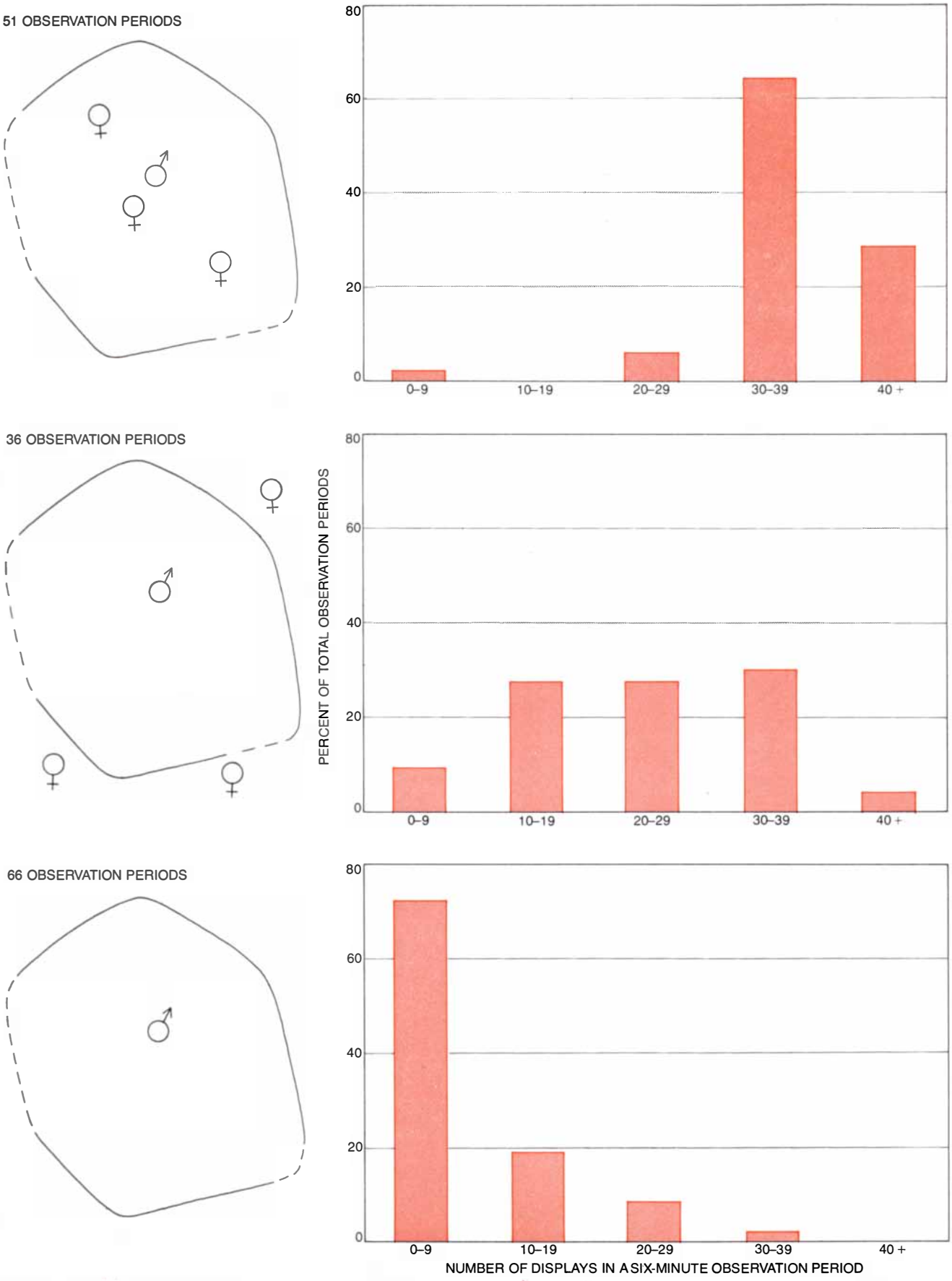
What is more difficult to explain is the evolution of a social structure that features such an extremely unequal distribution of copulations by males; sage grouse practice the most extreme polygyny known among birds. Most biologists now agree that the evolution of social behavior, like the evolution of any other trait, is best explained in terms of the optimization of the individual's "Darwinian fitness," that is, the optimization of the rate at which the genes of the individual are conveyed to its descendants. An explanation of the evolution of a mating system must explain the advantages of the system with respect to the Darwinian fitness of both males and females.

As to male fitness in polygynous societies, the delay before males achieve successful reproduction complicates matters. The rate at which an individual's genes propagate to its descendants depends not only on the individual's fecundity but also on the age at which the individual and its descendants begin to breed. In simple terms, a delay in reproduction increases the generation time and thus lowers the rate at which descendants multiply. A male that delays reproduction in effect tends to sacrifice the advantages of high fecundity once breeding begins.

To see how this works, consider an imaginary bird society. Its males and females have identical survival rates but the males begin to reproduce at a later age than the females. More males than females in each cohort will die before they reach breeding age; as a result fewer males than females will breed in any one season. Such a society necessarily engages in polygyny.

Imagine further that the size of the population is constant, so that over a lifetime each bird leaves on the average one descendant of the same sex, and also that once the males begin to breed they all share the available females equally. In such a simple society polygyny offers neither advantages nor disadvantages to the male. The longer the males defer breeding, the more fecund they are when they begin to breed. The two effects exactly compensate for each other. Yet for the delayed-breeding characteristic of lek-mating males to have evolved at all the individual male grouse must realize some advantage in terms of the propagation of their descendants.

Two oversimplified and inadequate theories of male advantages in lek mating systems have long had currency. They may be called respectively the "sex appeal" theory and the "trial by ordeal"

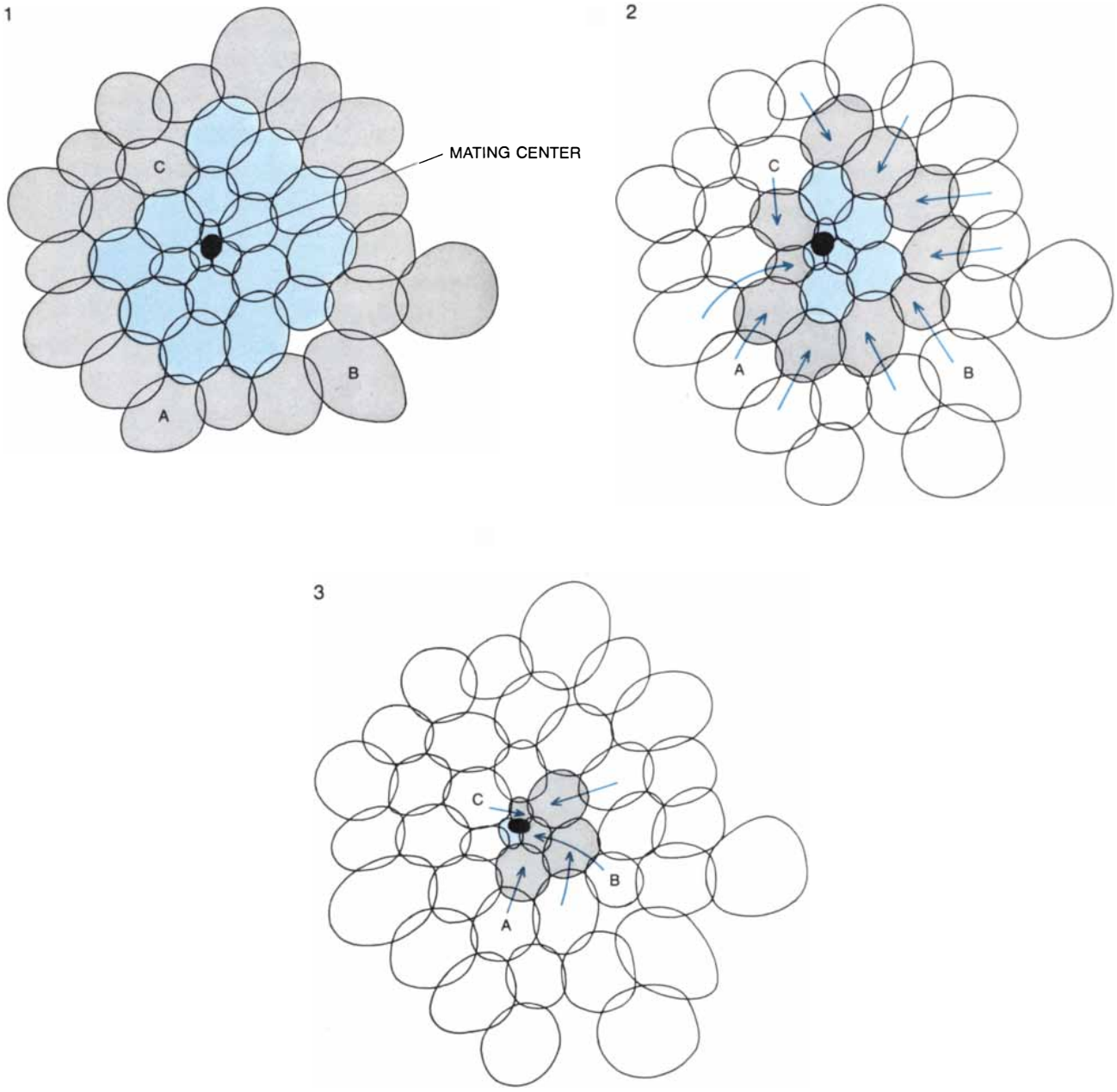


FREQUENCY OF DISPLAYS by male sage grouse is directly related to the nearness of females. A total of 51 observations proved that males usually displayed more than 30 times during a six-minute interval when females were inside a male's territory (*top*). When the females were outside a male's territory but inside a neighboring territory (*center*), the frequency was lower, although males still strutted between 10 and 39 times every six minutes. When no females were adjacent (*bottom*), most male displays fell to fewer than 10 in six minutes.

theory. The first theory proposes that successful males in polygynous societies possess a higher evolutionary fitness than unsuccessful males because they have higher fecundity. The second theory proposes that the successful males have a higher fitness because they have survived longer. As we have seen, however, the high fecundity of successful male grouse does not necessarily mean that such males have higher evolutionary fitness, and neither does a greater life span. Fitness consists, rather, in the optimum distribution of the individual male grouse's time and energy to the promotion of its survival and the exercise of its fecundity over the entire span of its life.

One hypothetical advantage for males in polygynous societies seems at least plausible. If males that breed less are more likely to survive, such an increase in survival, if it is sufficient, could increase the evolutionary fitness of the males that defer reproduction to later ages. Whether or not a hypothesis along these lines can help to explain sage grouse polygyny is not yet clear. Verification in the field would not be easy; it would require comparisons of the longevity and fecundity of males that start breeding at different ages.

When earlier naturalists speculated on fitness, they often equated the behavioral competition between individuals with evolutionary competition. My findings on sage grouse show that this equation cannot be accepted in every case. Competition of the first kind has to



PROGRESSION TO MATING CENTER is shown in idealized form here. At start (*1*) 20 young males have established territories (*gray*) on the periphery of a lek during their first mating season; the more central positions are occupied by older males. By chance the territory of male *C* is closer to the mating center (*black*) than the territories of males *A* and *B* are. By the next spring (*2*) about half of the preceding year's yearlings have died, as have half of the older males. Males *A*, *B* and *C* and others of their cohort (*gray*) are now closer to the mating center; the better starting position of male *C* has brought it closest. The following year (*3*) only five of the cohort still survive. The territories of males *B* and *C* now overlap the mating center, and the territory of male *A* is adjacent to it; the ontogenetic trajectories of males *B* and *C* mean that they will sire many of the young produced during the season. Male *A*, if it survives, will probably reach center the next year.

do with which individual wins fights, whereas competition of the second kind has to do with which individual's genes pass on to descendants. After observing a lek it would be tempting to conclude that the successful males are simply the winners in a competition with the unsuccessful males. In a behavioral sense they are: the males at the mating center exclude intruders from their territory by means of threat and overt aggression. That, however, is not necessarily evolutionary competition. If indeed males increase their evolutionary fitness by deferring full reproductive activity, then the fact that an older male successfully excludes a younger male from the opportunity to copulate might have nothing to do with differences in Darwinian fitness. Quite possibly both grouse are acting in accordance with an evolutionary strategy that enhances the fitness of both.

Does the polygynous mating system offer any advantages to the female grouse? One consequence of such mating is reduced or nonexistent parental care by males. Of the 16 grouse species, 12 are polygynous, and only one of the four monogamous species practices dual parental care. Single parenthood would certainly be disadvantageous for the monogamous and polygynous species alike if grouse nestlings required, as many newly hatched birds do, a prolonged period of feeding until they mature to a state of independence. As it happens, however, all 16 species of grouse, like domestic chickens, give rise to precocial young that are able to follow their mother and feed themselves soon after hatching. Hence a potential disadvantage of polygynous mating has been largely nullified. Nevertheless, three species of grouse have single parental care but practice monogamy. Evidently the evolution of a social pattern of single parenthood, and for that matter the evolution of the precocial young that makes single parenthood possible, although necessary prerequisites to the evolution of polygyny, are scarcely sufficient causal factors.

On balance the adaptive advantage gained by the female grouse depends on the advantages of the male's strategy. Each female's genes are transmitted equally to its male and female descendants; consequently the best strategies for each sex are not in conflict. By breeding with males that practice the optimal male strategy the females increase their own evolutionary fitness: the rate at which their genes propagate to descendants. Hence from generation to generation both the male and the female sage grouse have evolved a mating relationship in accordance with a delicate balance between the disadvantages of single parental care and the advantages of sexual bimaturism.

The Adjacency Principle in Visual Perception

The visual system integrates information about objects from different sources including relative, or contextual, cues. The adjacency principle describes how relative cues are weighted to achieve this integration

by Walter C. Gogel

"Why then do things look as they do?" Kurt Koffka asked in *Principles of Gestalt Psychology,* and he argued that it is surely not "because they are what they are." If things looked as they do only because of what they are, they would continue to look the same as long as they remain the same. The fact is they do not look the same; they look different depending on their context, and more specifically depending on whether they are seen in isolation or with other objects.

There is a striking demonstration involving the effect of context on the perception of motion. A single point of light moving repetitively right and left in an otherwise dark field is perceived as doing just that: moving horizontally. If another point is simultaneously moved up and down nearby, however, the perceived motions of the two points moving at a right angle to each other turn out to differ markedly from their horizontal and vertical motions [*see A in illustration on page 128*]. As Gunnar Johansson of the University of Uppsala has put it, the perceived motions include relative motion vectors (the points appear to move toward and away from each other along a diagonal path) and common motion vectors (they may also appear to move as a group along another diagonal at a right angle to the first).

This clear change in the perception of an object brought about by the introduction of another object (or several other objects) into the field of view has been demonstrated not only for motion but also for such perceived characteristics as color, size, shape, distance and orientation. The factors that determine the perceived characteristics of an object independently of other objects are absolute cues; the factors that change the perception when other objects are introduced are relative cues. The object whose perceived characteristic is being measured is the test object; an additional object whose presence modifies the perception is the induction object. Research in my laboratory at the University of California at Santa Barbara has suggested a general rule that helps in predicting the power of a relative cue to modify a perception. This rule, which we call the adjacency principle, states that the weight the visual system gives to a relative cue is inversely related to the apparent separation of the test object from the induction object in three-dimensional space. Here I shall consider the major evidence for the adjacency principle in the perception of size, orientation, distance and motion, and then discuss briefly what some of the consequences of such a principle might be.

A basic assumption underlying the measurement of adjacency effects and well supported by the experimental data is that the visual system is able to combine information from sources that are not in agreement. Suppose there are two sources, one source that by itself would lead to one perception and another that by itself would lead to a different perception. The assumption is that when the two sources are presented together, they will give rise to yet a third perception, to which both sources contribute. This synthesis of diverse information is demonstrated by the apparent motion induced in a point by a moving frame [*see B and C in illustration on page 128*]. If a physically stationary point is surrounded by a frame moving to the right and left repetitively in an otherwise dark field, the point will appear to move in a direction opposite to that of the frame's physical motion. In a more complicated case the point moves vertically: upward as the frame moves right and downward as the frame moves left. Here the point will have two components of apparent motion, one component being an induced horizontal motion and the other resulting from cues associated with the physical vertical motion. The components add vectorially, and the point appears to move diagonally rather than either horizontally or vertically. A similar horizontal induction effect is perceived if only two horizontally moving points are present [*D in illustration*] instead of the entire frame.

It is not clear whether the apparent vertical motion of the point within a frame should be attributed to an absolute motion cue (the point's physically vertical motion) or to the cue of relative motion between the point and the horizontal elements of the frame. The perceived diagonal motion could be a resolution of a conflict of absolute (vertical) and relative (horizontal) cues or a resolution of a conflict between different relative cues, one involving the horizontal parts of the frame and the other involving the vertical parts. There is evidence that both kinds of cue conflict are resolved by the visual system: it can combine discrepant information from either relative or absolute cues, or from both, for a variety of perceived characteristics.

One way to measure adjacency effects is to vary the distance separating a test object from a single induction object, either in a frontoparallel plane (a plane parallel to the one containing the observer's eyes) or in depth (perpendicular to the line of sight). According to the adjacency principle, increasing either separation should decrease the magnitude of the induction. Another way is to change the apparent position of the test object in relation to two induction objects that are separated either in a frontoparallel plane or in depth and that have opposite effects. According to the adjacency principle, the induction effect should change direction as the test object is moved from the vicinity of one induction object to the vicinity of the other.

Let me begin to review our evidence by describing an experiment of this second kind. An observer is presented with points of light moving in an otherwise

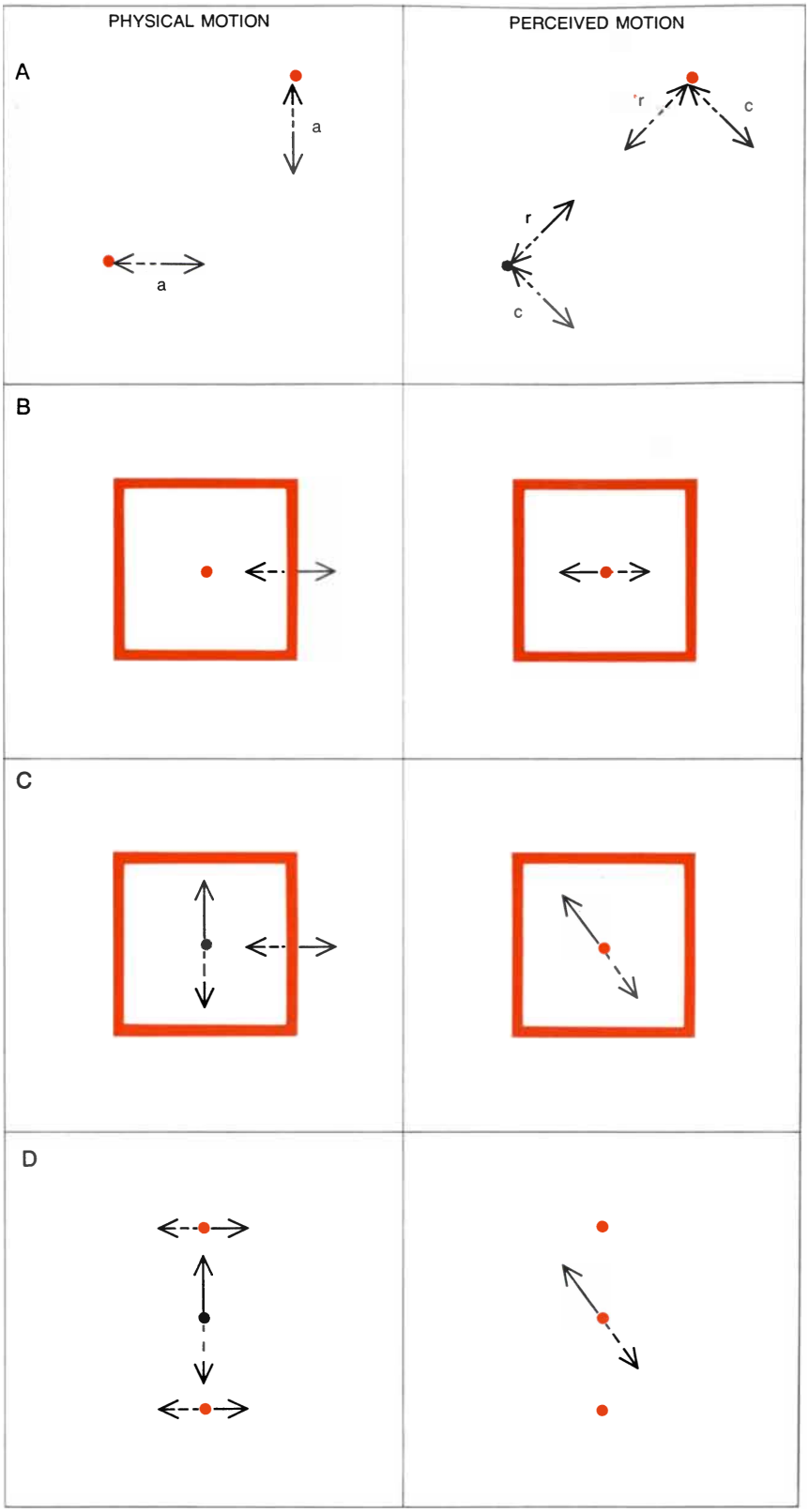
dark field: a test object oscillating horizontally and two induction objects oscillating vertically [*see illustration on page 130*]. The phase of the movements is such that the apparent motion induced in the test object by one induction object is at a right angle to the apparent motion induced by the other induction object. At different times in the experiment the test object is moved progressively farther away from one induction object and closer to the other. Observers viewed the spots of light binocularly and were asked to indicate, by adjusting a comparison rod, the path along which the test object seemed to oscillate.

The results provided strong support for the adjacency principle. The test object [*2 in illustration on page 130*] appeared to move between upper right and lower left when it was near induction object *3* [*a*], approximately horizontally when it was about equally separated from *1* and *3* [*b*] and between lower right and upper left when it was near induction object *1* [*c*]; that is, it was more affected by the induction object to which it was closer and was about equally affected by each induction object when it was equidistant from each. The average magnitude of the deviation of the motion of point *2* from the horizontal was 17 degrees in one extreme case [*a*] and 25 degrees in the other [*c*], which is considerably less than the 45 degrees one would expect if only the relative cue generated by the nearby induction object were having an effect. Clearly, in addition to the dominant effect from the nearby induction object, there was also some effect from the more distant induction object or from the absolute motion of the test object, or from both.

We adapted this experiment with moving points to the situation where only one induction object was present, at varying distances from the test object, by presenting point *2* either with point *1* or with point *3* rather than with both of them together. In agreement with the adjacency principle, the magnitude of the induction effect tended to decrease as the test point was separated increasingly from the single induction point. Although the results were not as conclusive as they were with the two induction points, there was evidence that absolute cues had some effect even when the test point and the induction point were adjacent to each other. Overall the results of this experiment clearly support the conclusion that the effectiveness of relative cues diminishes as the distance between the test object and the induction object increases, but the results also suggest that the test object is influenced somewhat by relative cues from the more distant induction object and by absolute cues from the test object itself.

In another set of experiments we stud-

SPATIAL ADJACENCY EFFECTS are demonstrated when a trapezoidal window, made by masking and shading portions of an electroluminescent panel, and two luminous disks are viewed binocularly in an otherwise dark visual field. One end of the window (*here the right end*) is closer than the other, but perceptually it is farther away. The perceptual error is transmitted to the disks. They are physically equidistant from the observer, but perceptually the right disk is beyond the left one. If the disks are moved along the tracks together, they appear to move at different speeds while they are in the vicinity of the window. The influence of the window on their perceived position (and motion) diminishes as they move away from it. (The window's downward slant here results from the angle at which the photograph was made.) Application of the adjacency principle to these phenomena is illustrated in diagram on page 136.



APPARENT MOTION is induced in one object by another object nearby. In the first example (*A*) two points oscillate, one vertically and one horizontally. Presented alone, they would be perceived as doing just that. When they are presented together, their diagonal relative motions (*r*) and often their common motions (*c*) are perceived instead of their absolute motions (*a*). An oscillating frame (*B*) induces an apparent horizontal motion of opposite phase in a physically stationary point within the frame. If the dot is physically moving up and down (*C*), the frame produces apparent horizontal vector, which with vertical vector results in apparent diagonal motion. Similar perception is induced if two points, rather than frame, act as induction object (*D*).

ied the effect of frontoparallel separation on a different characteristic: perceived location in distance. The distance cue under investigation was the one provided by the relative size on the retina of the eye of similar objects that were probably assumed by the observer to be physically identical in size. If two such objects subtend different sizes on the retina, the retinally smaller object is perceived as being farther away; equality of the retinal size of similar objects is accepted as information that the objects are at the same distance. Three playing cards and a gray square were presented by back illumination of photographic transparencies, all at the same distance in an otherwise dark room, and were viewed monocularly by the subject [*see illustration on page 132*]. One card was larger than normal and the other two were of normal size.

If the gray square had not been present, apparently overlapping the large card and itself overlapped by the upper normal-size card, the apparent relative distances of these two cards (The induction objects) would have been determined by the difference in their retinal sizes, and the normal-size card would have appeared to be farther away than the large card. The gray square, however, provided an "interposition cue" that made the normal card appear to be in front of, and thus closer than, the large card. The test object was the lower card of normal size and was presented close to the large card in one experiment [*a*] and equally separated from the large card and the upper normal-size card in the other experiment [*b*].

In both experiments there are relative size cues between the test card and each of the induction cards. The relative cue between the test card and the large card tends to make the test card appear to be behind the large card (and therefore, because of the interposition cue, far behind the upper normal-size card). The relative cue between the test card and the upper card tends to make the test card appear to be at the same distance as the upper card (and therefore, because of the interposition cue, not behind the large card but in front of it). That is, the presence of the interposition cue means that the two relative size cues affecting the test card are in conflict.

The adjacency principle predicts that when the test card is near the large induction card [*a*], the relative size cue between the test card and the large card should make the test card appear to be far behind the upper normal-size card. And that is how it seemed to our subjects. With the test card equally displaced from both induction cards [*b*] the adjacency principle predicts less effect by the large induction card on the test card, which indeed was then said to seem to be about midway between the

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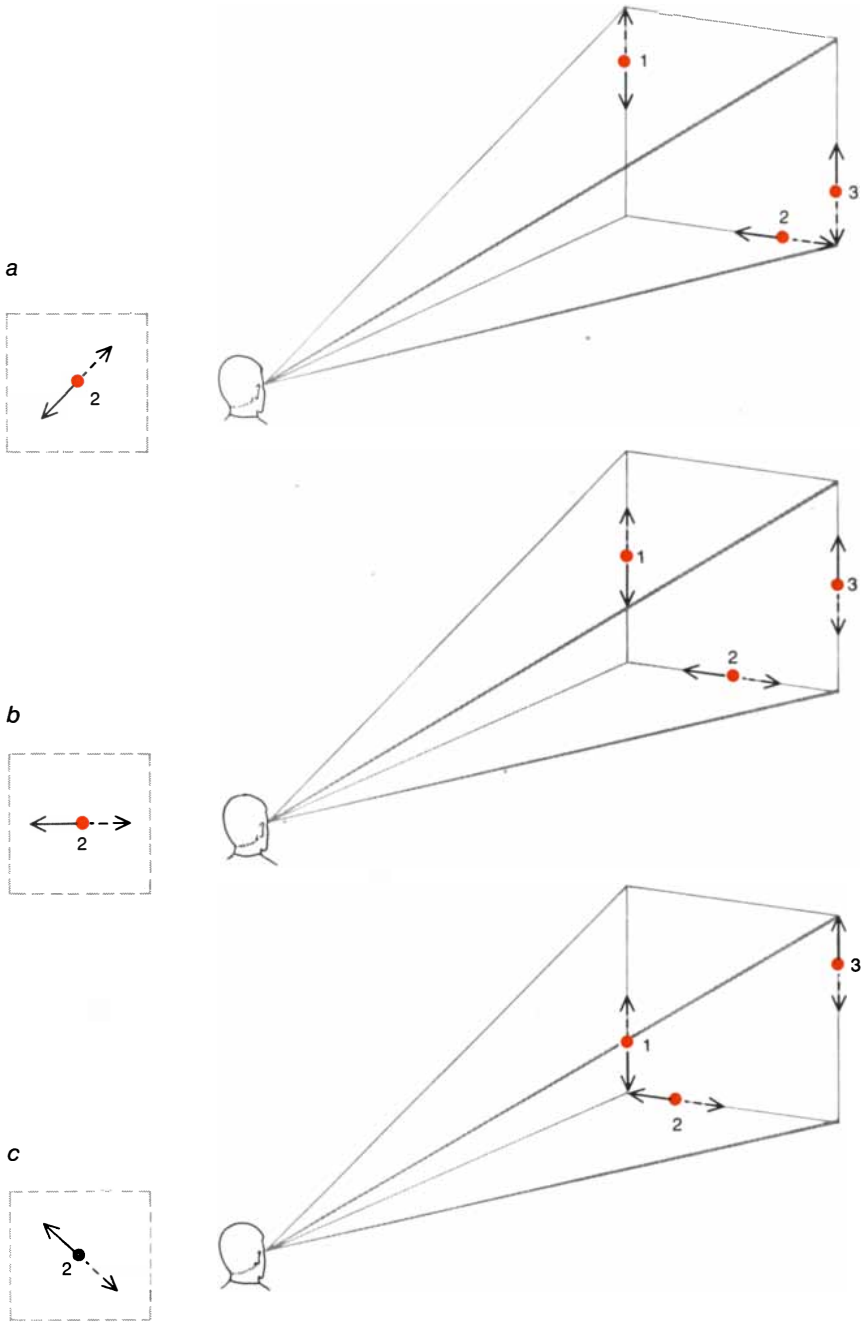
two induction cards in depth. The results suggest that the relative size cues between both the adjacent and the displaced induction cards contributed to the apparent distance of the test card. In agreement with the adjacency principle, however, the contribution was greater for the induction card that was closer to the test card in the frontoparallel plane.

Because separation in a frontoparallel plane and separation on the retina are essentially proportional it is possible to interpret the effects of frontoparallel adjacency in terms of adjacency on the retina. Evidence that adjacency effects are not determined by retinal separation, however, comes from studies demonstrating that the effectiveness of relative cues is reduced by separation in depth of the test object and the induction objects. For example, in some of our experiments two induction objects calculated to have opposite effects on a test object are presented binocularly at different distances from the observer; the test object can be presented at the distance of either the far induction object or the near induction object or midway between the two. In each case the far induction object is made just enough larger than the near one so that the two objects subtend the same size on the observer's retina. As far as retinal stimulus is concerned, therefore, the effects on the test object of these two equal but opposite induction objects should cancel. The adjacency principle predicts, on the other hand, that there will be an induction effect whose magnitude and direction are determined more by the induction object that is at the same apparent distance as the test object and less by the one that is separated from it; when the test object is midway between the opposing induction objects, the effect should be reduced or absent.



EFFECT OF ADJACENCY on cues of relative motion is measured by placing a test object (*2*) at different distances from opposing induction objects (*1 and 3*). Points of light oscillate along paths defined by the length, direction and phase (*solid or broken line*) of arrows at the right; point *2* oscillates either in the vicinity of point *3* (*a*), midway between the induction points (*b*) or in the vicinity of point *1* (*c*). Arrows at the left indicate what the direction of point *2*'s motion would be in each case if the nearer induction point completely determined the observer's perception. In agreement with the adjacency principle the experimental results indicate that although both induction points probably contribute to the apparent motion of point *2*, the nearby point has more influence. (In this experiment and the experiments that follow only the test object and induction objects were visible to the observer in an otherwise dark visual field.)

In one of these depth-adjacency experiments we manipulated the elements of the Ponzo illusion, a visual illusion in which two bars are positioned within a wedge-shaped figure; the bars are identical in size, but the one nearer the apex of the wedge appears to be larger. We presented two wedges (the induction objects) simultaneously at different distances, one pointing to the right and the other pointing to the left, and presented the bars (the test object) at one of three distances: the distance of the far wedge, the distance of the near wedge and the distance midway between them [*see A in illustration on page 135*]. As predicted by the adjacency principle, the direction of the illusion reversed as the bars were moved from the far plane (where there was an average illusion of 8 percent in one direction) to the near plane (where there was an average illusion of 10 percent in the other direction).

An experiment done by Robert E. Newton and me based on the rod-and-frame illusion produced similar results. Here a vertical rod surrounded by a tilted frame appears itself to be tilted in a direction opposite to the physical tilt of the frame [*B in illustration*]. Again the illusion reversed in accordance with the location in depth of the vertical rod (the test object). The average tilt reported by our subjects was four degrees counterclockwise at the far position and two degrees clockwise at the near position. Although the differences in induction effect from the far to the near distance may not appear to be large for either of these illusions, they are substantial

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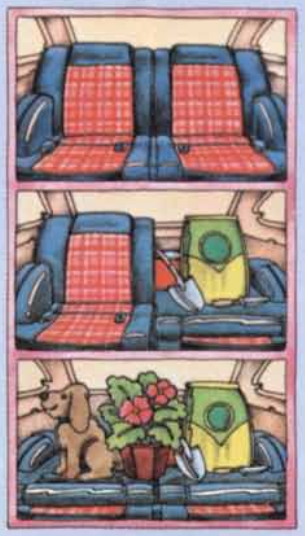

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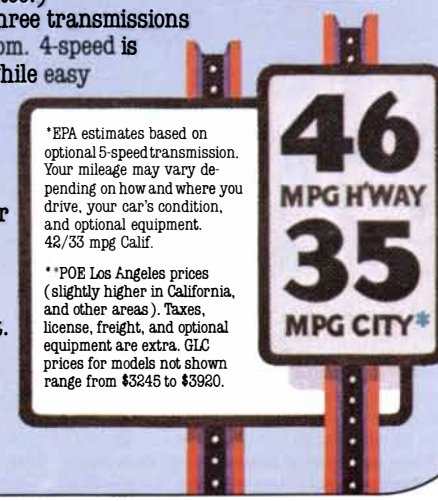

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when they are evaluated against the normal magnitude of such illusions.

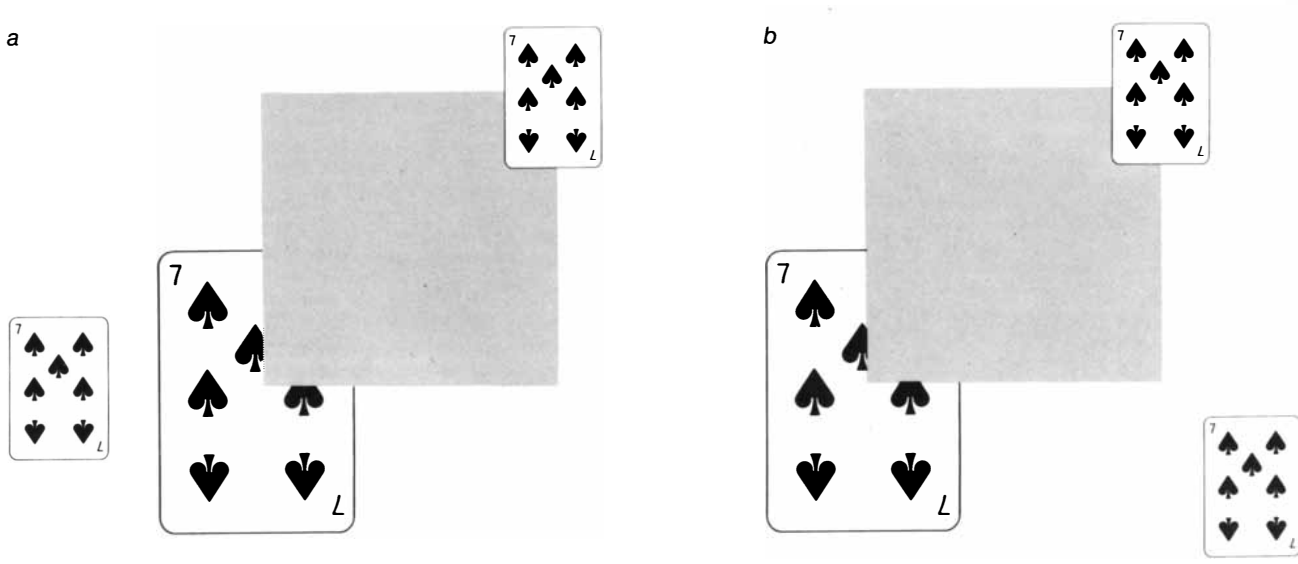
In two other experiments on depth adjacency we measured the motion induced in a test point by induction objects that had opposite effects. Michael Koslow and I investigated the magnitude and direction of the motion induced in a stationary point by two frames that oscillated horizontally, in opposite phase, at two distances from the observer [*C in illustration on page 135*]. Again we found that the direction of induced motion of the point was determined by the induction frame at the same distance as the point and that the magnitude of the induction was reduced when the test object was midway between the two induction frames. Jerome D. Tietz and I tested the motion induced in a vertically moving test point by induction objects consisting of two horizontally oscillating points [*D in illustration*]. The far set of induction points moved to the right as the test point moved up, and the near set moved to the left as the test point moved up. The results were consistent with the adjacency principle: the test point appeared to oscillate between the upper left and the lower right when it was in the far plane and between the upper right and the lower left when it was in the near plane. The effect of adjacency was large: there was about a 35-degree difference between the two perceived directions of motion of the test point.

In these four depth-adjacency experiments the effect of the adjacent induction object was greater than that of the more distant one, but in each case the more distant induction object retained some influence. The evidence suggests that the decrease in the effectiveness of a visual cue with increasing separation is gradual—a continuous function rather than a step function.

We modified three of the depth-adjacency experiments (the Ponzo and rod-and-frame illusions and the point in a moving frame) by presenting only one induction object at a time. With the far induction object the test object was presented either in the same plane or at one of two distances in front of it; when the near induction object was presented, the test object was either in the same plane or at one of two distances beyond it. In all three cases the induction effect decreased sharply with increasing distance in front of the induction object but not with increasing distance behind it. Possibly the lack of a consistent decrease for positions behind the induction object is due to an inverse relation between the effectiveness of absolute cues about the test object and the distance of the test object from the observer. According to this hypothesis, as the test object moves toward the observer (in front of the induction object) both the decreased effectiveness of induction predicted by the adjacency principle and the increased effectiveness of the absolute cues contribute to eliminating the induction effect. As the test object moves away from the observer perhaps the effectiveness of both the relative cues (induction) and the absolute cues diminishes, so that the induction effect remains about the same.

We found, however, that displacing a test object behind the induction object does reduce the magnitude of a particular induction effect: one produced on surrounding objects by binocular observation of an Ames trapezoidal window presented at an illusory slant. The psychologist Adelbert Ames, Jr., devised a trapezoidal window frame that, when it is presented at one slant in depth, tends to appear to be rectangular and to slant in the opposite direction. We presented the window under indirect illumination, with its small end sometimes to the right and sometimes to the left but always physically closer to the observer than its large end; the physically near end appeared to be the more distant one even though the window was viewed binocularly. With the window we presented two points of light, one to the right of the window and one to the left [*see illustration on page 136*].

The pair of lights was presented at seven different distances (only three of which are shown in the illustration) from the observer. Although the two lights were moved together and were always equidistant from the observer, the observer's error in perceiving the window's orientation induced a substantial error in his perception of the relative distances of the two points. When both points were at about the same distance as the center of the window (305 centimeters from the observer), the median depth reported between the left point and the right point was about 60 centimeters. Positioning the points increasingly far in front of the window or beyond it reduced this error in distance perception sharply, with the error be-



EFFECTIVENESS OF RELATIVE SIZE CUES decreases with increasing distance between test object and induction objects. Two normal-size cards and a double-size card are displayed with what appears to be an interposed gray square, all at the same physical distance. They are viewed monocularly. One relative size cue (from the large induction card) would make the lower normal card (the test card) appear to be behind the large card. Another relative size cue (from the upper normal-size induction card) would make the test card appear to be at the same distance as the upper normal card. These two relative size cues are rendered incompatible by the interposition cue from the gray square. As is predicted by the adjacency principle, the large card had more influence when the test card was near it (*a*), that is, the test card appeared to be behind both induction cards. The two induction cards were more nearly equal in influence when the test card was equidistant from both of them (*b*); then the test card appeared to be between the two induction cards in depth.

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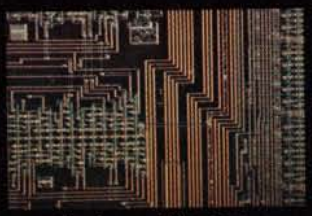

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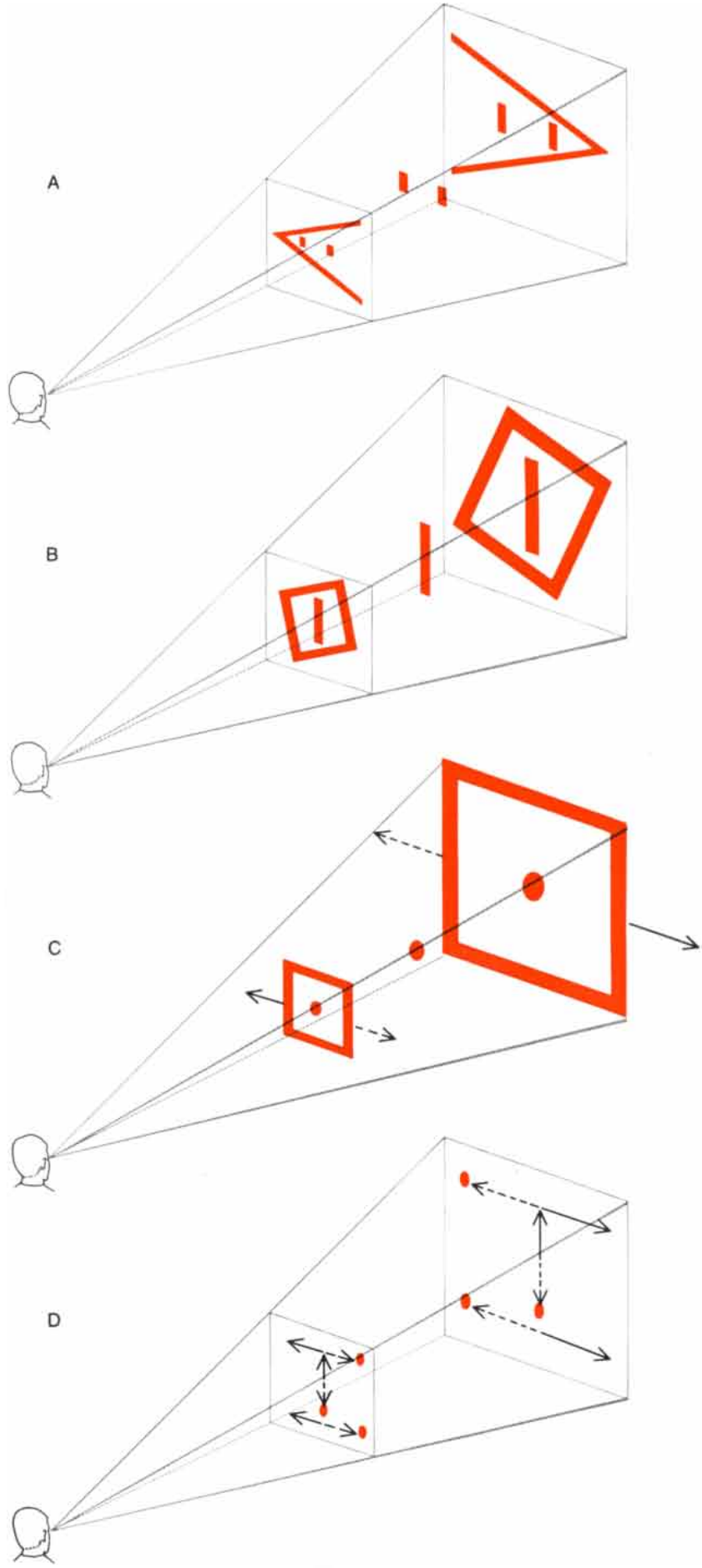
coming small (the points appearing to be about equidistant) when the points were physically about 75 centimeters in front of or beyond the window. In other words, it was only when the points of light were at about the same distance as the window that the large error in its perceived orientation was reflected in an error in the perceived depth separation of the two points. The tendency of the visual system to give greater weight to cues between adjacent objects than to cues between more separated objects was thus demonstrated impressively for the relative cue of binocular disparity.

How might one account for the effects of adjacency? Effects in a frontoparallel plane might be explained by the decrease in visual acuity that comes with increasing displacement of the image from the center of the fovea, the part of the retina that is most densely populated with light-sensitive receptor cells. Cues between objects close to one another in the visual field could be given more weight by the visual system than cues between separated objects because they have greater clarity or are more precisely represented in the nervous system. Adjacency effects in depth could have a similar explanation. Because objects that are fixated are seen with particular clarity as a result of the accommodation and convergence of the eyes the visual system could rely more on cues between objects that are at the fixated distance than on cues between objects at other distances. A different but somewhat related explanation might be that adjacency effects are determined by attention. Cues between adjacent objects could be given greater weight than those between separated objects because it is easier to attend simultaneously to objects that are close together.

We examined the attention explanation in the course of the experiments with playing cards. In those experiments we elicited judgments of the apparent



PRINCIPLE IS TESTED by binocularly presenting, simultaneously at different distances, two induction objects having opposite effects on a test object positioned either in the plane of one or the other induction object or sometimes between them. (Only one test object is presented at a time.) The effect of the wedge (*A*) is to make the vertical bar in the apex appear longer than the other bar. The effect of the tilted frame (*B*) is to make the vertical rod appear tilted. The moving frame (*C*) makes the stationary point appear to move horizontally. The horizontally moving induction points (*D*) make the vertically moving point appear to move diagonally. In each case the two induction objects are sized to subtend the same visual angle and thus to be equal in retinal size. Yet the two oppositely oriented induction objects do not cancel. In accordance with the adjacency principle, the induction object at the same apparent depth as the test object determines the direction of either the static illusions (*A, B*) or the apparent motions (*C, D*).

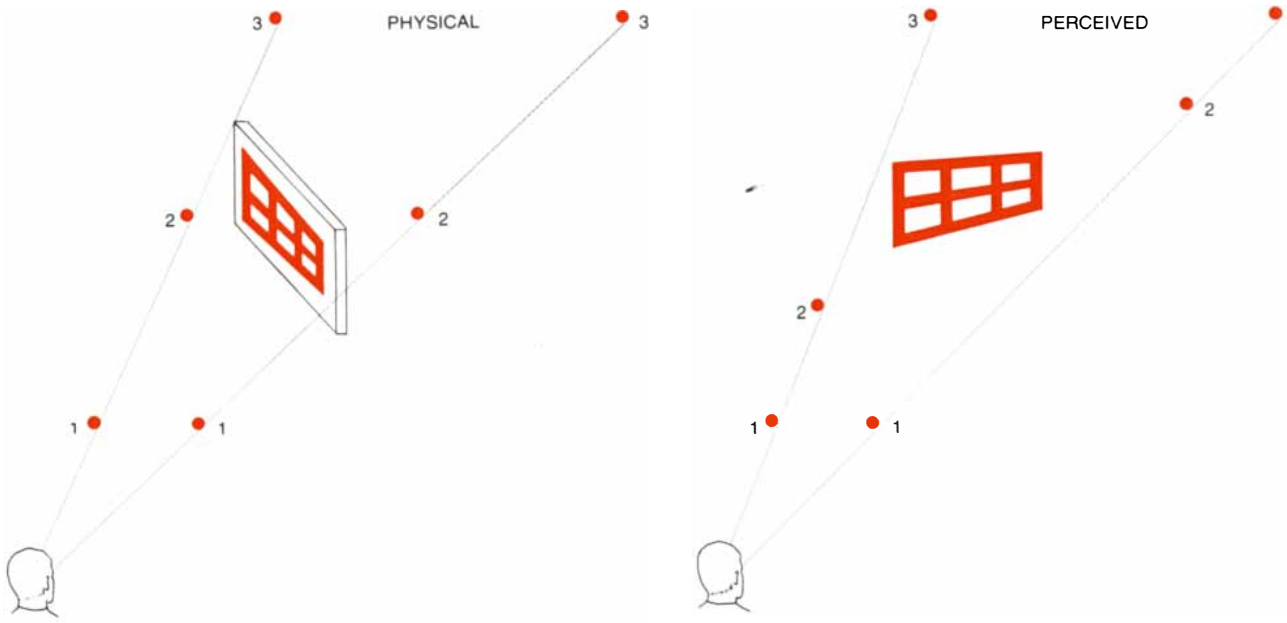
separation in depth between each of the objects in the displays. We hypothesized that if attention was important, asking the subject to judge the position of the test card in relation to a particular induction card should increase the attention given to the relative size cue between the test card and that induction card. The increased attention should in turn increase the effectiveness of the relative cue between the two cards and thus be reflected in the apparent distance of the test card. We analyzed the results to test this hypothesis and found that "task set," a form of attention, accounted for 18 percent of the adjacency effect in the first experiment [*"a" in illustration on page 132*] and for 35 percent of the effect in the second experiment [*b*].

A more direct test of the attention explanation was conducted with the three-dimensional display involving the vertically and horizontally oscillating points [*D in illustration on preceding page*]. Observers were asked to indicate the direction of the test point's apparent motion while they were attending to one pair of induction points and ignoring the other pair. We measured the ability of attention to account for adjacency effects by noting how the apparent direction changed as attention was directed to one or the other set of induction points. Attention accounted for about half of the total adjacency effect. (The overall adjacency effect was large in this particular experiment, and the change attributable to attention was also large.)

Under some conditions, then, attention accounts for a substantial part—but not for all—of the adjacency effect. Its failure to account for all the effect suggests that adjacency and attention are based on different processes. As for perceptual clarity, it may contribute to adjacency effects, but it cannot account for their magnitude. For example, depth-adjacency effects are present (in such situations as the oscillating-point experiment) even when the separation between induction objects is less than the depth of focus of the eye, so that both induction objects are clearly seen. The experiments support the conclusion that although factors such as voluntary attention and visual clarity may contribute to adjacency phenomena, a core of adjacency effects remains that requires the postulation of some kind of unconscious weighting process determined by the perceived spatial separation of the objects.

The role of spatial adjacency in the process by which information from various sources is integrated in the visual system is probably the same whether the information is complementary or opposed. One should not, however, underestimate the frequency with which visual cues conflict with one another. Some of the cue conflicts in our research were unusual, such as those produced by the interposition cue and by the trapezoidal window. Other kinds of cue conflict are unavoidable in everyday visual experience, however; among them are conflicts between absolute and relative cues in general and conflicts between differing relative cues of motion in particular. For example, whenever two objects at the same apparent distance move in relation to each other, there is a relative motion cue, and it is in conflict with at least one of the absolute motion cues. Whenever three objects at the same apparent distance move differently in relation to one another, several relative motion cues are in conflict. The integration of conflicting information seems to be a normal requirement for the visual system.

Together, absolute and relative cues constitute all the stimulus information available to the visual system. Absolute cues support the perception of the characteristics of an object independently of the characteristics of other objects; relative cues reflect the perceptual interrelations among objects. In the absence of relative cues the perceptual world would consist of independent parts, and it would be very difficult to respond meaningfully to such a fragmented world. To appreciate the degree of diffi-



TRAPEZOIDAL WINDOW that physically slants one way but appears to slant the other way affects the perception of the distance between two points near it when the window and the points are observed binocularly. (The window is made differently from the one in the photograph on page 127.) The points are always equidistant from the observer (*left drawing*), whether they are in front of the window (*1*), near it (*2*) or beyond it (*3*). The error in perception of the window's orientation (*right*) induces a corresponding error in the perceived separation in depth of the points when they are near the window (*2*); the error diminishes as the points are displaced from the window (*1 or 3*). The results agree with the adjacency principle. For a point close to the window in depth (*2*) the binocular-disparity cue between it and the adjacent part of the window—not the displaced part—determines the point's apparent distance: the right point is physically beyond and also appears to be beyond the right end of the window, and the left point is physically in front of and also appears to be in front of the left end. When the points are displaced in depth from the window, binocular cues directly between the points (rather than between each point and the window) are given more weight, and so the points tend to be perceived correctly as being equidistant.

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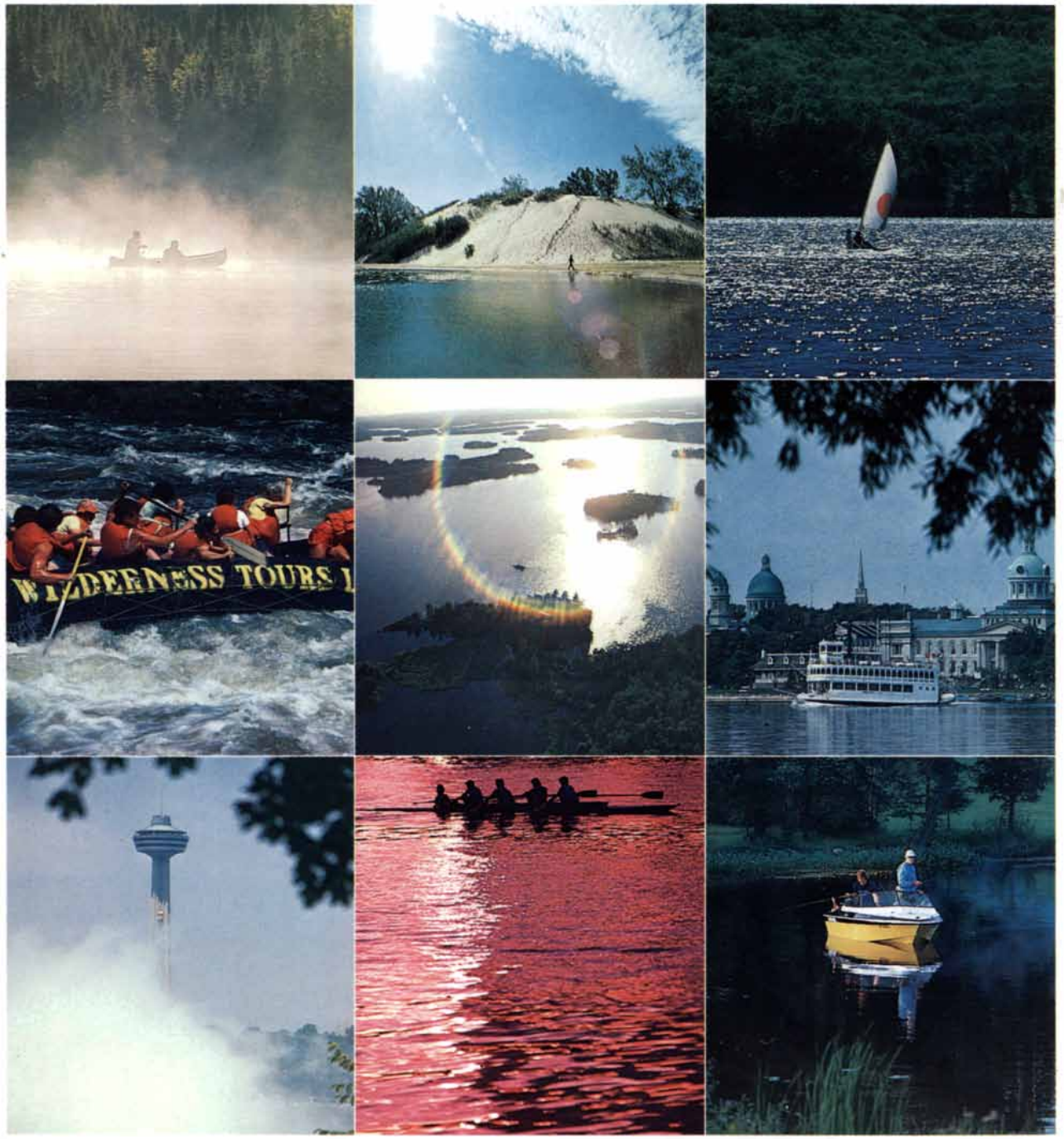

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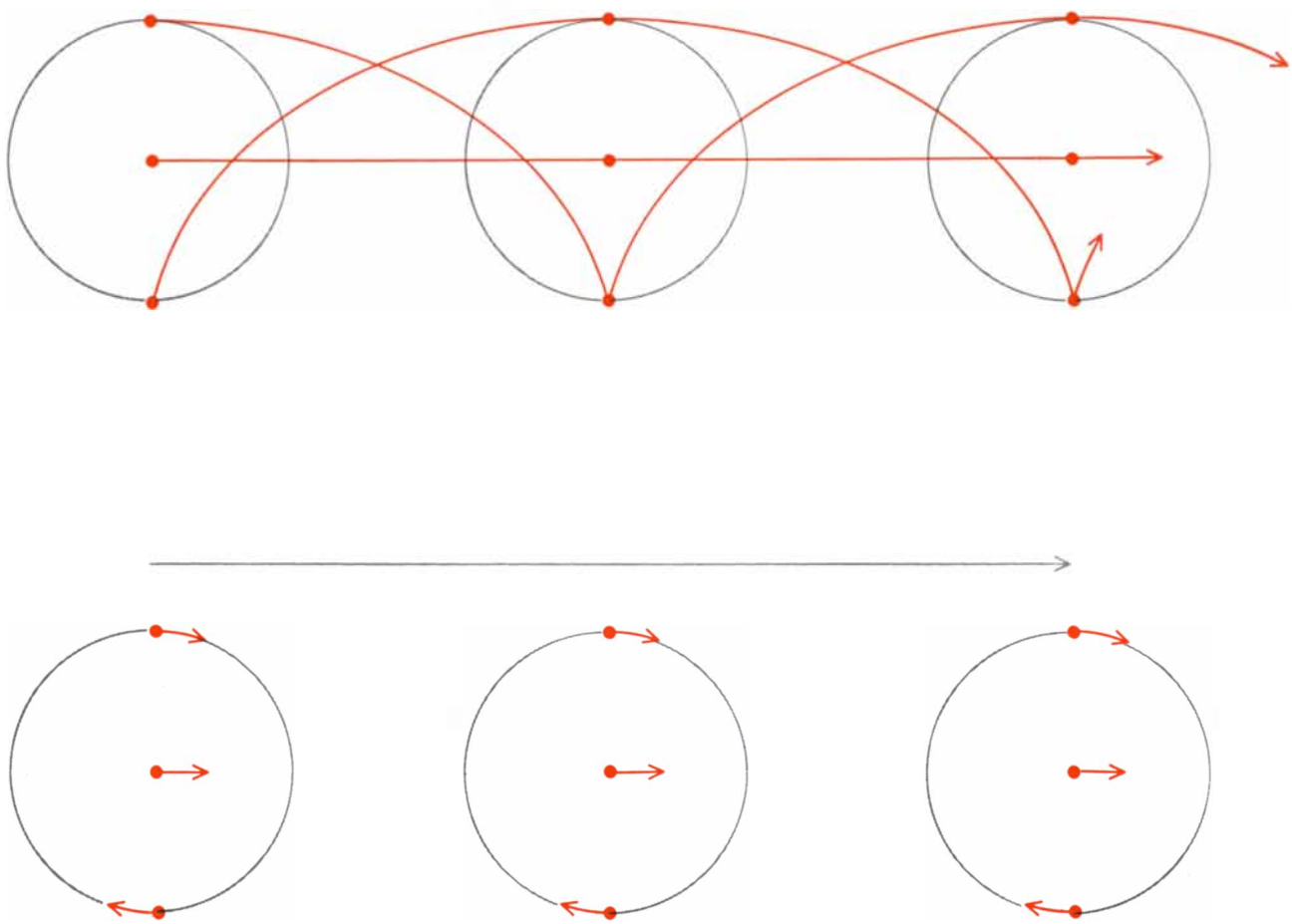
culty consider the case, discussed by Johansson, of a rolling wheel whose only visible parts are several points of light on the rim and a single point at the hub [*see illustration below*]. The trajectories of the absolute motions of the points would be a straight line (for the point at the hub) and cycloid curves (for points on the rim). A perception based on these absolute motions would be complex, and it would become more complex if the number of visible points on the rim were increased. Actually, however, the relative motions of the points on the rim and the point at the hub produce the perception of a unitary object (a wheel) that moves in a direction (to the right) defined by its common motion vectors.

Generalizing from this example, it can be seen that great perceptual simplicity derives from the organizing process that groups stimuli into perceptual objects determined by relative position and relative motion, and perhaps by other relative cues. It is far simpler to perceive an object moving as a unit than to perceive a large number of perceptually independent motions of different points.

What is the contribution of spatial adjacency to this kind of perceptual organization? The tendency to perceive the relative rather than the absolute motion of spatially adjacent points, and thus to perceive organized stimuli (such as a rolling wheel), is consistent with the adjacency principle. As the Gestalt psychologists emphasized, proximity in a frontoparallel plane is an important factor in perceptual grouping. According to the adjacency principle, proximity is an important factor not only in two-dimensional but also in three-dimensional space. The degree to which relative cues of position, motion and perhaps other characteristics can organize stimuli into perceptual groups, or objects, depends on the rate at which the effectiveness of these relative cues decreases with increasing spatial separation, in other words, on what might be termed the adjacency function. The perceptual world would tend to be too fragmented if the adjacency function were too steep; it would tend to be too undifferentiated if the function were too shallow.

Spatially separated patterns of moving stimuli (two rolling wheels, for example) become grouped into perceptually distinct objects rather than one overall complex object at least partly because of adjacency effects. The common motions of the parts of each perceptually segregated object become the perceived absolute motions of the object as a whole. If the common motions of the several perceived objects are different, those motions can become relative motions for higher orders of visual organization. As a result of this process the visual world becomes articulated and structured instead of being a kaleidoscope of perceptually independent items. The adjacency principle can be expected to apply to this more global kind of organization as well as to the simpler grouping involved in the perception of a single object.

Finally, the adjacency principle may be at the root of some individual differences in perceptual ability or style. In testing adjacency effects we have often noted large differences among individuals. If these differences in individual adjacency functions are found to be stable over a period of time and characteristic of individual observers, the differences may account for some of the variation in the way individuals perceive objects visually and perceive their world as being composed of organized, interrelated parts.



RELATIVE CUES help to make sense of what would otherwise be fragmented visual stimuli. If cues of absolute motion alone governed the perception of a rolling wheel, invisible except for lights on its rim and hub, only curves traced by the lights would be seen (*top*). Visual system's response to relative and common motions of the lights achieves a simpler perception: an object rolling to the right (*bottom*).

Junctions between Living Cells

Where the cells of certain key animal tissues meet they do not simply touch. They are linked by specialized structures, the architecture of which is revealed by electron microscopy

by L. Andrew Staehelin and Barbara E. Hull

The tissues of higher organisms are made up of vast numbers of cells that have relinquished some of their independence to function together as a coherent, unified whole. To accomplish this unification and to promote the necessary interactions between cells, regions of the cell surface have become specialized for intercellular contact. These surface specializations, termed intercellular junctions, are vital for the development and normal functioning of all higher forms of life.

If one were given the task of constructing an organism out of individual cells, one could foresee the need for three functional categories of intercellular junctions: (1) impermeable junctions that would enable an organism or an organ to maintain an internal environment that is chemically distinct from its surroundings, (2) adhering junctions that would promote adhesion between the cells of a tissue, reinforcing its physical integrity, and (3) communicating junctions that would enable cells to exchange nutrients and signal molecules and thereby coordinate their activities. During the past 20 years cell biologists not only have confirmed that these types of junctions exist but also have obtained a wealth of information about their molecular architecture.

Every living cell is enclosed by a plasma membrane, a thin envelope that selectively regulates the flow of nutrients and ions between the cell's interior and its external milieu. The membrane consists of a double layer of phospholipid molecules with globular protein molecules either embedded in it or associated with its inner or outer surface. An intercellular junction is a small region of the plasma membrane specialized for one of the functions listed above. The small size of cells and thus of the junctions makes it necessary to employ the electron microscope in order to observe the junctions' fine structure.

There are two principal specimen-preparation methods for rendering cells suitable for examination in the electron microscope: thin-sectioning and freeze-fracturing. To make thin sections the cells are chemically stabilized, stained, dehydrated, embedded in plastic and cut into extremely fine slices with a microtome. By examining the slices that include a junctional region with the electron microscope it is possible to reconstruct some aspects of the junction's three-dimensional organization. Freeze-fracturing calls for freezing a sample of tissue at minus 150 degrees Celsius in liquid Freon and transferring the sample to a chamber that is then pumped down to a high vacuum. The tissue is fractured by passing a microtome knife through it, and a platinum-carbon replica is made of the exposed surfaces. The replica can be examined in the electron microscope after the underlying tissue has been digested away.

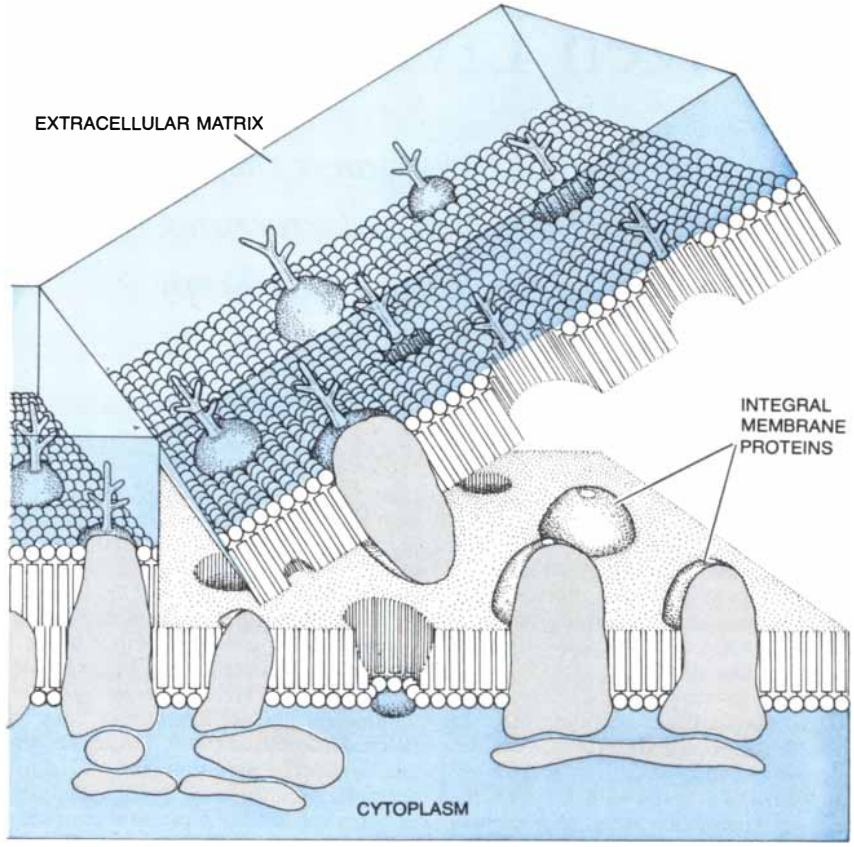
Freeze-fracturing has added a new dimension to the understanding of membrane structure because at minus 100 degrees C. the fracturing process splits the cell membranes along the central plane of the lipid bilayer. Half of the membrane remains attached to the underlying cytoplasm and the other half remains attached to the extracellular matrix. Globular protein molecules embedded in the membrane (integral membrane proteins) appear as small bumps protruding from the smooth surface of one or the other of the half-membrane faces (providing that the proteins extend through the central plane of the bilayer). Within the region of an intercellular junction the integral membrane proteins assume specific configurations that can be made visible in freeze-fracture replicas. Hence freeze-fracturing and thin-sectioning can provide complementary information on the structural elements of these specialized regions of the cell surface.

Intercellular junctions play a particularly important role in epithelial tissues, which cover the surface of the body and line its cavities. For example, in the small intestine the epithelial cells that line the interior space of the intestine (the lumen) selectively take up nutrients and transport them across the cell so that they can be absorbed into the bloodstream. This transport system would clearly be very inefficient if nutrients that had been taken up by the cells at the expense of metabolic energy could then leak back into the lumen through the spaces between the cells. The intercellular junctions called tight junctions serve to prevent the free passage of molecules across an epithelium.

In the region of a tight junction the plasma membranes of two adjacent epithelial cells appear to fuse, providing a region of intimate contact that completely encircles each cell. As was demonstrated by Marilyn G. Farquhar and George E. Palade at the Rockefeller University, when the inner surface of an epithelium is exposed to a solution of an electron-dense marker substance, such as the protein ferritin, the marker readily penetrates the intercellular space but is stopped at the level of the tight junction. In thin-section images of tight junctions it is apparent that the two plasma membranes are not cemented together but rather are fused at a series of points.

The two-dimensional structural organization of the membranes in the region

REGION OF CLOSE CONTACT between two cells in the lining of the frog's small intestine is magnified 135,000 diameters in the electron micrograph on the opposite page. The specimen was prepared by the freeze-fracture method, in which cells are broken at extremely low temperatures and then shadowed with platinum and carbon to reveal their three-dimensional detail. Here the fracturing process has removed most of the overlying cell, leaving only a small fragment of the cell membrane associated with the surface of the underlying cell. Visible at the top of the micrograph are microvilli, tubular extensions of the underlying cell membrane that vastly increase the absorptive surface area of the intestine. Immediately below them is a honeycomblike network of ridges called a tight junction, which bridges the space between the adjacent cell membranes. The width of the intercellular space is indicated by the bright "escarpment" at the bottom right, where the fracture plane jumps from overlying to underlying cell.



FREEZE-FRACTURING splits the cell membrane along the central plane of its double layer of lipid molecules, revealing its internal structure. As is shown in this schematic diagram, half of the membrane remains associated with the underlying cytoplasm and the other half remains associated with the extracellular matrix. The globular protein molecules normally embedded in the bilayer are exposed, and in platinum-carbon replicas they appear as bumps scattered over the smooth surface of each half-membrane face. In the region of an intercellular junction these integral membrane proteins take up configurations related to the junction's architecture.

of the tight junction was deduced in 1968 from freeze-fracture studies conducted by one of us (Staehelin), who was then working in the Department of Scientific and Industrial Research of New Zealand in collaboration with Tapen M. Mukherjee of the University of Otago. In freeze-fracture replicas the tight junction is characterized by a network of ridges on the cytoplasmic half-membrane face of the plasma membrane and complementary grooves on the external half-membrane face. Where the fracture plane jumps from the plasma membrane of an underlying cell to that of an overlying cell the ridges appear to span the width of both membranes.

The available evidence suggests that the tight-junction ridges are composed of two rows of tightly packed particles (integral membrane proteins), with one row contributed by each of the adjacent plasma membranes. These rows of particles make head-to-head contact in the form of a modified zipper, holding the two membranes so close together that the intercellular space is obliterated. As a result the particles form lines of attachment (sealing strands) that physically block the passage of molecules across the epithelium.

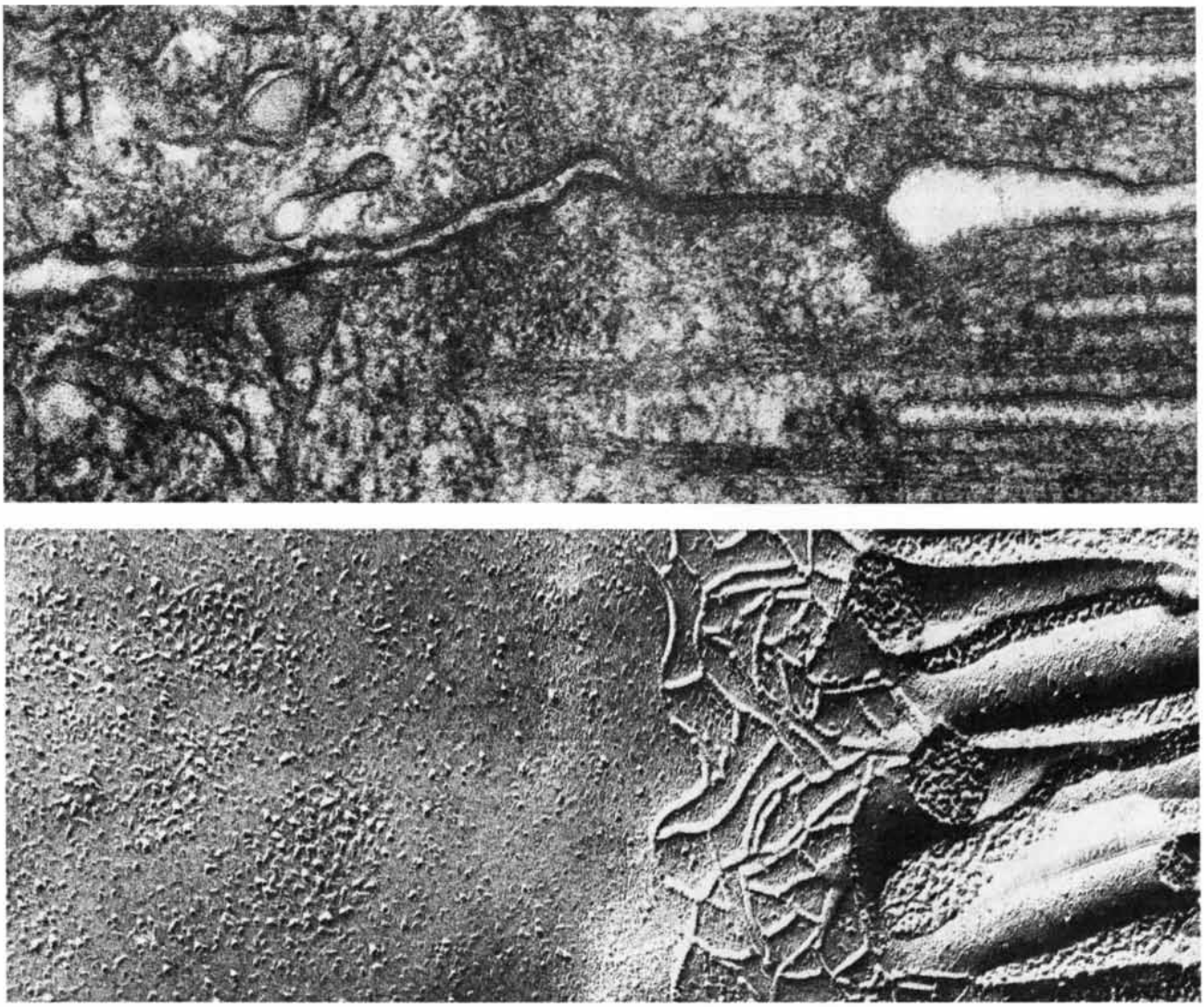
Tight junctions vary from one tissue to another in the number of sealing strands they possess. If the sealing strands provide a permeability barrier, then the greater the number of strands is, the more impermeable the junction should be. A rough indication of the tightness of the seal can be obtained by measuring the transepithelial resistance: the resistance of an epithelium to the movement of ions across it. Philippa Claude and Daniel A. Goodenough of the Harvard Medical School have demonstrated a good correlation between the transepithelial resistance of a tissue and the number of sealing strands in the tight junctions between its cells. Tissues in which the tight-junction networks incorporate only one or two sealing strands, as in the proximal tubule of the kidney, offer little resistance to the passage of ions. On the other hand, junctions incorporating six or more sealing strands, as in the urinary bladder, possess a high electrical resistance and allow the formation of steep concentration gradients across the epithelium.

Tight junctions in different tissues also vary in the extent to which the sealing strands interconnect with one another to form a network. The amount of such cross-linking would appear to determine the extent to which the network can respond to stress, much as the extensibility of a fabric depends on the closeness of the weave. Consistent with this hypothesis, we have found an evenly cross-linked polygonal network of sealing strands in cells that maintain a fairly constant shape, such as the epithelial cells of the small intestine. Conversely, irregular networks of sealing strands with only a few cross-links are found in cells that must expand to accumulate a secretory product (such as the mucus-secreting cells of the stomach) or periodically stretch under tension (such as the epithelial cells of the large intestine).

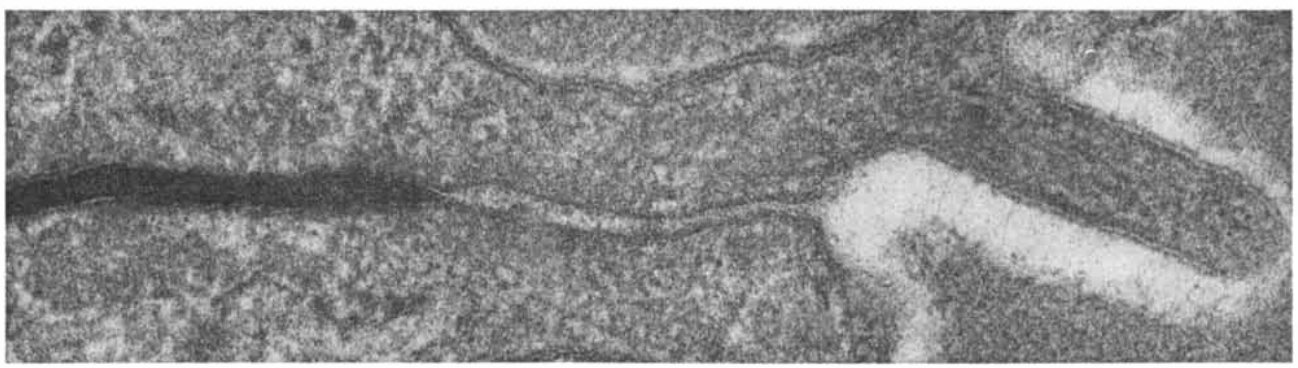
The design of the tight junction is clearly a beautiful example of biological engineering at the cellular level. The organization of the sealing strands into a network makes it possible for the tightness of the junction to be varied according to the physiological needs of the tissue. The sealing network is amazingly flexible and can be stretched, compressed or twisted without loss of sealing capacity. It also has a high inherent margin of safety, since the local rupturing of one or even several sealing strands in the tight-junction network will have little effect on the overall tightness of the seal.

As we have seen, the main function of tight junctions is to enable a group of cells to maintain an internal environment that is different from the external one. Less appreciated is the fact that tight junctions contribute significantly to establishing the polarity of the cell and the plasma membrane. Because the lipid bilayer of the plasma membrane is semifluid at physiological temperatures many integral membrane proteins tend to migrate within the plane of the membrane and distribute themselves randomly over the cell surface. Tight junctions, however, provide a physical barrier to the migration of such proteins from the outer surface of an epithelium to the inner surface, or vice versa. Without this barrier proteins involved in the transport of nutrients into the cell (from the intestinal lumen) could become intermingled with proteins involved in the transport of the same nutrients out of the cell (into the bloodstream). Tight junctions have been found as early as at the two-cell stage of embryos, and they appear to be essential for normal embryonic development.

A number of intriguing problems about tight-junction structure remain unsolved. How are the networks assembled from protein subunits in the membranes of adjoining cells, a feat that would seem to require coordination of the synthetic machinery of one cell with that of the other? Moreover, what factors account for the variations in the network patterns found in various tissues? The first clues have come from a study



COMPLEMENTARY VIEWS of intercellular junctions are provided by the techniques of thin-sectioning and freeze-fracturing. These two electron micrographs show the same region of close contact between the membranes of two adjacent cells in the epithelium (outer cell layer) of the small intestine. In the thin-section micrograph at the top three different types of intercellular junction can be distinguished. At the far right, close to the base of the microvilli, the adjacent plasma membranes of the two cells appear to fuse, forming a tight junction. At the center of the micrograph is the band desmosome, marked by dense mats of thin filaments adhering to the inner surfaces of the adjacent membranes. At the far left in the micrograph is a darkly stained junction called a spot desmosome. In the freeze-fracture image at the bottom the tight-junction network is clearly visible at the right. Just to the left of the tight junction is an inconspicuous zone containing few particles, which constitutes the belt desmosome. At the far left spot desmosomes appear as patches of irregularly shaped particles. Together the three types of junction form a "junctional complex." Magnification of micrographs is 117,000 diameters.



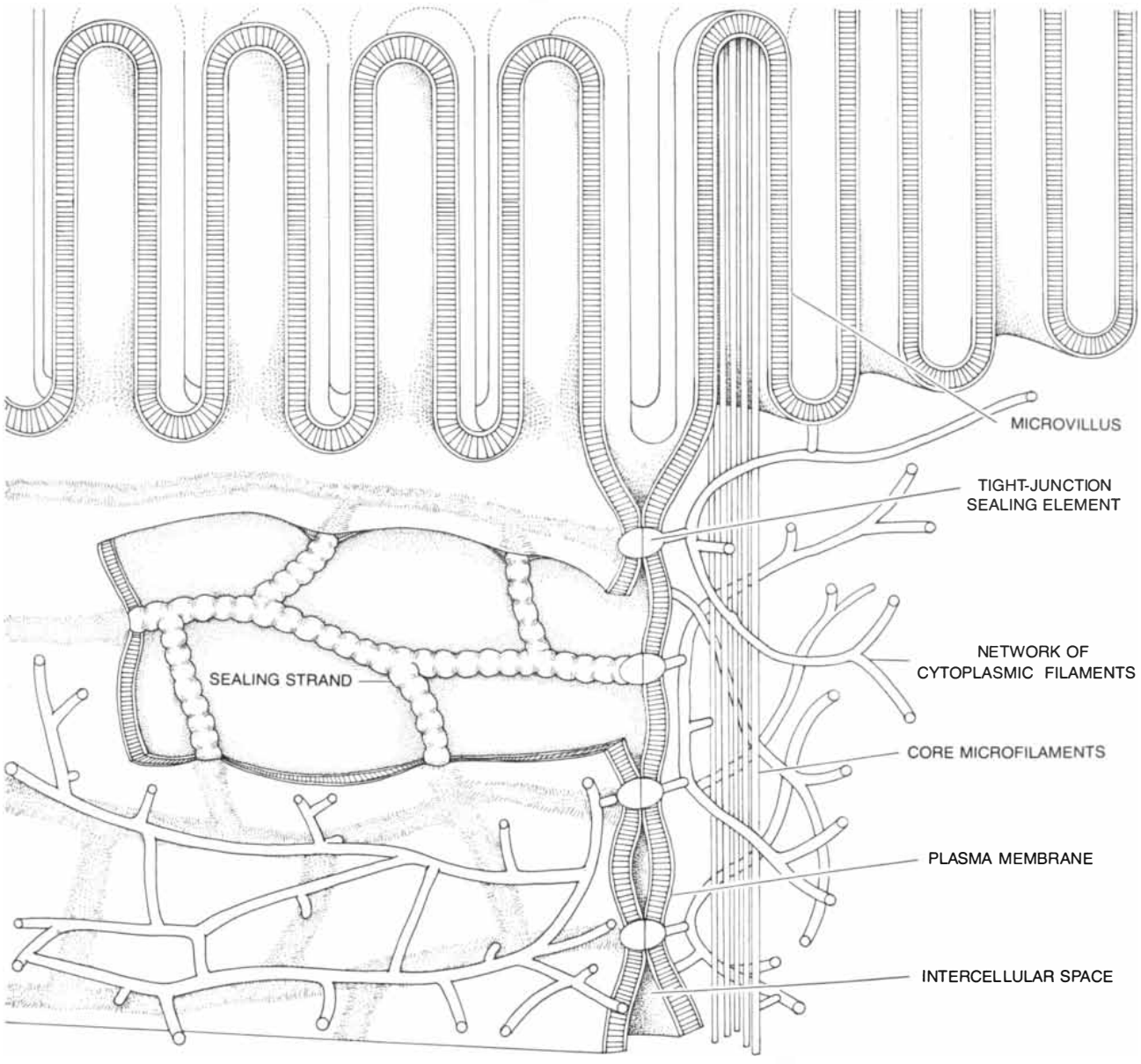
ARRESTED FLOW of the electron-opaque substance lanthanum hydroxide through the intercellular space occurs at the level of the tight junction, as is shown in this electron micrograph of epithelial cells from the pancreas. Tight junctions, which physically block the passage of molecules through the gap, are particularly important in preventing leakage of nutrients and ions across the epithelium of an organ. Here the sealing element of the tight junction appears as a point of fusion between the contiguous membranes. The magnification of the micrograph, which was provided by Daniel S. Friend of the University of California at San Francisco, is 127,000 diameters.

of tight-junction development carried out by Roberto Montesano, Alain Perrelet and Lelio Orci of the University of Geneva in collaboration with Daniel S. Friend of the University of California at San Francisco. These investigators examined the formation of the network pattern in the liver cells of the fetal rat and found that it follows an orderly sequence of events. In the region of the developing tight junction short rows of particles become organized around the edges of honeycomb-shaped depressions in the plasma membrane. The rows of particles progressively interconnect to form a loose network, becoming more closely packed to yield the smooth ridges characteristic of the mature tight junction. Close analysis of these events at the molecular level should be possible within the next few years.

The adhesion between the cells in a tissue is maintained by adhering junctions called desmosomes, which enable groups of cells to function together as a structural unit. These junctions can be classified in two main categories, belt desmosomes and spot desmosomes, on the basis of the types of cytoplasmic filaments with which they are associated.

The belt desmosome forms a band that links adjacent epithelial cells in the region just below the tight junction. Within this junctional zone the intercellular space is filled with fine filamentous material. Associated with the cytoplasmic surfaces of the adjacent plasma membranes are two sets of filaments: one set in the form of a bundle running along the inside of the membrane and the other originating at or near the junction and extending in a flat configuration into the cytoplasm.

The filaments associated with the belt desmosome are 70 angstroms in diameter, and they appear to contain actin, a principal protein of muscle cells, which suggests that they are able to contract. Indeed, Richard D. Rodewald and Morris J. Karnovsky of the Harvard Medi-



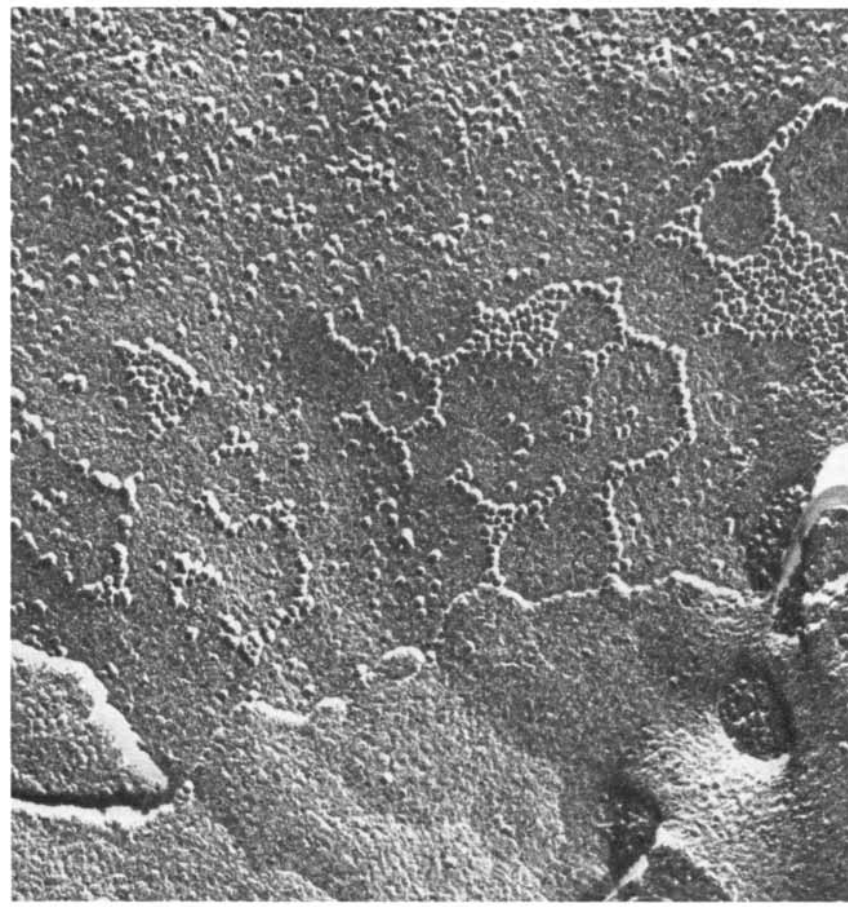
MODEL OF A TIGHT JUNCTION is illustrated in this schematic diagram. The adjacent cell membranes are held together by sealing strands, which form lines of attachment. Each sealing strand is composed of two rows of closely spaced particles (one row is contributed by each cell), which adhere tightly like a modified zipper. The arrangement of the sealing strands in the form of a network gives the junction considerable flexibility and the capacity to maintain the seal under a variety of stress conditions. Associated with the cytoplasmic surfaces of the junctional membranes are fine filaments that connect to the sealing strands and thereby structurally reinforce the junction.

cal School and Mark S. Mooseker and Lewis G. Tilney of the University of Pennsylvania demonstrated that the region of the intestinal epithelial cell that includes the belt desmosome contracts in the presence of the energy-storing molecule ATP and calcium or magnesium ions. Because the epithelial cells are physically linked to form a coherent sheet it is not clear what role the contraction of the belt desmosome encircling each cell might play. Most likely it serves to close gaps in the epithelium that result when cells die and slough away. The 70-angstrom filaments may also be responsible for the movements and the changes in shape of epithelial sheets during the formation of organs in the embryo.

The second type of adhering junction, the spot desmosome, was discovered in 1954 by Keith R. Porter at Rockefeller University. Unlike tight junctions and belt desmosomes, spot desmosomes do not form bands around epithelial cells but rather form buttonlike points of contact between the plasma membranes of adjacent cells at various levels, analogous to rivets or spot welds. Within the spot desmosome the two adjacent cell membranes are strictly parallel and are separated by a gap about 300 angstroms wide. Filamentous material fills the gap, which in thin sections appears to be bisected by a dense line termed the central stratum. On the cytoplasmic surface of each plasma membrane is a disk-shaped plaque. Connected to these plaques are filaments with a diameter of 100 angstroms, called tonofilaments. The tonofilaments are not contractile but seem to form a tensile, structural framework for the cell cytoplasm. Bundles of tonofilaments originating deep within the cytoplasm loop through the plaques of the spot desmosomes. Other bundles lie closely parallel to the plasma membrane and hardly change their direction when they pass through a plaque.

Thinner filaments arising within the plaques themselves project from the cell into the intercellular space, where they are connected to the central stratum in a staggered configuration. These "transmembrane linkers" apparently provide a direct mechanical coupling between the tonofilament networks of adjacent epithelial cells, creating a continuous structural network for the entire epithelium. Freeze-fracture studies have supported the existence of such mechanical coupling between cells. Unlike the membranes of the belt desmosome, which are nearly free of particles, the membranes of the spot desmosome contain disk-shaped plaques of irregularly fractured particles. These particles resemble filaments that have been broken off at different levels within the membrane and deformed in the fracturing process.

Hemidesmosomes, or half desmosomes, are a third type of adhering junction found in epithelial cells. They serve as anchoring sites for bundles of tonofilaments, but unlike spot desmosomes they do not link adjacent cells but rather join individual epithelial cells to the underlying matrix of connective tissue, thereby preventing the two layers from separating. Cells that are subjected to severe mechanical stress, such as those in the cervix of the uterus, possess unusually large numbers of spot desmosomes and hemidesmosomes. These junctions are interconnected by networks of tonofilaments, which serve to limit the distensibility of the cells and, through the transmembrane linkers, to distribute the shearing forces acting on individual cells to the epithelium as a whole and to the underlying tissues. In this way the junctions minimize the disruptive effects of such forces.

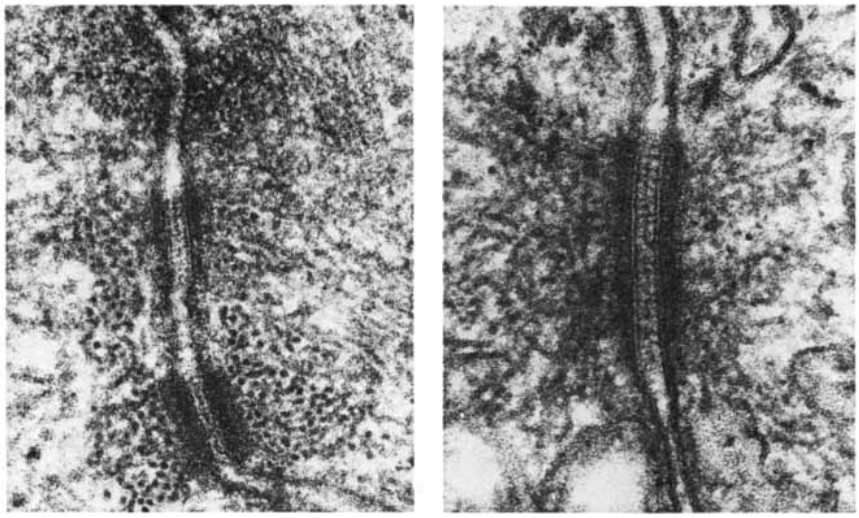


DEVELOPING TIGHT JUNCTION between two cells in the liver of a fetal rat is shown in this specimen prepared by freeze-fracturing. The formation of the junction follows an orderly sequence of events. Clusters of particles first give rise to rows of particles, which then form the honeycomblike network of sealing strands, the beginnings of which are visible here. Magnification of the micrograph, provided by Lelio Orci of University of Geneva, is 102,000 diameters.

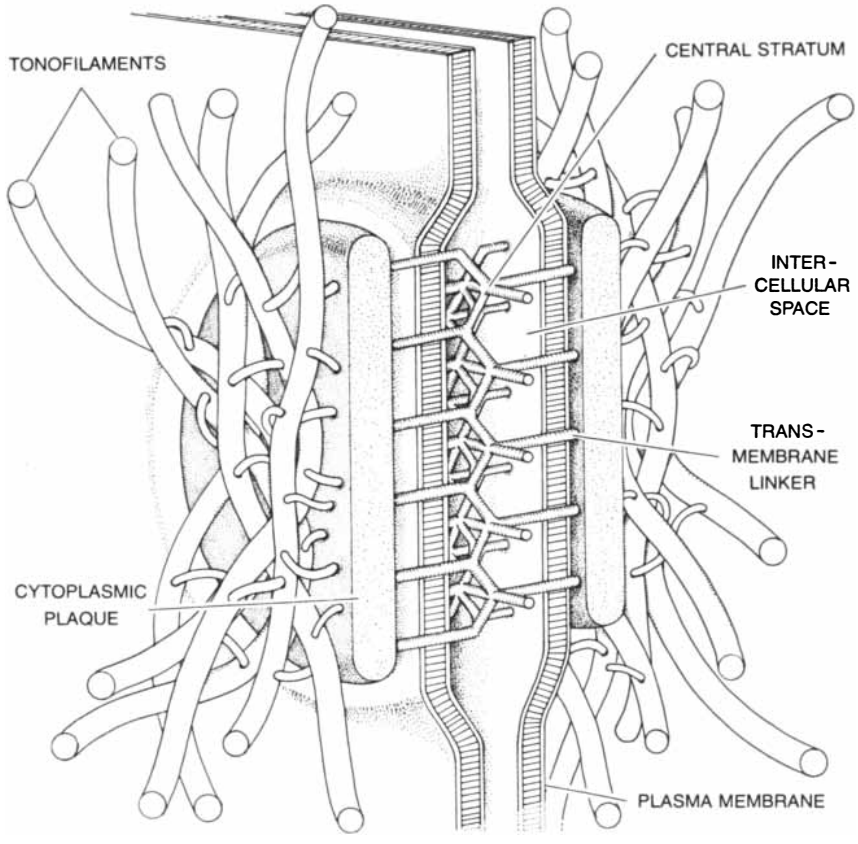
The development and maintenance of organization within an organism depends on the exchange of information among its constituent cells. Structures that mediate the direct transfer of chemical messages between cells are generally referred to as gap junctions. In recent years gap junctions have been intensively investigated because they offer the potential for exploring one of the fundamental problems of modern biology: the control of cell growth and differentiation in higher organisms.

In electron-microscopic sections of gap junctions the intercellular space appears to be narrowed from its normal width of about 250 angstroms to a width of about 30 angstroms. The space is often obscured if the sections are cut too thick or if the membranes have been inadequately stained; as a result for several years after gap junctions were initially discovered they were often mistaken for tight junctions. It is now clear, however, that the two types of junction have very different structural and functional characteristics.

As was first shown by Jean-Paul Revel and Karnovsky at the Harvard Medical School, gap junctions do not impede the flow of heavy-metal tracers such as lanthanum hydroxide through the intercellular space. If one makes a thin section tangential to the junction, however, the electron microscope reveals a hexag-



TWO TYPES OF ADHERING JUNCTION, the belt desmosome and the spot desmosome, provide strong mechanical links between cells and prevent them from being torn apart when a tissue is stretched. In the micrograph at the left, magnified 105,000 diameters, the belt desmosome is at the top with two spot desmosomes below it. The fibers associated with the belt desmosome, called 70-angstrom filaments, are clearly of smaller diameter than those associated with the spot desmosome, called tonofilaments. (Those filaments that have been cut in cross section appear as black dots.) The micrograph at the right, with a magnification of 135,000 diameters, is of a spot desmosome. Lining the inner surfaces of the adjacent cell membranes in the region of the junction are two darkly stained plaques, to which bundles of tonofilaments are attached. Thinner filaments originating within the plaques extend through the cell membranes, connecting in a staggered configuration to a darkly stained structure called the central stratum.



MODEL OF A SPOT DESMOSOME is outlined in this diagram. The tonofilaments, 100 angstroms in diameter, form a tensile network that extends throughout the interior of the cell. They are attached to the plaques of the spot desmosome through poorly defined filamentous structures. Other filaments, called transmembrane linkers, connect the plaques of the spot desmosome across the intercellular space. The junction therefore serves to couple the tonofilament networks of adjacent cells, allowing the dissipation of shearing stresses throughout the tissue.

onal array of cylindrical structures into which the stain has not penetrated. The stain occasionally fills a central hole in these cylinders, suggesting that it is the opening of a narrow channel. In freeze-fracture replicas the adjacent plasma membranes in the region of a gap junction contain a disk-shaped array of closely spaced particles, and it can be shown that the particles of the two arrays are aligned within the intercellular space.

The gap-junction particles appear to form intercellular pipes or channels that bridge both the adjacent membranes and the intercellular space, thereby allowing the exchange of molecules between cells. This model explains the ability of heavy-metal markers introduced into the intercellular space to permeate the gap junction. If by analogy one visualizes the two adjacent cells as a pair of metal tanks and the gap junction as an array of short pipes connecting them, it is clear that substances external to the tanks will be able to pass through the spaces between the pipes, although they will not be able to get into either the pipes or the tanks.

The basic elements of the gap-junction model were postulated in the early 1960's by Werner R. Loewenstein at the Columbia University College of Physicians and Surgeons, on the basis of electrical measurements made on living cells [see "Intercellular Communication," by Werner R. Loewenstein; SCIENTIFIC AMERICAN, May, 1970]. Loewenstein (and somewhat earlier Silvio Weidman at the University of Cambridge and Edwin J. Furshpan and David D. Potter at University College London) had found that when an electric current was injected into a cell, resulting in a shift of voltage across the cell membrane, a voltage shift of almost the same magnitude could be detected in adjacent cells. Loewenstein concluded that the cells must possess low-resistance electrical connections that enabled them to pass along their voltage changes, a hypothesis that contradicted the long-standing concept that cells were completely autonomous entities. Indeed, when small tracer molecules such as the fluorescent dye Procion yellow were injected into a particular cell, the dye turned up in the cells to which that cell was electrically coupled.

This finding suggested that the cell-to-cell channels of the gap junction allow the passage of certain substances from one cell to the next. By utilizing fluorescent tracer molecules of different sizes it has been possible to show that molecules with a molecular weight of up to 1,000 daltons can readily pass from one cell to another through the connecting channels, which are approximately 20 angstroms in diameter. In this range fall ions, most sugars, amino acids (the

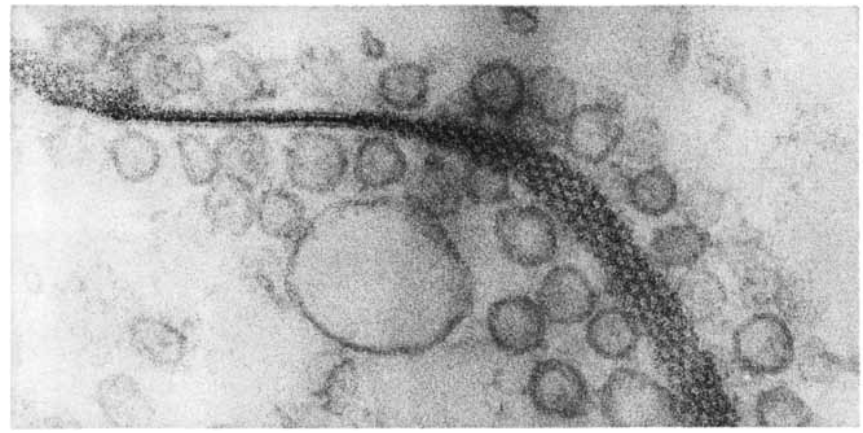
building blocks of proteins), nucleotides (the building blocks of nucleic acids), vitamins and "messenger" molecules such as steroid hormones and cyclic AMP. Cells connected by gap junctions can therefore draw from an intercellular pool of such substances.

The exchange of postulated regulatory molecules through gap junctions may be important in regulating the growth and differentiation of large groups of cells during embryonic development. Metabolic coupling also appears to be vital for the distribution of nutrients in embryos before the circulatory system is established. As was shown by Potter and Furshpan, and also by Edwin S. Lennox of the Salk Institute for Biological Studies, the yolk cells of squid embryos are electrically coupled with all the other cells in the embryo until the onset of blood circulation. After the circulatory system becomes functional the yolk cells are coupled only with other yolk cells.

In electrically excitable tissues gap junctions serve to transmit electrical signals, and in this capacity they are termed electrotonic synapses. These junctions allow the electrical activity of one cell to be transmitted to an adjacent cell without the need for mediation by a neurotransmitter, or messenger substance. Since electrical transmission is virtually instantaneous, electrotonic synapses are usually found in tissues where either the speed of the response or the precise synchronization of the activities of many cells is crucial. For example, gap junctions synchronize the contractions of the muscle cells of the heart and the contractions of the smooth-muscle cells responsible for the peristaltic movements of the intestine.

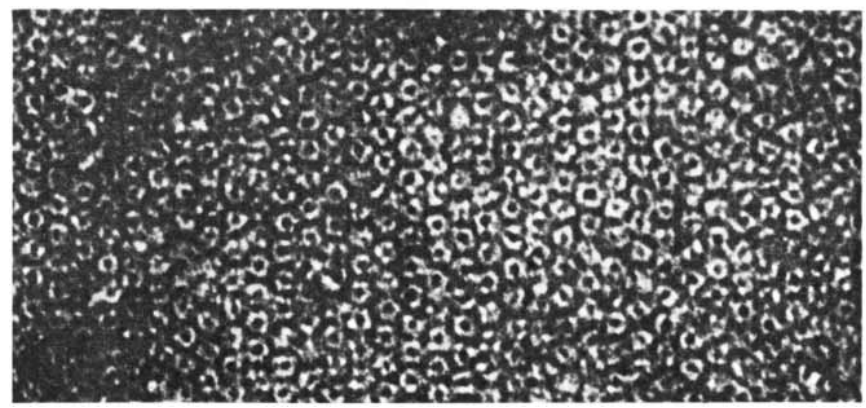
A more exotic function of gap junctions was observed by Michael V. L. Bennett of the College of Physicians and Surgeons while he was studying the nervous control of the electric organ of the South American mormyrid fish, which stuns its prey with an electric shock. In such electric fishes the strength of the shock depends on the precise synchronization by motor-nerve cells in the spinal cord of the discharges of the large numbers of excitable cells that make up the electric organ. Bennett found that when he stimulated one of the motor-nerve cells innervating the organ, all the other innervating neurons fired simultaneously, since the impulse was passed along from one neuron to the next through gap junctions.

The permeability of the gap-junction channels is strictly regulated by the concentration of calcium ions within the cell. Normally the level of free calcium ions in the cytoplasm is quite low. When calcium is injected into the cell, the cell quickly becomes uncoupled from its neighbors. If the cell is then left alone,



THIN SECTION THROUGH A GAP JUNCTION reveals aspects of its structural organization. This electron micrograph shows a crayfish gap junction that has been soaked in the electron-opaque substance lanthanum hydroxide. In vertical cross section (*left*) the lanthanum deposit appears to fill the narrow intercellular space. In tangential section (*right*) the stain outlines a hexagonal array of lightly stained particles. Magnification of micrograph, made by Camillo Peracchia of University of Rochester School of Medicine and Dentistry, is 100,000 diameters.

REPLICA OF A GAP JUNCTION prepared by freeze-fracturing reveals a disk-shaped array of particles on the cytoplasmic half-membrane face of the underlying cell and a corresponding array of pits on the external half-membrane face of the overlying cell. The gap-junction particles terminate within the intercellular space, where they meet the set of particles from the overlying cell. (This latter set of particles was torn away during the fracturing process.) Note the narrowing of the intercellular space within gap junction. Magnification is 100,000 diameters.



ISOLATED GAP JUNCTION that has been stained appears as a lattice of cylindrical particles with stain-filled cores. The cores serve as intercellular channels. Micrograph, which magnifies junction 410,000 diameters, was made by N. Bernard Gilula of Rockefeller University.

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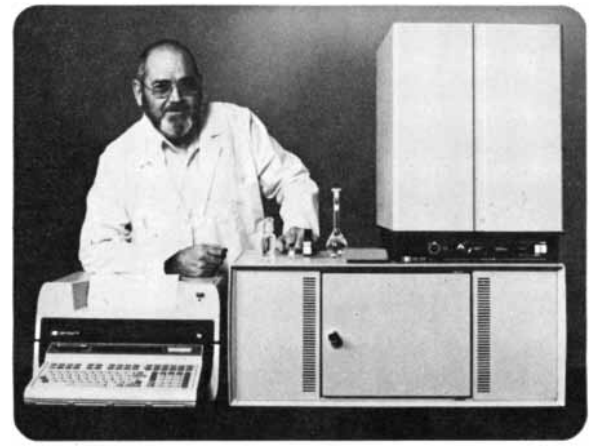

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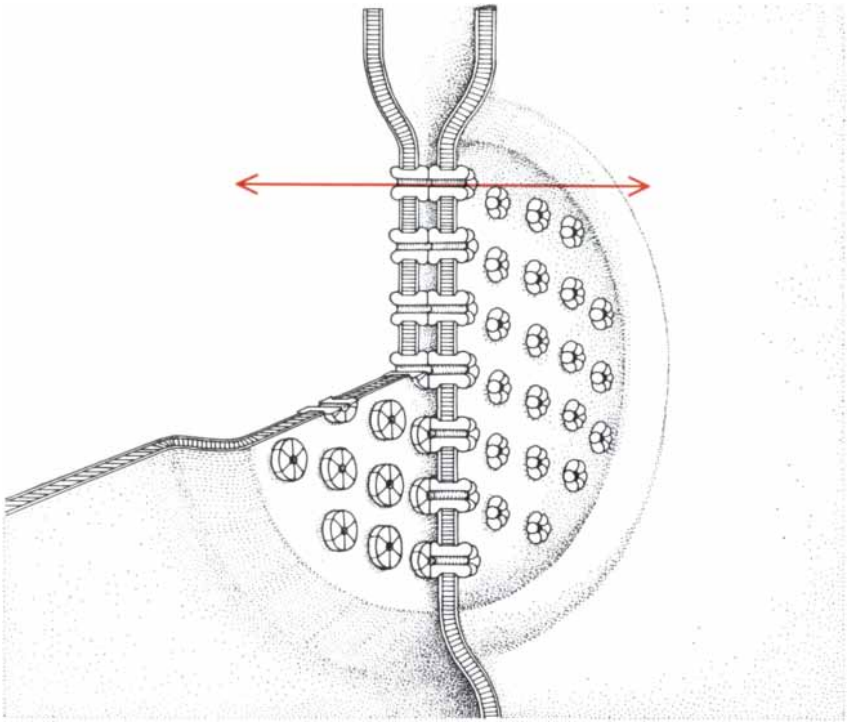
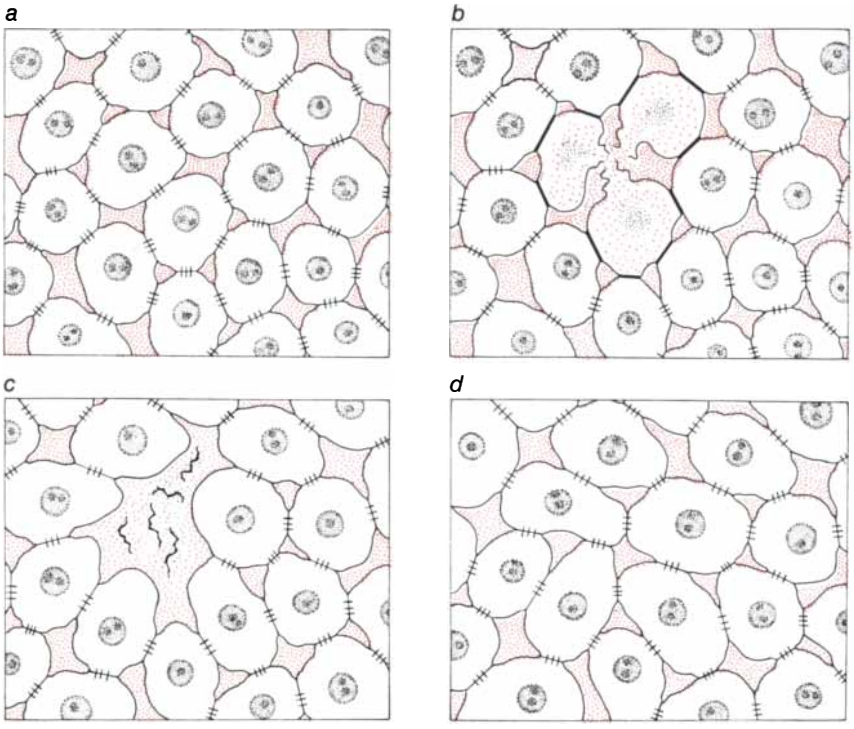


MODEL OF A GAP JUNCTION depicts the structural elements that allow the exchange of nutrients and signal molecules between cells without loss of material into the intercellular space. The communicating "pipes" are formed by pairs of abutting particles, which are in turn composed of six dumbbell-shaped protein subunits that span the lipid bilayer of each cell membrane. The channel passing through the cylindrical particles is about 20 angstroms in diameter, limiting the size of the molecules that can pass through it. Unlike the tight junction, fluids and tracers in the intercellular space can permeate the gap junction: they flow around the pipes.



INITIAL REACTION OF CELLS TO INJURY is the sealing of gap junctions at the wound border, preventing the loss of vital nutrients from the intact cells. This reaction is triggered by the influx of calcium ions into the ruptured cell from the surrounding fluid (*a, b*). As the wound closes, coupling is reestablished among the intact cells within about 30 minutes (*c, d*). If the gap junctions were not sealed after injury, a tissue with many gap junctions, such as that of the stomach or the liver, could not survive destruction of even a single cell. This illustration is based on one developed by Werner R. Loewenstein of the University of Miami School of Medicine.

the mitochondria inside the cell will gradually sequester the excess calcium until the level returns to normal and the channels become functional again. The injection into the cell of a synthetic substance that binds free calcium ions, such as ethylene diamine tetraacetic acid (EDTA), also restores electrical coupling that was blocked by the previous injection of calcium.

Loewenstein, who is now at the University of Miami School of Medicine, has suggested that the sensitivity of gap junctions to calcium ions is essential to the ability of tissues to repair themselves after injury. If a hole is punched in a cell, the relatively high levels of calcium in the surrounding fluid rush in, causing the gap junctions of the damaged cell to close. As a result the loss of nutrients from the adjacent undamaged cells is minimized. When the cells make contact with other normal cells as the wound closes, they form new, functional gap junctions within 30 minutes. Camillo Peracchia of the University of Rochester School of Medicine and Dentistry has observed that as the gap-junction channels close, the diameter of the gap-junction particles decreases, which suggests that closure is brought about by the "collapse" of the channel elements.

Considerable effort is now being focused on attempts to isolate and chemically characterize the gap-junction particles. Goodenough has found that isolated gap junctions contain one major protein, connexin, which has a molecular weight of 18,000 daltons and consists of two chains of amino acid units. Recently, in collaboration with D. L. D. Caspar, Lee Makowski and W. C. Phillips of Brandeis University, he has examined isolated gap-junction particles with electron-microscopic and X-ray-crystallographic techniques and has concluded that they are made up of six dumbbell-shaped subunits that aggregate to form a cylindrical structure about 70 angstroms in diameter with sixfold symmetry and a central channel.

It is still largely not known how intercellular junctions are assembled at the molecular level. One approach to the question has been to isolate the junctions and resolve them biochemically into their component parts. Other investigators have looked for changes in the intercellular junctions of cancer cells, which grow uncontrollably and separate from their neighbors to spread throughout the body. Although many cancer cells appear to be normal in their intercellular coupling, some have a low level of coupling, which suggests that one cause of uncontrolled cell growth might be the inability to send or receive signal molecules across gap junctions. Such a defect might arise either from a paucity of gap junctions or an alteration in the structural organization of the gap-junction particles. Cancer cells that have

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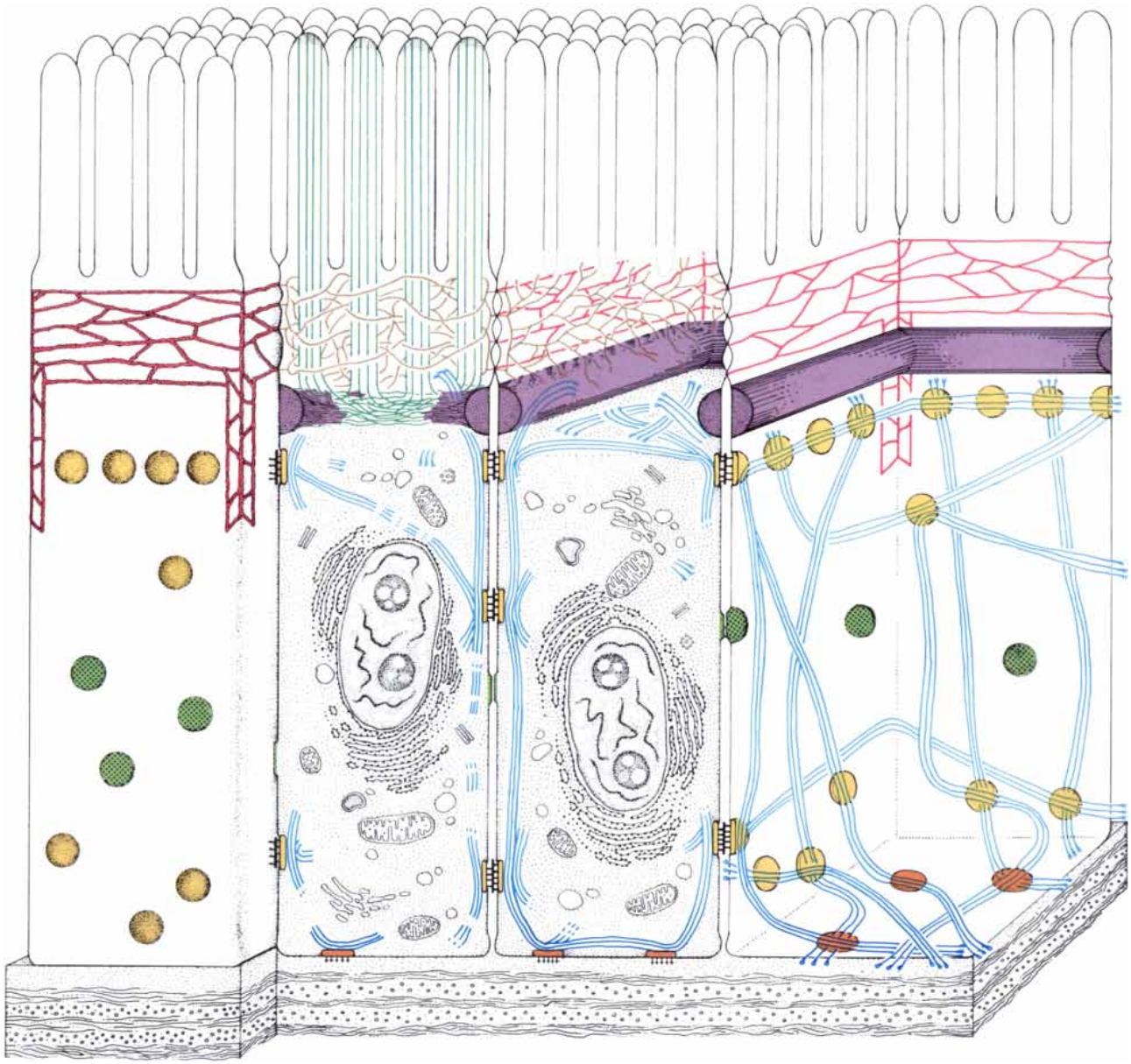
normal gap junctions, on the other hand, may possess some defect in their ability to respond normally to the transferred signal molecules. In any case it seems clear that the health of an organism, like that of a society, depends on how well its constituent units communicate with one another. Gap junctions are apparently the major pathway for direct intercellular communication.

In sum, the functions of the three major categories of intercellular junctions are closely correlated with their structure. The tight junction is composed of two plasma membranes held very close together by interlinked rows of integral membrane proteins, which create an impermeable seal. The desmosomes are composed of peripheral and integral membrane proteins that bridge the plasma membranes and connect the internal tensile skeletons of adjacent cells. The gap junction involves integral membrane proteins organized in the form of tubes that provide channels of communication between the cytoplasms of adjacent cells. Continued exploration of the architecture and function of intercellular junctions should increase our understanding of how cellular integration gives rise to higher forms of life with capabilities beyond those of individual cells.



DISTRIBUTION OF JUNCTIONS in the epithelium of the small intestine is illustrated in this schematic diagram. The tight junction (*red*) forms a band around the rim of each cell and is reinforced by a network of fine filaments (*brown*). Just below it is the belt desmosome (*purple*), which girdles the inside of the cell membrane with bundles of contractile filaments. Associated with these bundles is a mat of interwoven filaments called the adherens web. The web is derived largely from the splaying out of filaments from the bundles of core microfilaments (*dark green*), which extend up into the microvilli and maintain their shape. Below the adherens web are the spot desmosomes (*yellow*), which resemble spot welds between the lateral cell membranes. Then come the gap junctions (*light green*), patchlike areas of close intercellular contact. At the base of the cell the hemidesmosomes (*orange*) couple the epithelial cells to the underlying matrix of connective tissue. Bundles of tonofilaments (*blue*) crisscross the cell interior from one desmosome to another, providing a tensile framework for the cytoplasm. In sum, the adjacent cells in the epithelium are coupled both mechanically (through spot desmosomes) and metabolically (through gap junctions) and separate the digestive fluids in the intestine from the tissue fluids (through tight junctions).

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Roman Hydraulic Technology

The achievements of the Romans in impounding, moving and delivering water on a large scale were not matched for 1,500 years. The aqueduct systems in particular embodied many remarkable feats of engineering

by Norman Smith

The Romans have come down in history with the reputation of having been particularly good at engineering. Their various waterworks show that the reputation is justified. Indeed, their achievements in impounding, moving and delivering water (often over long distances and in spite of numerous obstacles) were not matched for some 1,500 years after the decline of the Roman empire.

A good place and time to begin a consideration of Roman waterworks is Rome at the end of the first century. In A.D. 97 a new man took over as water commissioner of the city. He was Sextus Julius Frontinus, who had at one time (A.D. 74 to 78) been the governor of Britain and was the author of works on land surveying and warfare. For seven years up to the time of his death he worked hard to bring a measure of order and efficiency to the operation of a public utility that had been mismanaged and neglected for years. In *De aquis urbis Romae* he set down his experiences in running the largest public water-supply system in the ancient world.

By the end of the first century Rome was supplied by nine aqueducts. The oldest of them, the Aqua Appia, had been built more than 400 years earlier; the most recent, the Aqua Claudia and the Aqua Anio Novus, had been in and out of service for less than 50 years. The bulk of the water supply, and all the water of the best quality, came from the valley of the River Anio (from the river itself and from springs). The lengths of the aqueducts varied from 12 miles to more than 50; in all, Frontinus found himself responsible for some 300 miles of covered channel (*specus*) with cross sections that varied from about nine square feet to as much as 40 square feet.

The popular picture is that Roman aqueducts were carried throughout their length on the tops of lines of arches. Such a picture is quite misleading. As far as was practicable—and the Romans were eminently practical engineers—the routes of aqueducts, at Rome and elsewhere, followed a steady gradient at or below ground level. The use of tunnels, long arcades, high bridges over river valleys or pipelines across deep depressions was a last resort when difficult conditions could be met in no other way. Indeed, the evidence is clear that Roman engineers would go to some lengths, quite literally, to avoid any compromise of their basic rule. In the system of aqueducts serving the city of Rome, for example, only about 5 percent of the mileage was carried on bridges.

Surface and underground conduits were easier to build and to maintain. Access for the cleaning and repairing of underground conduits was provided at intervals along each *specus* through shafts or openings called *putei*. The debris cleaned from the aqueducts was dumped beside the *putei;* modern archaeologists have been able to find the long-abandoned conduits below by identifying these piles of stone, gravel, silt and calcareous deposits.

In order to maintain the required gradients five of Rome's aqueducts had to be carried for a few miles on bridges, the magnificent arcades that are still such a dominating feature of the Campagna. Expediency prevailed, and so the five conduits utilized only two bridges. The Aqua Tepula and the Aqua Julia were carried on the bridge first built to support the Aqua Marcia, and the Aqua Anio Novus shared the bridge of its contemporary, the Aqua Claudia. In purely constructional terms such extensions were not difficult to build; it was simply a matter of putting a new channel (or two channels) on top of the existing one. Concrete faced with brick served for the channels of the Aqua Tepula and the Aqua Julia above the Aqua Marcia, and brick lined with watertight concrete carried the Aqua Anio Novus over the bridge of the Aqua Claudia.

In the long run the elevated sections of aqueduct were not an unqualified success. Both archaeological and written evidence indicate the need for extensive and frequent repairs, which entailed lengthy interruptions in the flow of water. Frontinus comments on the damage resulting from "defects in the original construction." For example, the Aqua Claudia (which was 14 years under construction) was completed in the year 52, repaired in 71 after 10 years of use and nine of disuse, repaired again in 80 and worked on once more in 84. The evidence of such remedial work is manifest in the sections of the Aqua Claudia that still stand. Many of the arches have been crudely built up with thick layers of brick, tile and mortar that often extend several feet down the piers.

The root cause of the problem is obscure. Conceivably the superposition of one or two channels on an existing bridge proved to be too much for the supporting arches, causing joints to open up. Alternatively, increasing the load on the piers may well have led in time to differential settling and consequent overstraining of the arches. Frontinus, who was conscious of the effects of temperature, observes that an advantage of underground channels is that "they not being subjected to either heat or frost are less liable to injury."

In any event the upshot of these and other structural failures was leakage, which, together with the theft of water from the open channels and from the buried sections if they could be reached and penetrated, resulted in substantial reductions in the volume of water finally delivered to Rome's private citizens and public cisterns. This was the issue that occupied Frontinus more than any other. In the end it defeated him, not least because he was unable to calculate either the theoretical or the actual quantities of water flowing. (Remarkably, Frontinus was under the impression that the volume of flow was a function only of cross-sectional area, depending not at all on velocity. Whether or not such ignorance was confined to civil servants is impossible to test in the absence of a single surviving word from a Roman hydraulic engineer.)

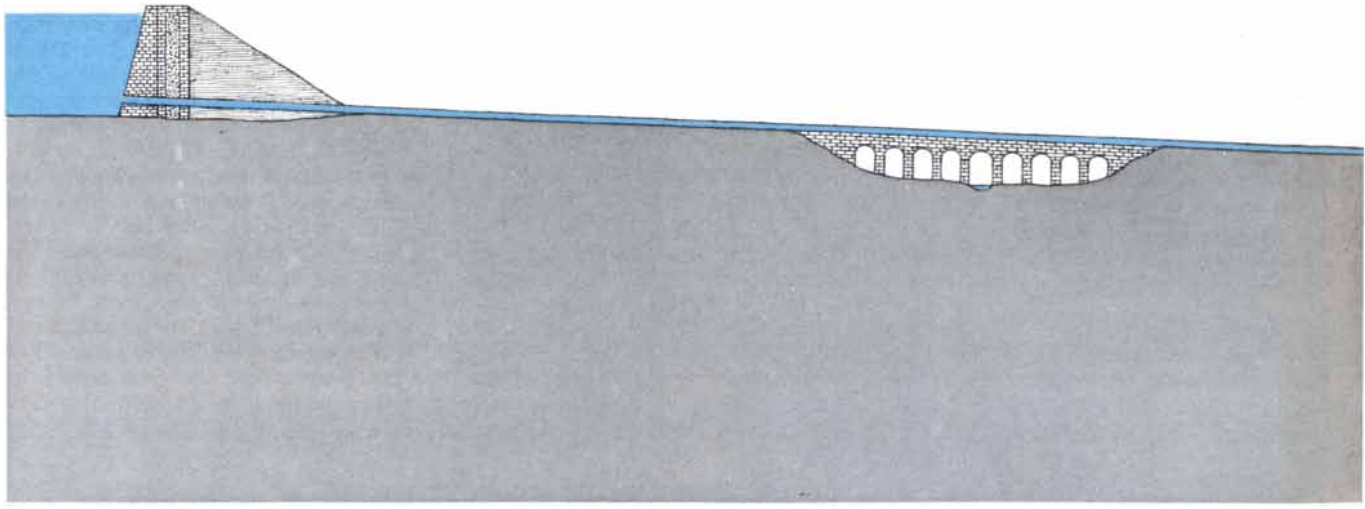
What can a modern calculation tell us of the quantity of water delivered to Rome's inhabitants, who in Frontinus' time may have numbered perhaps a million? The answer is nothing; the data available fall far short of the minimum

required. Although the cross-sectional areas of the conduits are known, one cannot be sure that the conduits ever ran full, because their size was determined as much by the need for work space as by that for water space. The layout and capacity of the inlets for the aqueducts is uncertain, and the quantity of leakage is not known. Moreover, it is certain that only rarely, if ever, were all the aqueducts fully operational at the same time.

Notwithstanding the structural and hydraulic defects that continually disturbed the operation of the system and made difficulties for Frontinus, Rome's water-supply system was a superb achievement. The principle was a classic solution to a fundamental problem of urban population growth on a large scale. Frontinus was so impressed that he is moved at one point in *De aquis* to remark: "With such an array of indispensable structures carrying so many waters compare, if you will, the idle Pyramids or the useless, though famous, works of the Greeks." (The comment is puzzling because it was Greek cities that had pioneered the technology Frontinus regarded as being so beneficial to urban living and such a mark of civilized development.)

In any assessment of the development of Roman engineering it is important to remember how much was absorbed from conquered peoples in general and the extent to which Greek engineers in particular worked for the Romans and thereby diffused ideas and practices. It is equally certain, however, that Roman engineers took water-supply engineering much further. Rome itself was unique only in the sheer size of its water-supply system; on a lesser scale the same public utility was provided in many cities all over the empire. Fundamental to this display of expertise in civil engineering were two important Roman innovations: the construction of arches and the development of hydraulic concrete, which was quick-setting (even

ARCHED BRIDGE carried two aqueducts a distance of 6.5 miles near Rome. The photograph shows part of the longest section still in existence, a length of some 1,500 yards including 153 arches. At this point the bridge is about 40 feet high. The broken bricked portion at the top carried the Aqua Anio Novus. Below it, just above the arches, the Aqua Claudia ran in a channel three feet wide and six feet high.



AQUEDUCT SYSTEM built by the Romans typically included most or all of the engineering features portrayed in this hypothetical aqueduct, which begins at the top left on this page and continues to the bottom right on the opposite page. At the source water is impounded behind an earth dam, which is faced on the side toward the water with a wall of masonry and concrete supported by a line of masonry but-

under water), strong and waterproof.

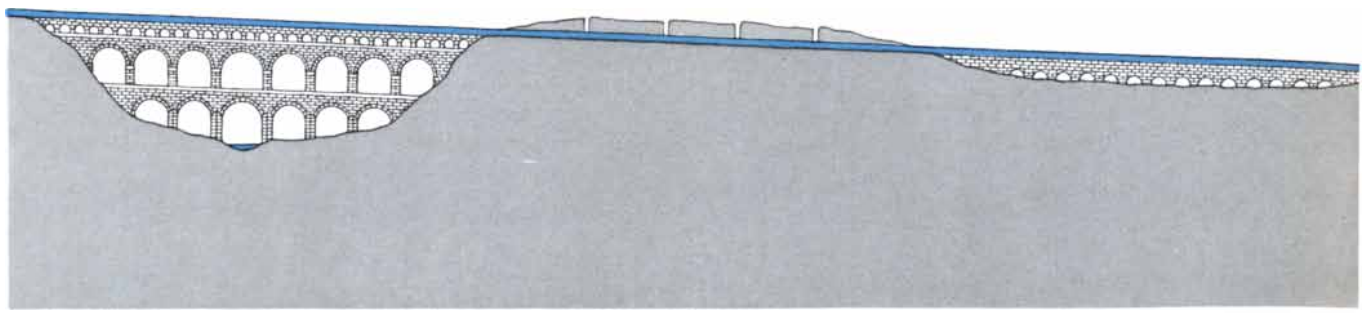
Long arcades were built to carry aqueducts across tracts of flat, low-lying country. In addition to the arcades near Rome fine examples survive in North Africa and at Mérida in Spain. No matter how carefully the route from the source to the city was surveyed or how carefully the options were weighed, however, Roman engineers frequently had to deal with two further topographical obstacles: hills and river valleys. High ground was usually overcome by going around it. The difficult, dangerous and expensive work of tunneling over long distances or at great depths was avoided wherever possible, as it would be in a modern undertaking. Few examples of Roman water-supply tunnels are known, one reason being the difficulty of making opposite sections of a tunnel meet. (We should not smile unduly, because the same thing happens today, albeit rarely. The successful meeting of the two parts of a long tunnel is still rightly an occasion for drinking champagne.)

As for river valleys, the choice between the two solutions that were available was dictated by the depth of the crossing. Up to about 150 feet a bridge would be built. The magnificent Pont du Gard near Nîmes in southern France is the outstanding example. Yet in spite of its impressive appearance the Pont du Gard is structurally clumsy. The Romans achieved its great height (more than 160 feet) by the primitive technique of stacking bridges one on another in three layers.

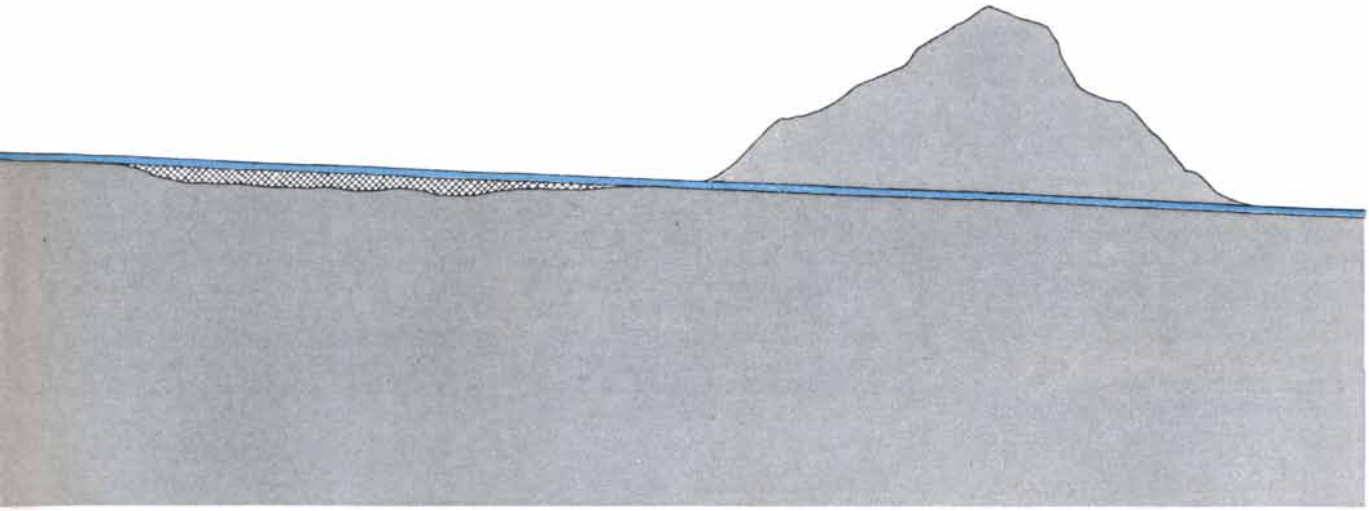
By degrees the Roman engineers improved their methods. In the first century the bridge-stacking approach was abandoned, and subsequently the use of concrete brought further structural refinement and elegance. In the bridges at Mérida and at Cherchell in Algeria the tall piers, made with concrete cores and faced with brick and masonry, are continuous columns from top to bottom, lightly braced at intervals and firmly connected only at the top by the arches that carry the *specus*. Roman aqueduct bridges are a highly instructive example of the process of structural evolution.

If a valley was more than about 150 feet deep, a bridge alone was unsuitable for carrying an aqueduct. The cost of providing materials, falsework, scaffolding and lifting gear became prohibitive. The sheer weight of the finished structure on its foundations might also have been a deterrent. The solution was to employ pipelines laboriously fabricated from lead or earthenware. From a header tank at the end of the approaching open channel the pipe system (which usually consisted of several pipes laid side by side) was carried downward at a steep angle on a broad masonry ramp. Having crossed the floor of the valley on a bridge (which was often quite a large structure itself), the pipes ascended the opposite side of the valley, again on a ramp, to the level of a receiving tank at the beginning of the next section of open conduit. The receiving tank was positioned sufficiently below the level of the header tank to ensure an adequate flow of water.

At Lyon a total of nine such pipelines



CONTINUATION OF AQUEDUCT shows the water being carried first across a fairly deep valley (up to 150 feet) by a three-tier bridge. (The Pont du Gard, a three-tier bridge, survives in France.) Thereafter it runs for a time belowground in a tunnel built by a "cut and cover" technique. Shafts called *putei* are provided at intervals for the cleaning and repairing of the tunnel. Over a stretch of flatland the



tresses. The water is drawn out through a tunnel and runs for a certain distance as an open channel. On reaching a shallow valley it is carried across on an arched masonry bridge, typically from 50 to 100 feet in height. In a shallower depression it is carried on an earth embankment. On the rare occasions when it was impossible to go around high ground, the Romans would build a tunnel to carry the water.

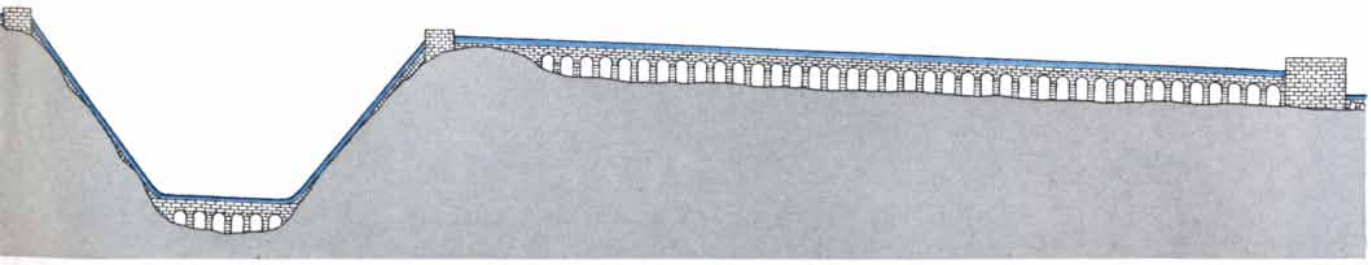
(the technical name for them is inverted siphons) served the four aqueducts that supplied the city. The major siphons varied in length from half a mile to three miles and reached depths of from 200 feet to more than 400. To contain such pressures the siphons consisted of as many as 10 lead pipes, each pipe some 10 inches in diameter with a wall thickness of three-quarters of an inch. The quantity of lead (perhaps 15,000 tons) that had to be mined, smelted, transported, fabricated and laid was staggering. It was done, though, and the system worked.

One feature of the siphons remains obscure, namely the question of their hydraulic design and how it achieved a satisfactory flow rate. Somehow the Roman engineers mastered the seemingly difficult job of matching the capacity of a multitube siphon to that of the connecting open channels. One suspects that the required configuration was arrived at empirically. Knowing from experience that a siphon had to descend about a foot for every 150 feet or so of its length, the engineer would build the header tank and the tubes first and then would resort to judicious trial and error to finally position the receiving tank. In any case a fairly coarse adjustment could be made by adding a pipe or removing one. Evidence of such an adjustment does exist.

Just as vital as the supply of drinking water to cities in quantity was the question of the quality of the water. As one might suppose, the standards applied were quite rudimentary, taking account only of such obvious factors as taste, smell, appearance and temperature. Surprisingly, the immense work of building the Aqua Anio Novus resulted only in a turbid supply while the source was the uncleaned water of the River Anio. In the reign of Trajan and during Frontinus' term of office a marked improvement was achieved by shifting the intake of the Aqua Anio Novus to a reservoir formed behind an immense dam near Subiaco. It is virtually impossible to reconstruct the details of the dam. According to monastic records, it collapsed in 1305. A medieval painting of it survives.

One can learn something about Roman achievements in this demanding branch of engineering from a few dams that still exist. Remarkably, two of them are still in service. Both were built to impound water for Mérida. Essentially they are earth embankments of massive proportions, suitably reinforced internally and externally with walls and buttresses of masonry and concrete. The survival of these remarkable structures (which now serve for irrigation purposes) is largely due to the awareness of the Roman engineers of the need for spillways, which are essential if an earth dam is not to be washed away by the first flood that overflows the crest.

Water storage behind large dams was an innovation indicative of Roman society's commitment to a reliable water supply even in regions of meager rainfall. Dams were equally essential for irrigation. A number of Roman irrigation dams, in varying states of repair, survive



aqueduct is carried on a low embankment pierced by arches. At a deep crossing an inverted siphon, consisting of lead pipes laid side by side from a header tank, carries the water down one side, across a low arched bridge and up the other side to a receiving tank. Toward the end, in order to maintain an appropriate gradient, the aqueduct is carried on a long arcade until it arrives at a distribution tank in the city.

in the Middle East and North Africa.

In terms of agriculture the Roman empire embraced three broadly different regions. North of the Alps the wet, heavy and thickly wooded lands of northwestern Europe presented agricultural problems the Romans never solved. In the Mediterranean basin most farming could be done without irrigation. Beyond the Mediterranean basin lay the ancient centers of irrigation farming based on rivers. The most important of them was the Nile, whose waters and unique basin-irrigation system made Egypt "the granary of Rome."

Egypt was exceptional. Elsewhere (to the east and south of the Mediterranean) desert farming required special techniques the Romans learned from the Nabataeans, an accomplished people who flourished in the Negev until they were overrun by the armies of Trajan in A.D. 106. The prime characteristics of rainfall in the Negev and along the northern coast of Africa are its intensity and its brief duration. The violent spates that inundate the wadi beds for a few days (perhaps for only a few hours) in the year carry surprisingly large volumes of water and enormous concentrations of silt. The art of wadi irrigation is the efficient capture of these brief floods for long-term use.

One of the methods that was developed employed diversion dams to direct water either to land under cultivation or to storage tanks. Alternatively, and it is in this form that the engineering becomes elaborate, a wadi was terraced by means of a carefully positioned series of dams, which in time became filled in behind by soil. Once a wadi had been stepped off in this way, each terrace could be planted to crops and cultivated with flood irrigation. The method was capable of surprising agricultural performance even when it was practiced on the relatively small Nabataean scale. It was developed on a large scale by the Romans, particularly in North Africa, with impressive results.

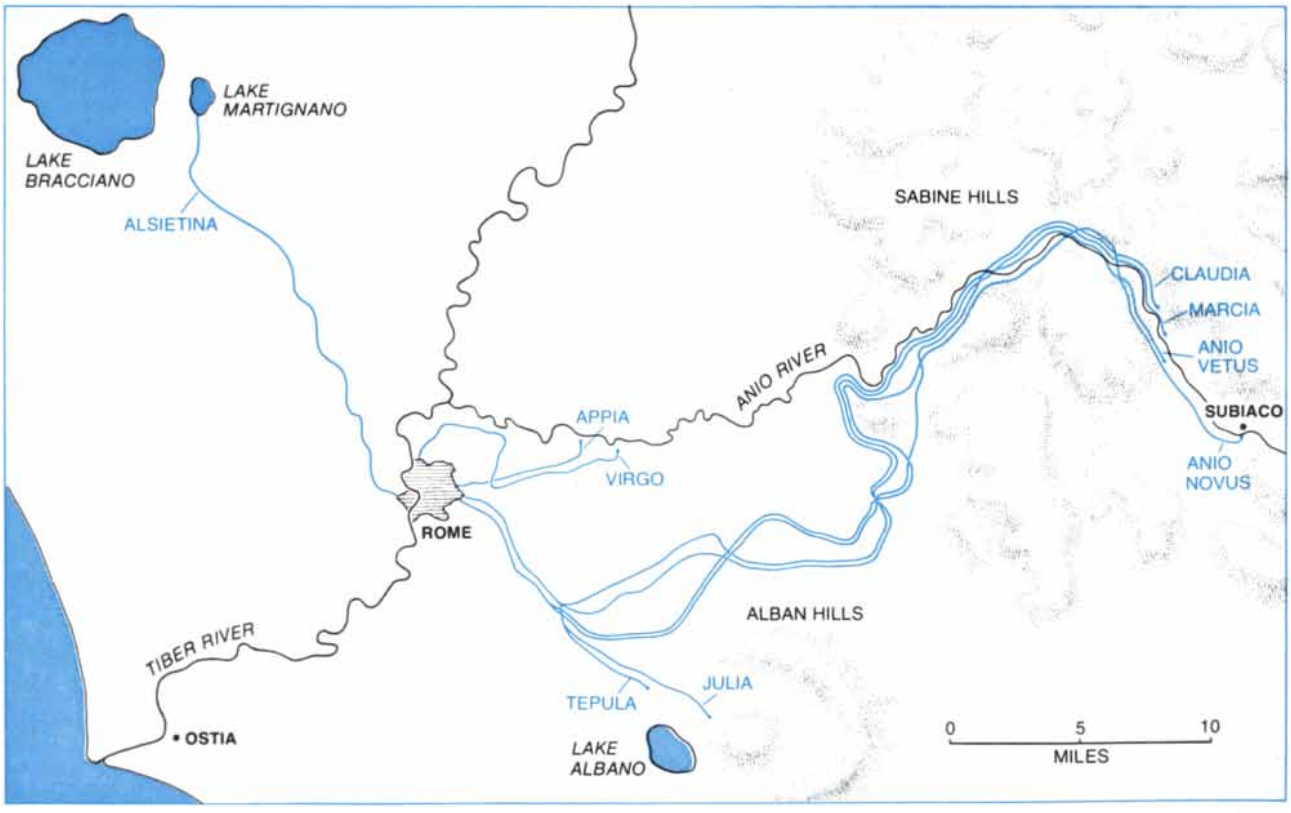
The construction of the North African irrigation dams varied according to the prevailing conditions. In steep, narrow wadis with good rock foundations the typical structure included a core of rubble and earth, sometimes consolidated with concrete, that was faced with carefully cut and fitted masonry blocks, whose joints were sealed with strong mortar made from hydraulic lime. The water face of a dam was sealed with *opus signinum,* a form of plaster made from hydraulic lime mixed with crushed brick or pottery. The air face was stepped and frequently buttressed to give added stability.

In broad wadis of gentler slope the dams were basically of earth construction and were presumably faced with masonry, so that they would be watertight and would resist erosion. Neglect over many centuries and inundations from the wadis have removed virtually all traces of these dams except for the masonry spillways.

The irrigation works of North Africa illustrate the comprehensiveness of Roman dam building. The full range of materials—masonry, earth, mortar and concrete—was utilized selectively; spillways and sluices were provided, and the dams were employed to divert water and to store it, generally for agriculture and occasionally for drinking. The work provides an impressive example of how a system of dams for flood control, water retention and soil conservation can at one stroke solve a series of related hydraulic and agricultural problems.

The most fundamental civil engineering problem in the Italian peninsula, as paramount in the past as it is today, was river control, with its closely related purposes of preventing floods and draining land. As the Roman engineer in North Africa was successfully capturing water and bringing it to the land his colleague in Italy was engaged in the opposite pursuit. His Etruscan predecessor had already tried his hand at this most difficult and intricate of all tasks of civil engineering.

In many parts of Italy poor drainage, compounded by the tendency of large rivers to flood low-lying ground, gave rise to conditions that were conducive to neither agriculture nor habitation. Often the attempt to build drainage canals, some of them navigable, was not unsuc-



AQUEDUCTS OF ROME at the end of the first century A.D. are identified. There were nine of them, the oldest (the Aqua Appia) having been built more than 400 years earlier and the most recent (the Aqua Claudia and the Aqua Anio Novus) being about 50 years old.

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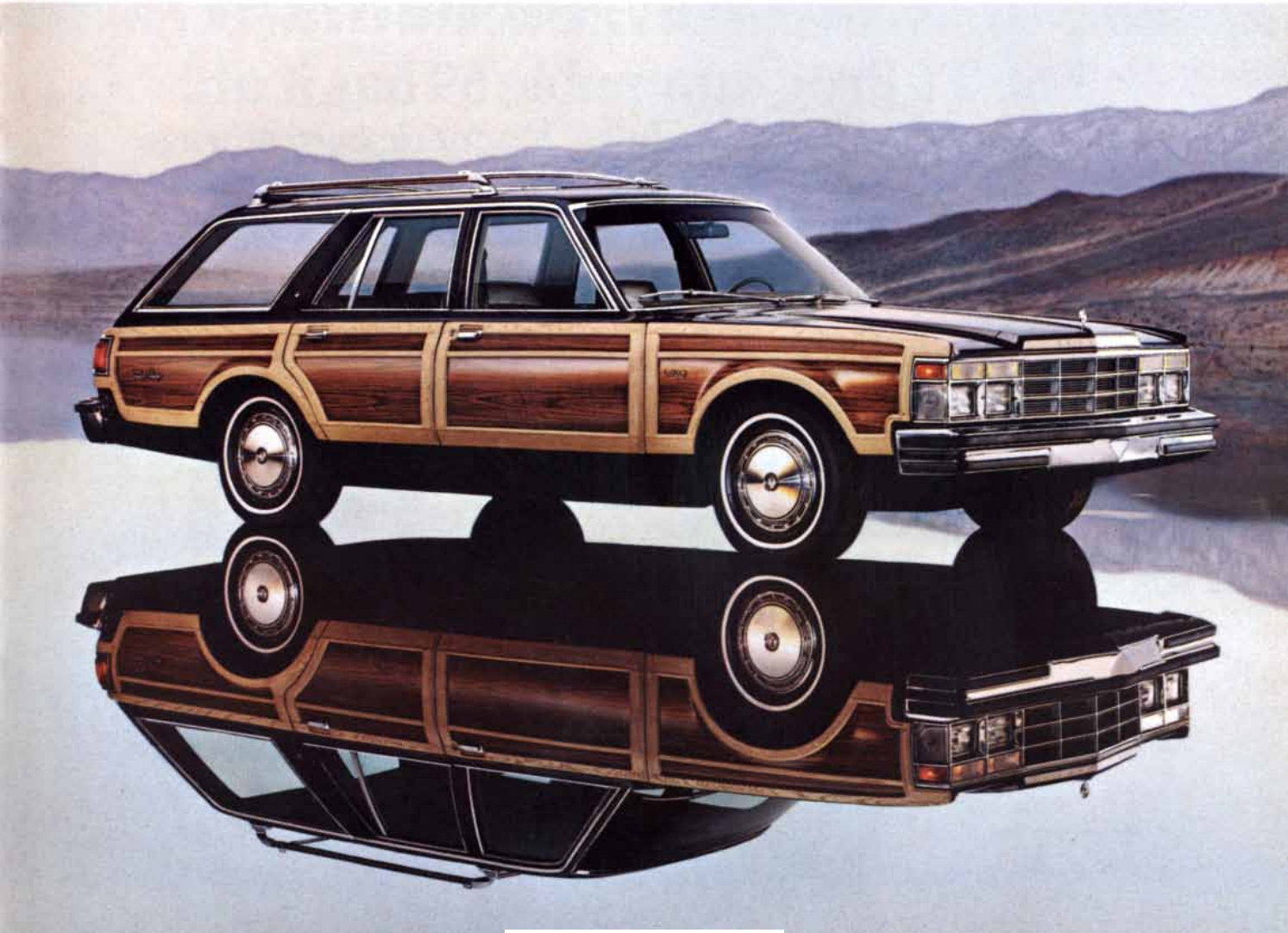

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cessful. The Romans worked hard to contain the disagreeable River Po so that valuable arable land would not be periodically swamped. Draining by canal was also tried on the Tyrrhenian coast, where one objective was the reclamation of the notorious Pontine Marshes. The problem was formidable; ultimately, for the Romans at least, it was unsolvable. The region was so wet, low and near the sea that, as modern engineers have discovered, the only solution was pumping on a scale unimaginable to the Romans.

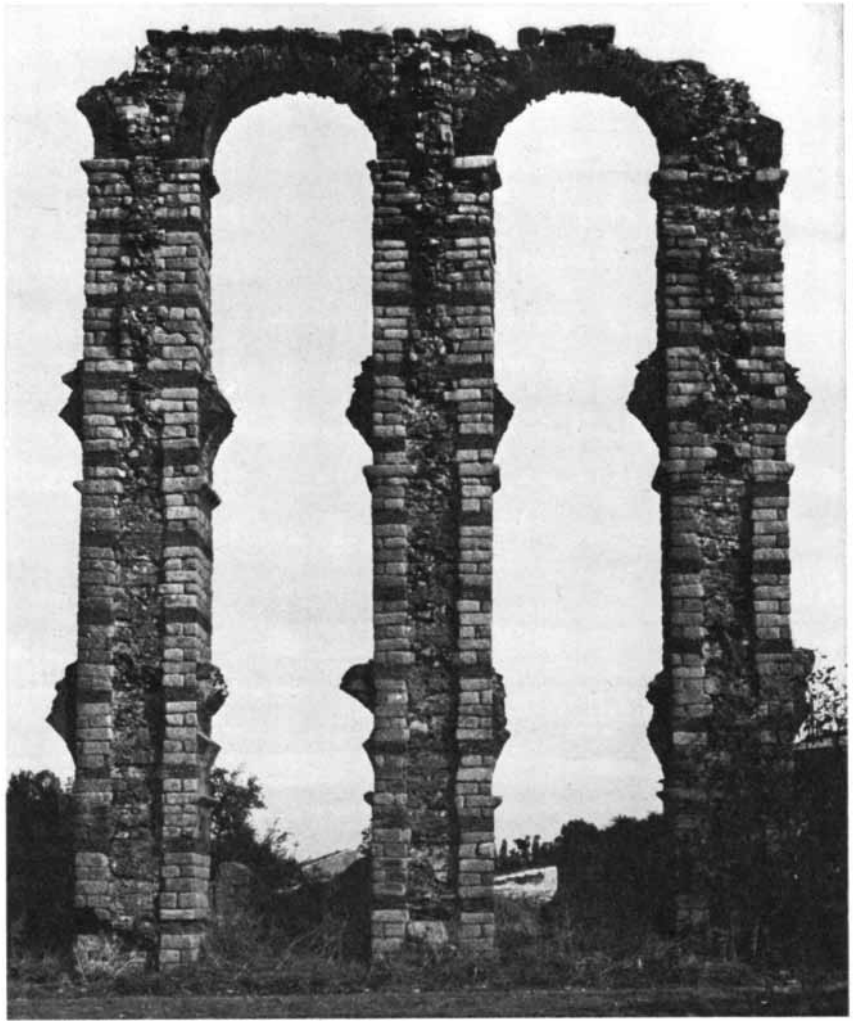
The most ambitious of all Roman land-drainage schemes was initiated by the Emperor Claudius. In A.D. 41 he embarked on a massive tunneling project, easily the biggest until railway tunnels were built, designed to drain the waters of Lake Fucinus (near the modern Avezzano) into a river three and a half miles away. Pliny the Elder, who visited the work in progress, was as impressed by this deep tunnel being cut through rock as by anything he had ever seen. When the system was reworked in the 19th century, sections of the Claudian tunnel and its Trajanic modifications were uncovered. Errors and inconsistencies found in the alignment of the tunnel suggested that the Romans probably gained little advantage from the immense effort they had expended.

The Romans' approach to hydraulic problems was essentially a civil engineering approach. Elements of their mechanical engineering are much harder to identify, and surviving relics are scarce. More than one important question is raised.

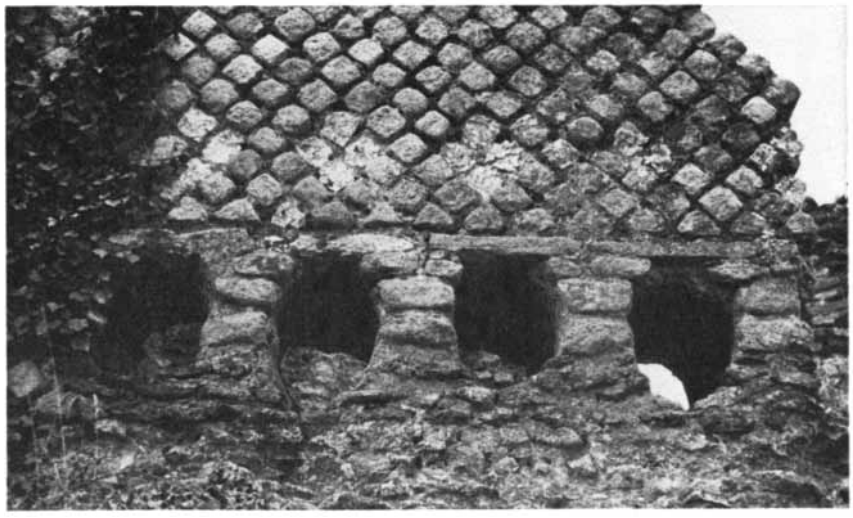
The origin, development and eventual diffusion of all early hydraulic machines is extremely obscure, although it is reasonable to guess that irrigation was the initial stimulus in the search for water-raising devices. One of the few sources of information is the *De architectura* of Vitruvius, a wide-ranging work on a variety of technical themes that is thought to have been written in about 25 B.C.

In the book are to be found matter-of-fact descriptions of a variety of water-raising and water-powered wheels. The implication is of regular but not necessarily widespread use. Three of the water-raising devices described by Vitruvius are closely related. The pot wheel is set vertically and is fitted around its periphery with containers; when the wheel is rotated, water is lifted to a height roughly equal to the diameter of the wheel. For higher lifts a chain of pots (*saquiyah*) is recommended. Here the wheel drives an endless pot-carrying chain, which can be as long as mechanical strength and the power of the driving agent will allow.

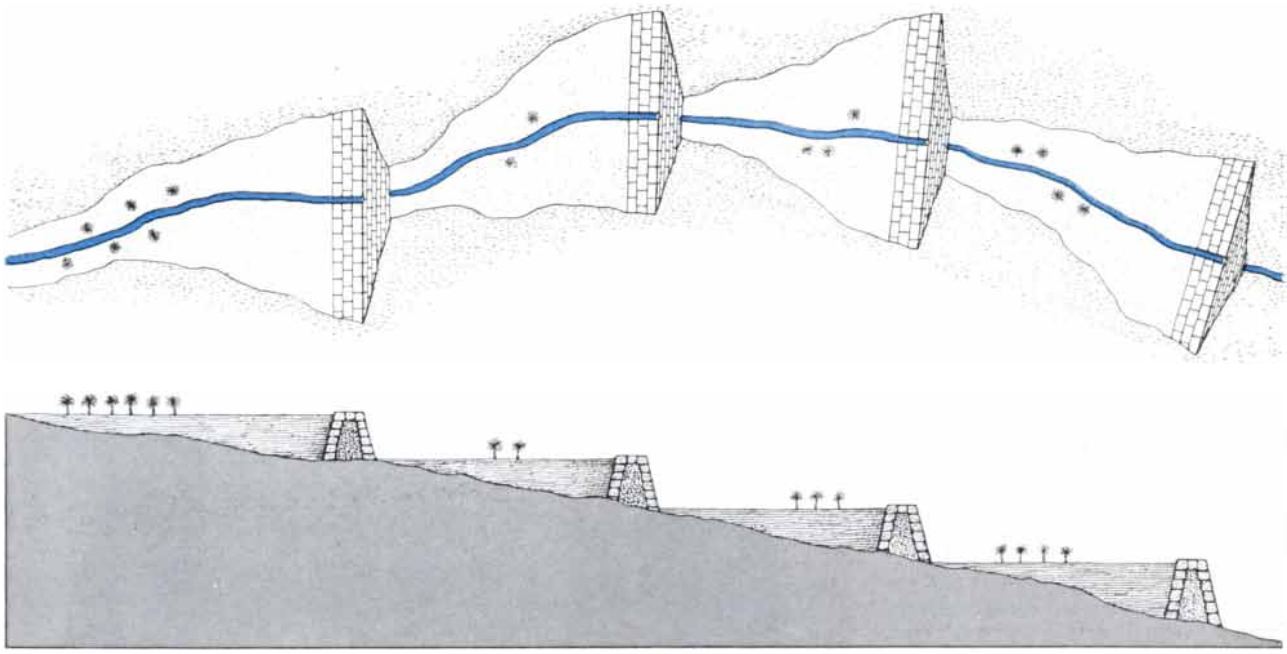
The third device is the *noria,* a pot wheel driven not by men or animals but by the current of the stream from which the wheel is taking water. Vitruvius' de-



THREE PIERS built by the Romans are part of the remains of the Los Milagros aqueduct bridge at Mérida in Spain. At two intermediate levels one sees the protruding remnants of "jack arches" that were built to brace the piers during construction. Full longitudinal bracing was achieved only when the channel and its arches were completed along the top of the bridge.



HEADER TANK remaining from a siphon on the Gier aqueduct serving Lyon indicates the size of the lead pipes that carried the water through the siphon. The end of each pipe, of which there were nine in this siphon, was fitted into one of these oval holes. In the foreground is the beginning of the ramp that carried the pipes steeply down to the floor of the valley. This siphon was 3,950 feet long and reached a depth of 304 feet. Little of the structure remains today.

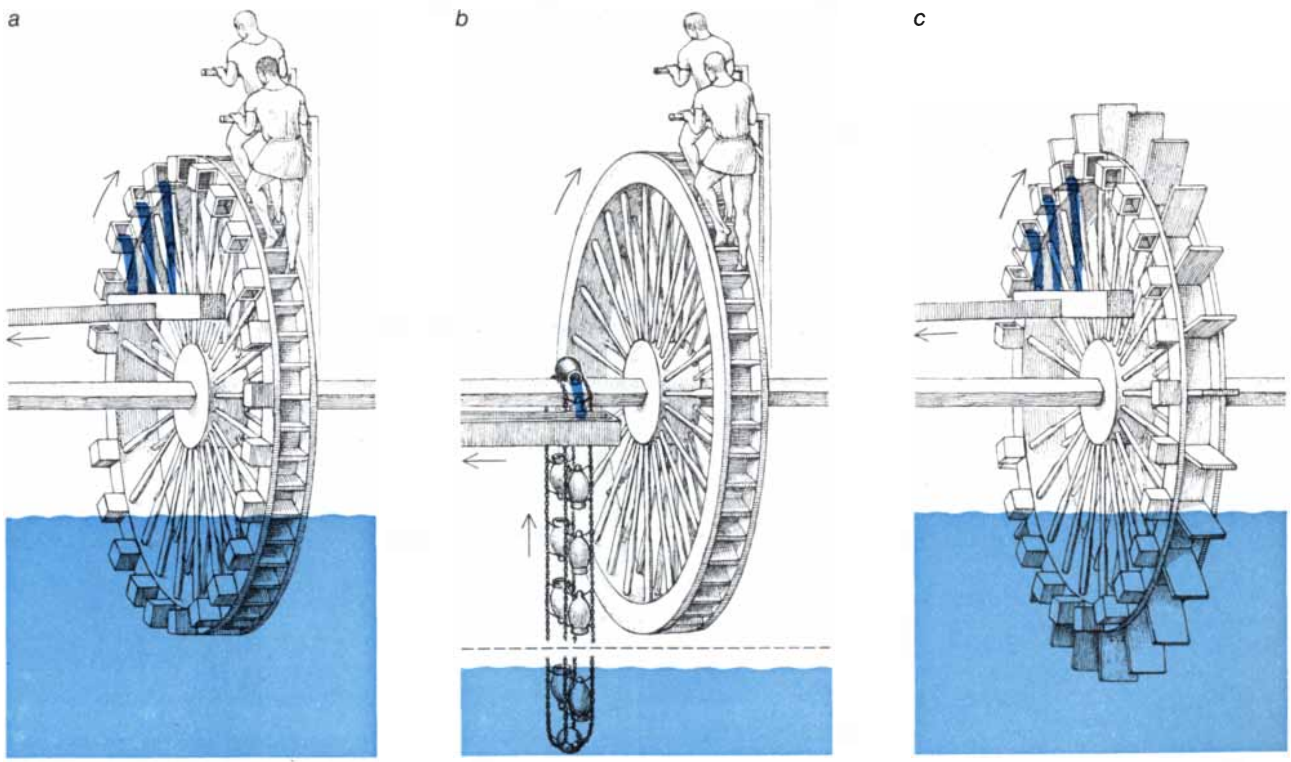


WADI IRRIGATION in desert areas required of the Romans some elaborate hydraulic engineering. A wadi is the bed of a stream that runs briefly but violently during seasonal rains, and the engineering objective is to make the water usable over longer periods. Here one sees in plan (*top*) and in elevation (*bottom*) how the Romans stepped off a wadi with a series of dams. Gradually the structures filled in behind with silt, and the land thus built up could in time be planted to crops. Crops were watered by flood irrigation done on the terraces.

scription of it is the first substantial reference to the harnessing of flowing water to do work. His passage on the *noria* is followed by a few lines on the water mill, a current-driven wheel that operates millstones through a right-angle gear drive. The origins of the water mill are obscure. In particular we do not know whether it was developed from water-raising wheels or vice versa.

Rotary machines were not alone in lifting water; reciprocation also came into play, and it is Vitruvius who provides the oldest description of a piston pump. He says the account is based on the long-lost description by the Hellenistic mechanic Ctesibius. In A.D. 61 the same twin-cylinder, hand-operated machine was described by Hero of Alexandria as a device for fighting fires.

The Romans' hydraulic engineering



WATER-RAISING MACHINES employed in Roman hydraulic projects included the bucket or pot wheel (*a*), the *saquiyah,* or chain of pots (*b*), and the *noria* (*c*), which was a water-driven device. The origin of these devices and most other early hydraulic machines is obscure.

presents us with a marked and intriguing contrast. Their civil engineering repertoire was vast and was applied on a lavish scale. Their commitment to construction, with all it implies in terms of materials, manpower, time and money, is impressive by any standard. On the other hand, their mechanical technology was only marginally developed.

At the end of the first century B.C. the Romans knew how to use water power, yet as far as one can tell they chose not to, at least not to any extent and then only at a late date. To modern eyes this apparent oversight is puzzling, and many attempts have been made to explain it. Probably the explanation is ultimately to be sought in attitudes toward and expectations from technology that are fundamentally different from our own. In short, Roman society simply could not grasp the concept of a power technology, did not think in terms of laborsaving machines and, because of the nature of the ancient economy, had no use for mechanized production. It is well to remember that in order to properly comprehend and objectively evaluate any part of ancient technology one must treat it in its context, being willing to come to terms with the attitudes and objectives of the time and resisting the urge to impose modern ones.

The Roman system of water supply stands as one of the great engineering achievements in antiquity. With the decline of the empire both the administrative authority needed to develop and maintain such systems and the very concept of public works were lost. It was to be a long time before the Roman approach could be taken again.

Even when in the 16th and 17th centuries a few European cities tried to obtain more water, they resorted to a different approach. Toledo, which had once been served by a fine Roman aqueduct, eventually failed in its efforts to pump the River Tagus. Paris succeeded in pumping the Seine and London the Thames, but neither river in the end could supply enough water through mechanical means. Moreover, the water was quite inferior in quality when it was not actually lethal. Mechanical engineering was not the answer. Only London's New River, an open channel built in 1613 to bring water from a stream 40 miles away, represented a solution in the Roman style.

A century or so ago urban populations were growing at an unprecedented rate, notably in Britain. Outbreaks of cholera, particularly in London, focused attention swiftly and sharply on the most critical of all Victorian urban problems: the need to supply water on a scale and of a purity rarely contemplated and never realized for 1,500 years. The solution was to resurrect the entire apparatus of the water-supply technology of the Romans.

THE AMATEUR SCIENTIST

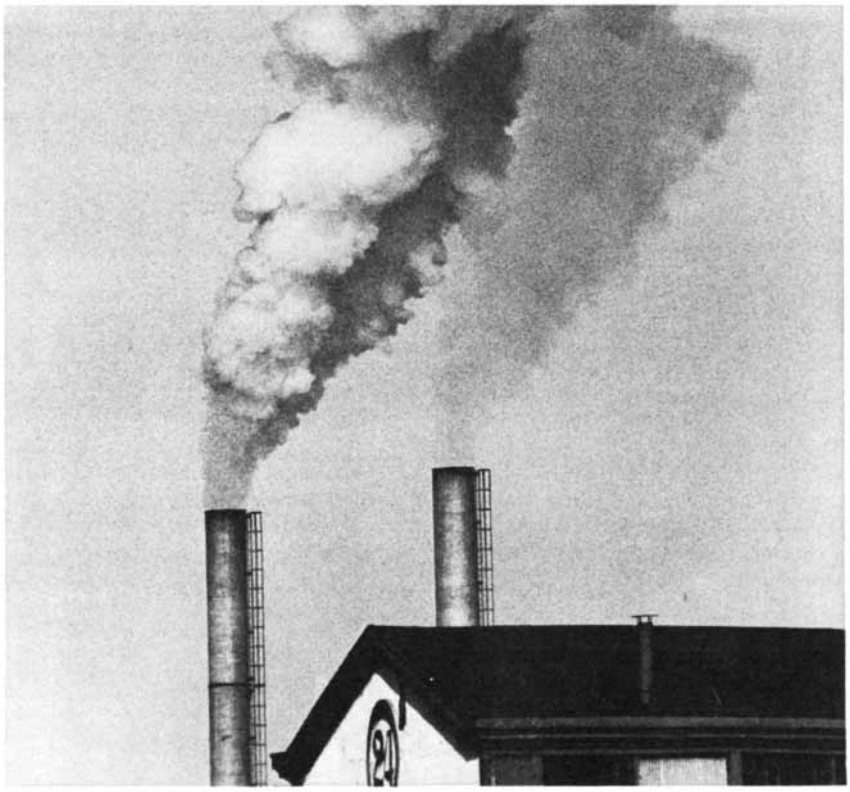
What plumes of smoke tell about the structure of the atmosphere

by Jearl Walker

Plumes of smoke in the air can be both interesting and instructive to watch. Much can be learned from them about how the temperature of the atmosphere varies with height. Smoke plumes can assume a large variety of shapes, which are determined mainly by the variation in the temperature of the air between the ground and some point higher than the smokestack.

There are two basic types of smoke plume: the momentum jet, in which the upward thrust of the plume is due to its initial momentum, and the buoyant plume, which rises or falls according to the relation between its temperature and the air temperature. On a windless day both types of plume rise in a spreading vertical cone whose apex is near the top of the smokestack (provided, in the case of the buoyant plume, that the gas in the plume is hot enough). In the cones of both types of plume the velocity is highest at the central axis of the cone and tapers off toward the outside.

One difference can be noted between the two types of plume: a pure momentum jet has an apex angle of about 24 degrees and a pure buoyant jet has an apex angle of about 18 degrees. I can find no simple or straightforward explanation of this difference. The numbers apparently come from field observations of many plumes. By photographing a vertical plume on a windless day and then measuring the angle of the cone in the photograph you should be able to determine which kind of plume it is. If the angle is smaller than 18 degrees, vertical updrafts near the chimney stack must have forced the plume upward faster and thereby decreased the angle of its cone.



A smoke plume of the roll-vortex type

A plume is buoyant (and therefore rises) if it is warmer than the air at the same height, but other effects are involved. Since atmospheric pressure decreases with height, a parcel of gas in the plume must expand if it is initially forced upward. The energy for the expansion comes from the energy of the molecules in the parcel rather than from some heat source outside it. This internal energy is the kinetic energy of the molecules as they randomly move about.

The temperature of the gas is a measure of its internal energy: the higher the temperature, the greater the kinetic energy of the molecules. If some of the energy goes toward expanding the volume, the temperature of the gas must decrease. Such a temperature change, which involves no exchange of heat with the environment, is said to be adiabatic. Thus a rising parcel of gas in a smoke plume expands and adiabatically cools. Similarly, if the parcel of gas in a plume is initially forced downward, it contracts and adiabatically warms as the outside air works on it.

In rising gas the continuation of buoyancy depends on how fast the temperature of the ambient air changes with height. For example, if the rising plume gas is cooled but remains warmer than the ambient air, it continues to be buoyant and accelerates upward. On the other hand, if the rising plume gas becomes cooler than the ambient air, it ceases to rise and subsequently sinks. If the temperatures match, the plume rises at a constant velocity.

When the gas initially moves downward, it warms adiabatically but its temperature can be above, below or the same as the temperature of the surrounding air at the new height, depending on how the air temperature changes with height. If the gas is then warmer than the air temperature, its descent stops. If it is cooler, its descent continues at an accelerated rate. If the temperatures are the same, the descent continues at a constant velocity. Many of the plume characteristics you will observe depend on this interplay of buoyancy and the rates of cooling and warming and hence on how the temperature of the atmosphere changes with height.

Whether a parcel of gas in a smoke plume moves up or down, it changes temperature adiabatically at the rate of about one degree Celsius for each 100-meter change in height. This rate is called the dry-adiabatic lapse rate, the word dry indicating that no condensation is involved. Depending on weather conditions and environmental sources of heat, the temperature profile of the atmosphere may decrease with height more or less rapidly or even at the same

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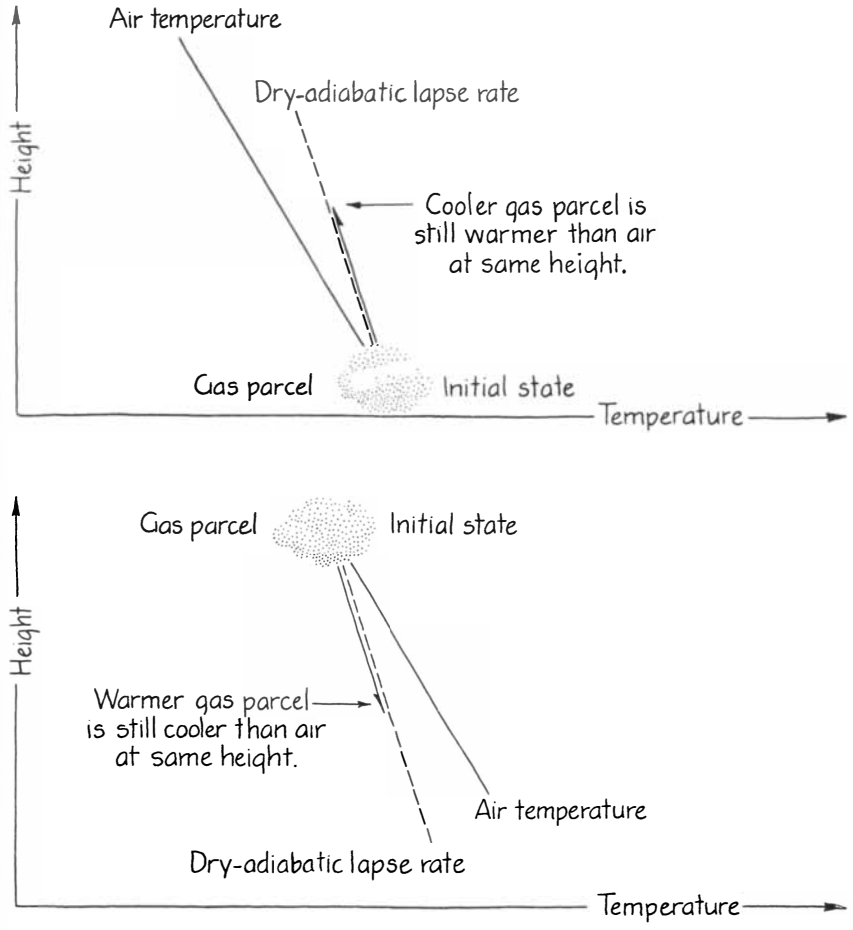
rate as the dry-adiabatic lapse rate. Each of these types of change is an example of a negative lapse rate for the air, because the air temperature in each case decreases with height. Occasionally, however, the air temperature increases with height, the condition termed a temperature inversion. Then the air has a positive lapse rate.

If the gas is wet, the lapse rate may change. The reason is that as the gas cools, its relative humidity increases; after 100 percent humidity is reached further cooling causes some of the water vapor to condense out as small drops. This change in state from vapor to liquid releases energy and prevents a rising parcel of gas from cooling as quickly as it would otherwise. In other words, part of the energy needed for expanding the gas now comes from the change in state of the water, and less energy is taken from the internal energy of the gas. The resulting rate at which a rising parcel of gas changes temperature with height is called the saturation-adiabatic lapse rate. When wet gases rise, they cool at the dry-adiabatic lapse rate until condensation begins, and thereafter they cool at the saturation-adiabatic lapse rate. This variation in cooling rates affects wet plumes of the kind emitted by power plants, since the plumes do not cool as rapidly while rising as a dry plume would.

It is possible for a plume to emerge as a momentum jet, diffuse somewhat and then behave primarily as a buoyant plume. Another type of plume that forms on calm days is strange to me. If the initial velocity of the emerging gases is small, which can happen when a home chimney has too large an opening at the top, the plume does not initially expand in a cone. Instead it converges until the upward velocity increases enough for the plume to expand thereafter as a normal buoyant plume.

You can see a similar but inverted example of this convergence in your kitchen sink. The stream of water from the faucet falls, speeds up and becomes narrower. The narrowing is not due to air pressure, which remains the same throughout the fall. To make sense of it consider a cross section through the stream near the faucet and another one farther down. A certain amount of mass is passing through the upper cross section every second. The same amount must also be passing through the lower cross section every second, otherwise mass would be magically appearing or disappearing between the two levels. Since the speed through the lower section is higher, less cross-sectional area is



Behavior of a rising parcel of gas **(top)** ***and a falling one*** **(bottom)**

needed by the water in order for the same amount of mass to pass through the area every second. The stream is therefore narrower.

The hot gases leaving a stack at a low speed cannot initially expand the way a normal buoyant plume does because the typical cone shape requires a certain ratio between the velocity and the buoyancy. As a result the gases first rise as a stream, accelerating upward because of their buoyancy and contracting in width as the speed increases. Eventually they are moving fast enough to achieve the required ratio, and then the plume can expand in a cone. You might like to search for converging plumes on windless days above house chimneys or hot bonfires.

The prettiest buoyant plumes are seen during steady light winds that bend the plumes over. Whether they then rise, descend, spread up and down, remain thin or loop depends on how the air temperature varies with height and on the extent of the turbulence in the region. The illustration on page 168 displays a variety of plume characteristics, together with the approximate atmospheric temperature profile required for each characteristic. The dry-adiabatic lapse rate is also shown, but that line can be shifted to the left or the right. The line indicates the rate at which a parcel of plume gas changes temperature as it changes height. Before the line could represent the temperature of the gas as a function of height the gas temperature at some particular height (say the chimney top) would have to be known. The line could then be moved to the left or the right to give that temperature at that height.

If the air temperature decreases with height somewhat less rapidly than the dry-adiabatic lapse rate, the bent-over plume is limited in its rise and fall. An ascent would adiabatically cool the gas, with the result that the ascent would eventually halt. A descent would adiabatically warm the gas, bringing the descent to a halt. The temperature profile is close enough to the adiabatic lapse rate, however, for diffusion to gradually spread the plume and produce what is called coning.

When instead the temperature profile decreases much faster than the dry-adiabatic lapse rate (such a profile is called a superadiabatic lapse rate), heat from the chimney stack or the ground can generate thermal eddies large enough to catch the plume and make it loop up and down. This condition occurs on warm days when the ground quickly absorbs a lot of solar heat before the air circulation can remove it. Looping never occurs when there is a strong wind to cool the ground or when there is a layer of snow on it.

If the air-temperature profile has a positive lapse rate, that is, if it increases with height in an inversion, the plume is limited to a relatively thin streaming called fanning. When part of it attempts to rise, it adiabatically cools and becomes considerably cooler than the ambient air, so that the ascent quickly stops. Similarly, if part of the plume attempts to descend, it warms adiabatically, becomes warmer than the ambient air and quickly stops descending.

Lofting is what happens when a temperature inversion below the top of the stack limits downward movement. This type of temperature profile is usually found in the evening, when the ground and the lower part of the atmosphere have begun to cool as the sun disappears but the part of the atmosphere near the stack top is still relatively warm.

Fumigation is the term for what happens when positive and negative lapse rates exist simultaneously, with an inversion above the region where the lapse rate is negative. The inversion prevents the plume from diffusing upward, and the warming near the ground generates a turbulent mixing that brings the plume to ground level. This situation typically occurs in the morning as the ground and the lower air begin to warm.

A similar temperature profile, but one that has a less steep lapse rate near the ground, creates a trapping of the plume between the inversion level and the ground. The plume diffuses to the ground without the aid of large-scale turbulent mixing from warm ground.

Plumes emitted in an otherwise coning or lofting situation might be hot enough to burst upward in thermals: blobs of hot air traveling upward in doughnut form with a strong upward motion in the center and a weaker downward motion on the outside. Such currents, found over well-heated ground or over factories, are used by glider pilots to gain lift.

The shape of the plume in each of these basic cases can be altered if the plume is initially released from the stack with a large momentum. For example, if the elevated inversion layer in fumigation or trapping is relatively shallow, a plume with enough momentum may be able to penetrate the layer instead of being confined below it. Some localities have frequent or persistent inversion layers, and chimneys there are often designed to give the escaping gas enough momentum to make the plume puncture the inversion before the plume levels off. In this way the pollution at ground level is considerably reduced.

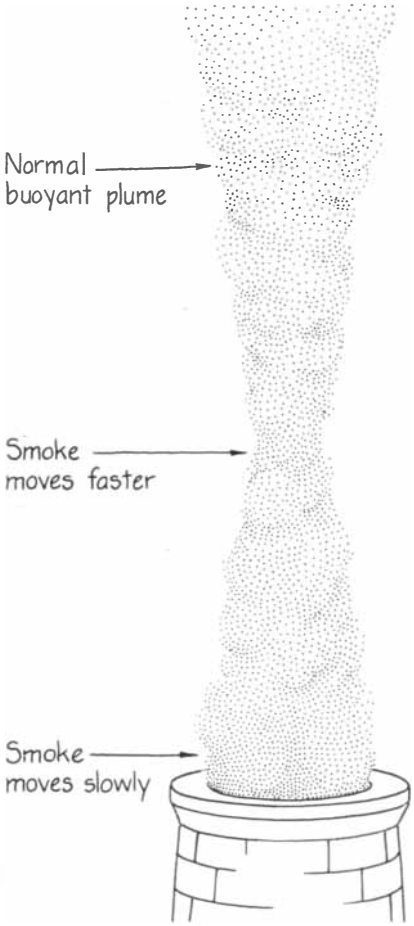
The shapes taken on by wet plumes may be somewhat different from those of dry ones because the adiabatic lapse rate is less steep once water begins to condense in the plume. Some plumes, such as those emanating from power plants, are visible because water condenses out almost immediately to produce a white stream. The mixing of the plume with the surrounding air quickly leads to evaporation, however, so that the visible part of the plume is short.

Sometimes the gas rising through a stack is washed with a spray of water to remove the pollutants. The plume then emerges with water already in the liquid state. When the water evaporates as the plume mixes with the air, the plume is cooled by the energy it loses to the evaporation. (When water evaporates from your skin as you stand in a breeze, you feel cool because your body heat provides the energy to change the water from liquid to vapor.) As a result this rapidly cooled plume will drop, probably reaching the ground near the stack.

If you watch and photograph plumes for an entire day, you will find them going through several changes as the ground warms and then cools off. In the early morning the ground and the lower atmosphere are cool and fanning or lofting plumes are likely. As the ground absorbs solar energy it and the lower level of air get warmer, which initiates turbulence. This warm and turbulent blanket gradually thickens and fumigation or trapping develops. Both effects bring the plume down to ground level. Later, as the upper air gets warm, the plumes may develop coning, thermaling or (if the ground heating is strong) looping. Late in the afternoon the intensity of the sunshine diminishes and the ground and the lower air begin to cool by radiation; then coning may develop in all the plumes. In the evening the lower part of the atmosphere develops an inversion because of the radiative cooling of the ground, and the plumes begin to fan or loft again.

You may be in a position to watch several stacks of different heights simultaneously. In Cleveland I can see at least a dozen such stacks in a shallow valley. By standing on the rim of the valley I can compare the kinds of behavior exhibited by the plumes. With an appropriate distribution of temperature the plumes emitted by the taller stacks can differ from the ones emitted by the shorter stacks because the two sets of plumes are in different parts of the atmospheric temperature profile. For example, tall stacks can emit into a region with a negative lapse rate and show lofting even as shorter stacks emit into an inversion and show fanning. With enough stack heights you can estimate where the change from a positive to a negative lapse rate comes. On days when there is an elevated shallow inversion you might see some plumes puncture the inversion while others are held below it.

Occasionally a plume clings to its smokestack. Sometimes the reason is that in the wind the stack sheds vortexes, which then force the plume initially downward along the stack. At other times a downwash results from the location of the stack with respect to buildings and hills. For example, if the stack is on the leeward side of a large obstacle, the wind is forced upward by the obstacle and then flows downward on the oth-

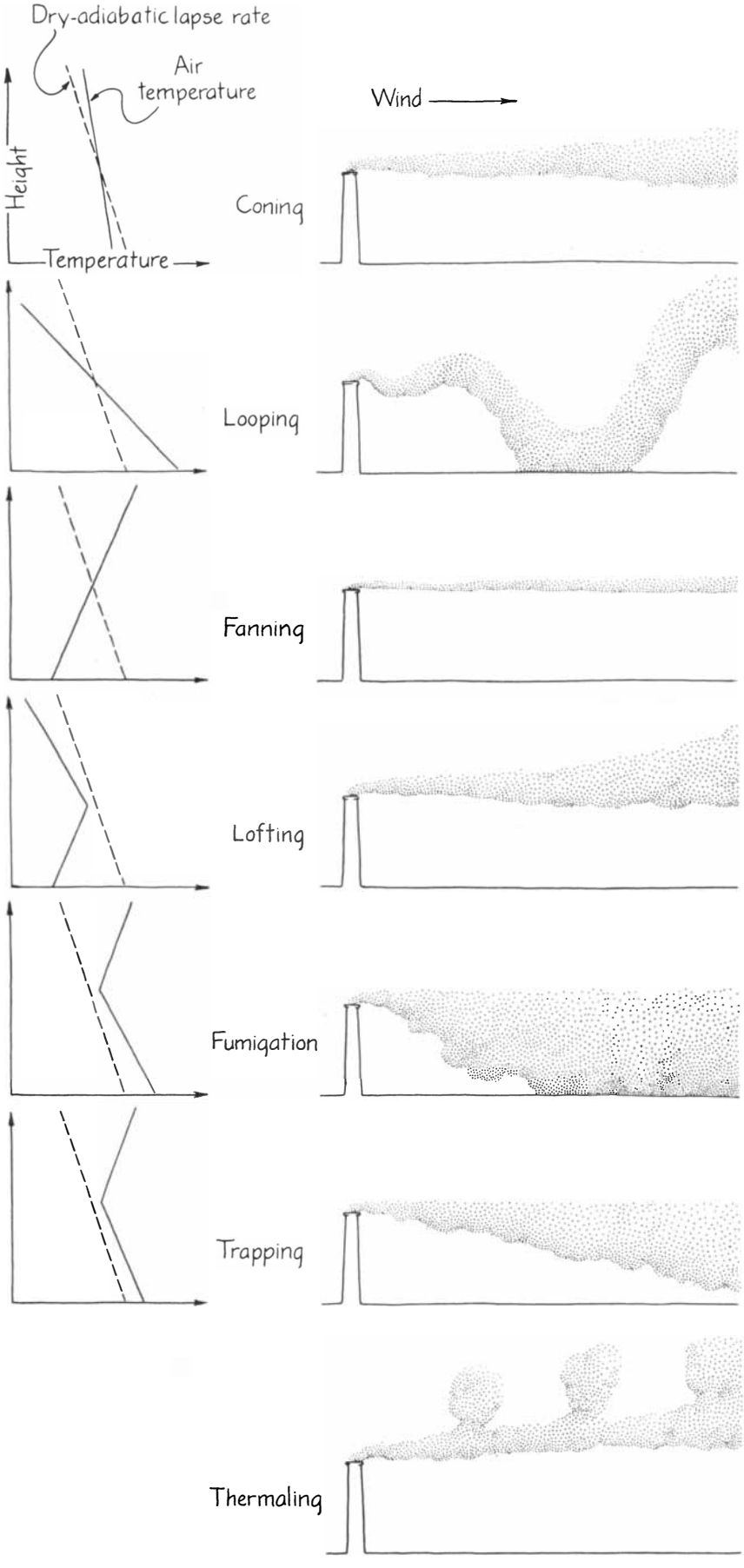


A converging buoyant plume

er side, thereby forcing the plume downward too. On the other hand, if the stack is on the windward side, the plume is likely to be lifted by the upward flow of the wind.

If the chimney opening is too large for the amount of gas it is discharging and the discharge is rather slow, you might find the chimney puffing. One moment it emits gas and smoke in the normal manner; the next moment the cold outside air flows into the chimney along the upwind side, temporarily cutting off the discharge. Eventually the hot gases build up and push their way out of the chimney again, producing another visible puff of smoke before the process is repeated.

If a stack discharges a buoyant plume that does not undergo much turbulent mixing, the plume almost immediately bifurcates. The velocity is greater in the center of the discharging plume than it is on the outside, forcing the plume to circulate in two roll vortexes with an upward motion in the middle of the bent-over plume and a downward motion on the outside. The resulting two roll vortexes split the plume. If you can get near a buoyant plume on a day with a steady nonturbulent wind, stand below the plume and look up into it. The rolling



Plume shapes and corresponding air-temperature profiles

vortex motion is likely to be quite apparent as you watch the plume emerge and move downwind. You may even be able to see the sky between the two streams.

To make a serious study of plume behavior you should try to correlate the mixing of a plume downward to the ground with the way the plume is blowing and with the ground conditions below it. For example, a stack may emit a plume that fans for as long as it remains over ground that is relatively cool and has few obstacles to create large-scale turbulence. If the fanning plume passes over a body of water, the chances are that the water and the lower air will be warmer than the ground. The turbulence associated with the warmer water and air gives rise to fumigation, which brings the smoke down to the water level. I have seen stacks in Cleveland emit thin brown plumes that were blown out over Lake Erie, where fumigation set in and the brown material was mixed down to the water level.

Fumigation may also develop from fanning if the plume passes over artificial heat sources such as the inner city. There the heat mixes the air up to a level about three times the height of the average building. If you can find a plume that remains visible for a great distance, you might be able to see the transition from fanning to fumigation as the plume passes over either a natural or an artificial heat source.

The local terrain may affect plumes in other ways. A narrow valley may aid in holding a plume near the ground if a thermal inversion develops above the cool air trapped in the valley. Any plume created below the inversion would then be unable to penetrate the inversion layer and escape unless it had a high enough exit momentum to achieve the penetration while still behaving as a momentum jet.

Such trapping of noxious plumes in a valley has led to some disasters. An inversion developed over the Meuse valley of Belgium in December, 1930, holding in the valley the emissions of the steel mills and chemical plants. In three days 60 people died, most of them probably of respiratory failure, and thousands became seriously ill. It is hard to believe that the authorities, instead of halting the emissions, laid the tenfold increase in deaths to some strange and unknown disease, one biologist even contending that the cause was plague. Although some time later industrial pollution was blamed, apparently little was done about it. In September, 1972, the valley once again suffered a thermal inversion and a trapping of pollution, which again led to much illness (but no deaths).

The famous fogs that once characterized London resulted from the heavy use of coal, both in factories and in homes, which poured tons of sulfur dioxide into the air daily. As water con-

On Photographing the Invisible

To the naked eye, it was a Swedish 80-ore postage stamp. A rarity, and very valuable.

The camera, however, told quite another story. The stamp was a counterfeit.

Faint traces of tampering that were hidden to the naked eye were revealed by the camera. Someone, somewhere, had ingeniously altered the stamp by chemically removing a surprint. The stamp was worthless.

To the naked eye (left), the stamp was genuine. To the camera (right), it was a counterfeit. Note the faint, dark traces of tampering now revealed in the upper section.

What manner of exotic camera was this that could "see" the invisible?

The lens: one of the 20 in the Hasselblad arsenal, the 105mm Zeiss UV-Sonnar f4.3. Designed for photography within the ultraviolet portion of the electromagnetic spectrum, its costly quartz elements can detect radiations that are unseeable by the human eye.

It has peered at objects in outer space, examined forgeries, laid bare the secrets of counterfeit money. Not a lens for everyone, obviously, but an indication of just how awesomely comprehensive the Hasselblad System is.

The camera: an otherwise perfectly standard Hasselblad 500C/M, normally fitted with an 80mm Zeiss Planar f2.8 multi-coated lens.

This is the basic model that allows you to tap into the vast Hasselblad System. It is one of the most bewilderingly versatile cameras the world has ever known. Yet so marvelously simple to operate that it often plays the part of the family snapshot camera.

A True System.

The Hasselblad System is a prodigious array of 4 cameras, 20 lenses, 8 viewfinders, 9 film magazines, and over 300 other accessories. Choose the right pieces, and your 500C/M would be equipped for sports, aerial, architectural, and fashion photography.

And portrait, landscape, medical, underwater, and news photography.

And wildlife, laboratory, industrial, and child photography.

And you would always have the right film in the camera at the right time. You can shift from color to black-and-white and back again to color—and resume shooting at precisely the right frame—by popping in the protective dark slide and switching film backs.

The Camera with Nine Backs.

There is a small button on the film back of every Hasselblad 500C/M. Slide it sideways with your thumb and the back will come away in your hand.

The standard back holds 12 exposures. Each frame of film is 2¼ inches square, *almost four times the area of a 35mm frame.* (See box, below right, for actual size.)

This is only the beginning. There are eight other backs available: Backs that let you change to a 6 x 4.5cm format...or a 4.5 x 4.5cm superslide format for showing in any 35mm projector. Backs that give you a choice of 1, 12, 16, 24, 70, or 500 exposures. A back that is a sheet-film adapter. Even two backs for Polaroid film, so you can check composition, lighting, and exposure ahead of time.

You begin to realize why eight out of ten top commercial photographers surveyed name Hasselblad as the medium-format camera used in their work.

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In an age when machines spew out cameras in the tens and hundreds of thousands, when flashy new models thrust last year's marvels into early obsolescence, Hasselblad goes its own way.

Planned obsolescence is taboo at Hasselblad. All but two of the accessories for the 500C/M will fit every Hasselblad made since 1957 (except the Super Wide C)...and will fit every future Hasselblad.

The greater part of a year is spent on building each camera, much of it crafted by hand. And fully one quarter of the work force devotes its time to nothing but quality control.

Little wonder, then, that a preowned Hasselblad commands such a high price...if its owner can be persuaded to part with it at all.

densed on the particles, thick brown fogs ("pea-soupers") were created. In December, 1952, as some 2,000 tons of sulfur dioxide were thrown into the air each day, a thermal inversion developed over cooler ground air and held all the factory and home plumes below the inversion. In the absence of wind to blow the material away the sulfur dioxide collected over the city for four days and nights, with the sky becoming first yellow, then brown and finally black. Some 4,000 people died as a direct result of the pollution and another 8,000 who died later were thought to have been afflicted by the respiratory problems brought about by the strong inversion.

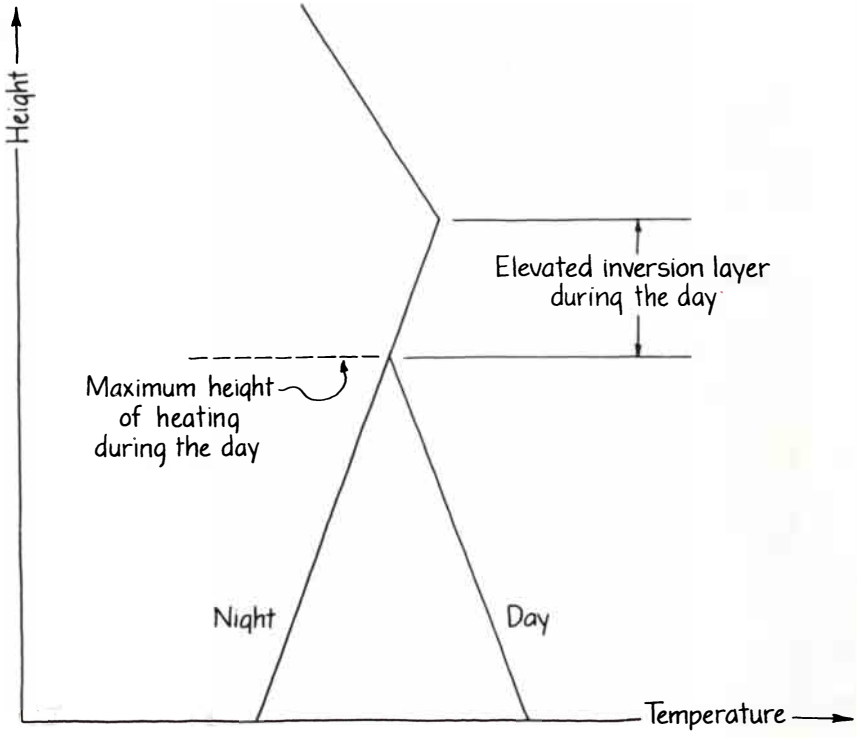
If the day is too rainy for you to go outside to watch chimney plumes, you can stay indoors and examine the smoke rising from a cigarette. The stream is smooth and narrow near the burning tip; several centimeters higher it breaks up into swirls and the plume spreads out. To see the transition you need either a room with no air currents or a large vertical glass tube open at both ends. When the gases emerge from the burning tip, they experience a buoyant force because they are hotter than the room air. Because the initial velocity is relatively small, however, the hot gases rise in a smooth stream. After several centimeters, perhaps as many as 30, the upward acceleration from the buoyancy has increased the speed to the point where the stream becomes unstable and begins to break up into swirls.

Similar transitions from laminar to turbulent flow occur in water moving through pipes. If the water moves slowly (what "slowly" means depends on the radius of the pipe and the density and viscosity of the water), it moves smoothly. Each small parcel of water flows along a line parallel to the pipe wall. At a certain higher speed the flow becomes unstable. Swirls develop, and each small parcel of water follows an irregular route along the pipe. You can make this swirling apparent in a transparent pipe by using dye tracers. In a cigarette stream the smoke particles act as the tracers.

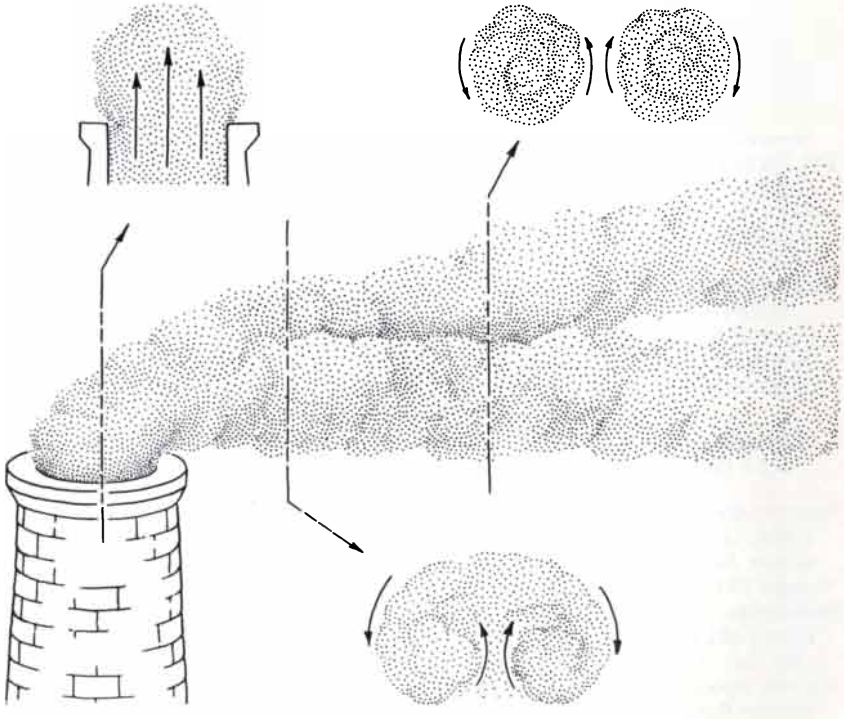
If the cigarette is unfiltered, you may notice a slow stream of smoke emerging from the unlighted end. After they have gone through the length of the cigarette, the gases carrying the smoke have cooled; they emerge at approximately the temperature of the room air and therefore have no buoyancy.

American Indians employed smoky bonfire thermals to communicate over considerable distances. In the book *Natural Aerodynamics* R. S. Scorer describes how aborigines in Australia sent up plumes as signs on a far larger scale. As several people lifted a bonfire with long poles, others threw on fresh brush. The lifting increased the airflow through the fire and thus the rate of burning, and the brush produced thick smoke. By means

of a coordinated effort of the workers a smoky thermal was sent upward. When this procedure was followed in the morning or evening temperature inversion, the thermal would rise until its temperature matched that of the ambient air, at which point the smoke diffused horizontally to yield a pattern resembling a huge mushroom. By carefully judging how hot to make the fire with the lifting, the workers could control the height at which the horizontal spreading took place. If the occasion was a particularly significant one, the workers apparently were able to stack as many as six mushrooms over the bonfire.



Daily variation of the air-temperature profile



A plume splitting into two roll vortexes

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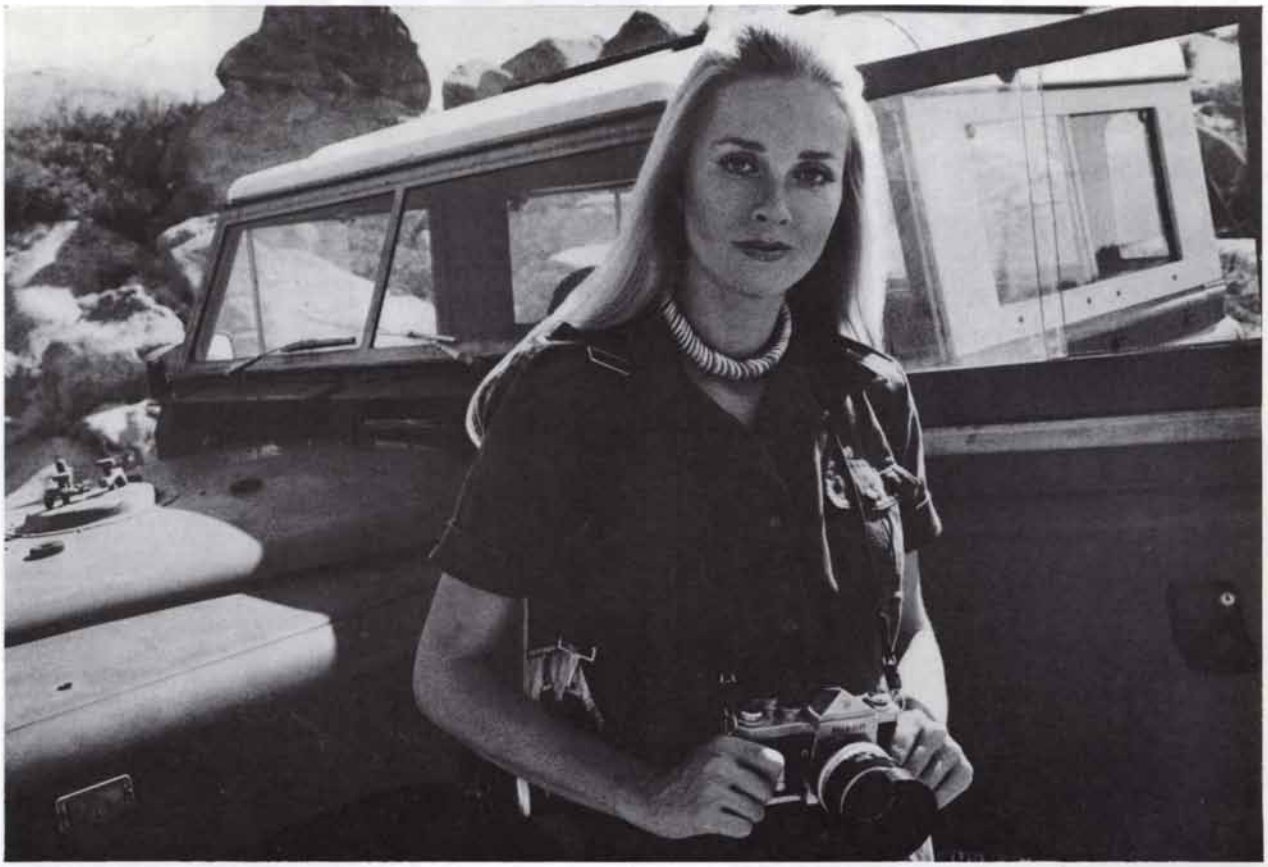

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